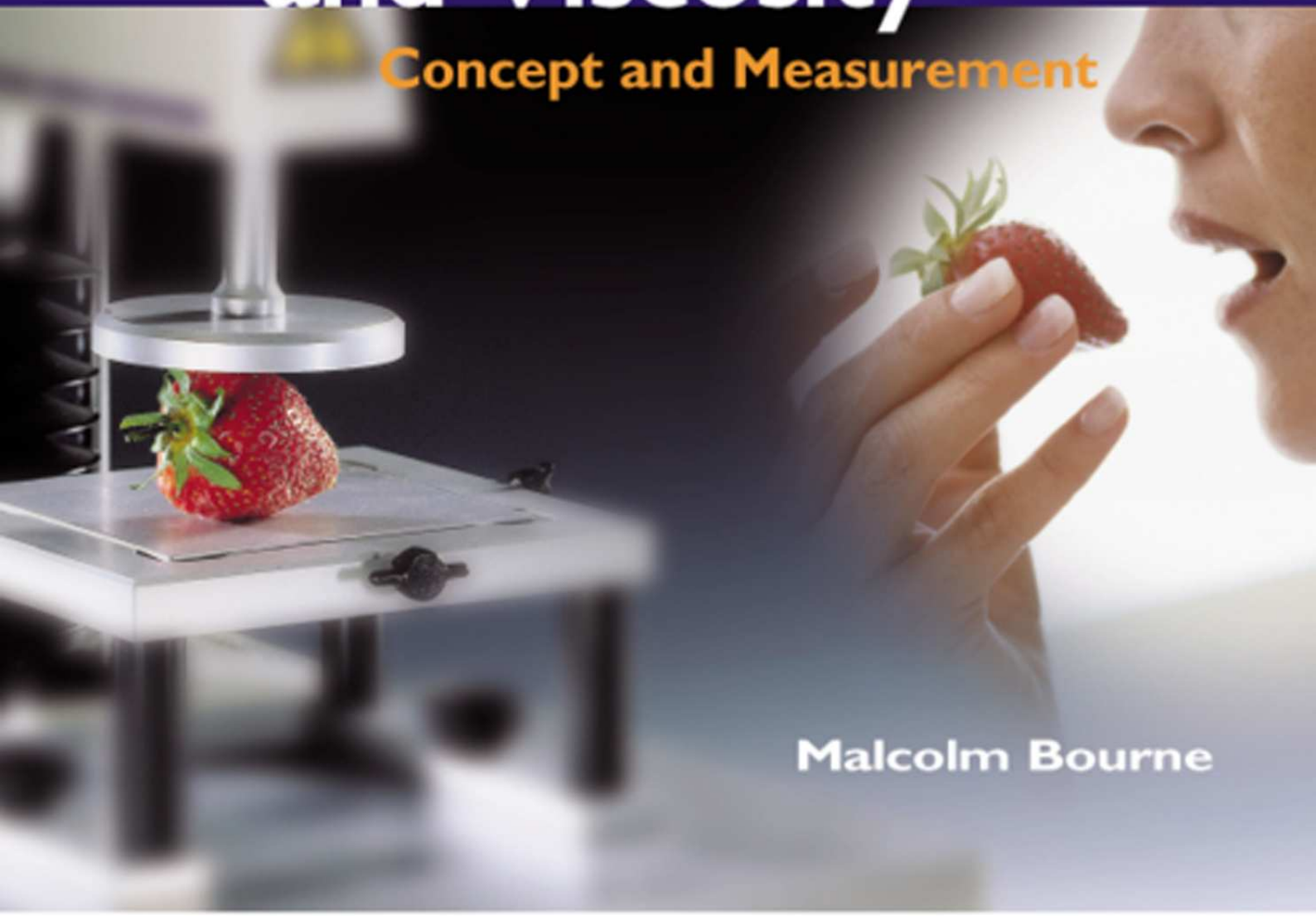
2nd Edition

Food Texture and Viscosity

Concept and Measurement



Malcolm Bourne

Food Science and Technology, International Series

FOOD TEXTURE AND VISCOSITY: CONCEPT AND MEASUREMENT

Second Edition

Food Science and Technology
International Series

A complete list of the books in this series appears at the end of this volume.

Food Texture and Viscosity: Concept and Measurement

Second Edition

Malcolm C. Bourne

New York State Agricultural Experiment Station and Institute of Food Science
Cornell University
Geneva, New York

ACADEMIC PRESS
An Elsevier Science Imprint

San Diego San Francisco New York Boston
London Sydney Tokyo

Academic Press
An Elsevier Science Imprint
Harcourt Place, 32 Jamestown Road, London NW1 7BY, UK
http://www.academicpress.com

Academic Press
An Elsevier Science Imprint
525 B Street, Suite 1900, San Diego, California 92101-4495, USA
http://www.academicpress.com

ISBN 0-12-119062-5

Library of Congress Control Number: 2001097268

A catalogue record for this book is available from the British Library

Typeset by Charon Tec Pvt. Ltd, Chennai, India
Printed and bound in China by RDC Group Limited

02 03 04 05 06 07 RD 9 8 7 6 5 4 3 2 1

To my beloved wife, Elizabeth

This Page Intentionally Left Blank

Contents

Chapter 3
Physics and Texture

Chapter 4
Principles of Objective Texture Measurement

Chapter 6
Viscosity Measurement

Chapter 7
Sensory Methods of Texture and Viscosity Measurement

Chapter 8
Correlation Between Physical Measurements and Sensory Assessments of Texture and Viscosity

Chapter 9
Selection of a Suitable Test Procedure

Preface to the Second Edition

Many wonderful advances have been made in understanding what texture is all about and in instrumentation to measure the texture and viscosity of foods since the first edition of this book was published in 1982. Hence the need for a second edition.

This book is still intended for those who want to know more about texture and viscosity of food, how these properties are measured and relate to human assessments of textural quality. It draws together literature from many sources including journals in chemistry, dentistry, engineering, food science, food technology, physics, psychology and rheology. Scientific and trade journals dedicated to special food groups, books, proceedings and commercial literature have also been utilized. *Journal of Texture Studies* has been a major source of information for new developments in the field.

The treatment is descriptive and analytical with the minimum of mathematics. Equations are given only when they illuminate the discussion and then only in the simplest form. Their derivations, however, are not given, this is not a mathematics text book. Additions have been made to every chapter, and although most of them are small, their cumulative effect is great.

Chapter 1 defines texture terms, discusses the importance of textural properties of foods, locates texture in the overall area of food science, gives some interesting general facts about texture, and a brief history of earlier developments in the field. Chapter 2 describes physical interactions between the human body and food – a necessary background for the ensuing chapters. A new section on the hand has been added because gentle squeezing of food is gaining increased attention. Chapter 3, a new chapter, describes the importance of physics in texture measurement. The rigor of the physics approach is needed in our field. However, the limitations of physics to resolve complex practical problems is also noted. Chapter 4 describes the principles of objective methods of texture measurement, including ideas that have yet to evolve into commercial available instruments, and provides a foundation for the following chapter.

A major goal of this chapter is to move the thinking about texture from a food-by-food basis to general principles that can be applied to all foods. Chapter 5 describes commercial instruments and their use. Although the use of universal testing machines and computer retrieval and analysis of force–time data have become widespread (a great advance in the author's opinion) there is still a place for the small, simple instruments that are also described. Chapter 6 provides a brief description of commercial viscometers. The description of the various types of viscous flow has been moved to Chapter 3 (physics). There have been a number of great advances in instrumentation, especially for controlled shear stress viscometers. Chapter 7 describes sensory methods for measuring texture and viscosity and is an essential component of this book. Many sensory scientists have no interest in texture. It is hoped this chapter will awaken their interest in texture as a sensory attribute. Chapter 8, a new chapter, covers our present level of understanding of correlations between physical measurements and sensory assessments of texture and viscosity. Chapter 9 outlines a system for selecting a suitable instrument, or a suitable test procedure for a universal testing machine with the minimum of time and cost. Appendix I lists the names and addresses of suppliers of instruments for those who are interested in purchasing equipment. Appendix II gives data on texture–temperature relationships that are too long to fit comfortably into Chapter 8. Appendix III lists test conditions for specific foods in universal testing machines. I have no vested interest in any corporation that sells texture-measuring instruments and have endeavored to be unbiased in describing commercial instruments, and to make the list as complete as possible. Appendix IV gives examples of sensory texture profiles on eleven different foods.

Many people will read this book selectively. The practising food technologist and quality controller will concentrate on Chapters 5, 6 and 9. The professor and college student might spend most time on Chapters 3 and 4. The sensory scientist will find Chapters 7 and 8 of greatest interest. The laboratory manager wanting to establish a texture laboratory will find Chapter 9 and Appendix I useful. Everybody should find Chapters 1 and 2 of great interest.

I have expressed my own opinions and interpretations in this volume because I believe most readers will appreciate some guidance rather than a simple listing of many facts of varying levels of usefulness and accuracy. Even if subsequent reports show the guidance to be wrong at times, I hope most readers will find useful the methods and yardsticks offered. My personal conviction that empirical tests have been responsible for most of the successes in practical food texture measurement is reflected in the extended discussion of empirical methodology. However, it is a pleasure to report that some of these empirical tests are now being given serious attention by the research community and are on the way to becoming rigorous, fundamental tests.

I acknowledge with thanks help from many sources in the preparation of this second edition. A number of individuals and organizations provided figures or compiled tables and their contributions are noted wherever that figure or table

appears. I particularly thank J. Barnard, O. Campanella, B. R. Heath, M. Peleg, A. S. Szczesniak and Z. M. Vickers, each of whom critically reviewed one or more chapters in the draft stage and made numerous suggestions for improvement. I also thank K. C. Diehl, S. A. Brown, J. Faubion, K. M. Hiiemae, G. J. Bourne, T. Gibson and N. Marriott who clarified specific points for me, and B. A. Andersen who typed the many additions and M. M. Walczak who typed the subject index. My colleague, Prof. M. A. Rao has provided encouragement and fruitful discussions for many years. Representatives from a number of instrument suppliers have been helpful in clarifying details about their instruments. I sincerely thank each one for their contribution.

The two pictures on the cover depict the dual nature of food texture measurement. Only humans can assess the textural quality of food. In this picture the firm, plump, succulent texture of strawberry is measured sensorially while the firmness is also measured by compression in a machine. Instruments that measure physical properties are widely used and have led to great improvements in building and maintaining a high level of textural quality in most of our food supply. Nevertheless, instrument readings are worth little unless calibrated against the human senses. I thank Stable Micro Systems Inc. for providing these cover pictures.

This Page Intentionally Left Blank

Texture, Viscosity, and Food

CHAPTER 1

Introduction

The four principal quality factors in foods are the following.

1. *Appearance*, comprising color, shape, size, gloss, uses the optical sense.
2. *Flavor*, comprising taste (perceived on the tongue) and odor (perceived in the olfactory center in the nose), is the response of receptors in the oral and nasal cavities to chemical stimuli. These are called 'the chemical senses'.
3. *Texture* is primarily the response of the tactile senses to physical stimuli that result from contact between some part of the body and the food. The tactile sense (touch) is the primary method for sensing texture but kinesthetics (sense of movement and position) and sometimes sight (degree of slump, rate of flow), and sound (associated with crisp, crunchy and crackly textures) are also used to evaluate texture.
4. *Nutrition* comprises major nutrients (carbohydrates, fat, protein) and minor nutrients (minerals, vitamins, fiber).

Other factors, such as cost, convenience, and packaging, are also important but are not considered quality factors of foods. Of the above listed the first three are termed 'sensory acceptability factors' because they are perceived by the senses directly. Nutrition is a quality factor that is not perceived by the senses.

The sensory acceptability factors of foods are extremely important because people obtain great enjoyment from eating their food and, furthermore, the enjoyment of food is a sensory pleasure that is appreciated from the cradle to the grave.

Importance of Texture

The importance of texture in the overall acceptability of foods varies widely, depending upon the type of food. We could arbitrarily break it into three groups:

1. *Critical*: Foods in which texture is the dominant quality characteristic; for example, meat, potato chips, cornflakes and celery.
2. *Important*: Foods in which texture makes a significant but not a dominant contribution to the overall quality, contributing, more or less equally, with flavor and appearance; for example, most fruits, vegetables, cheeses, bread, most other cereal-based foods and candy fall into this category.
3. *Minor*: Foods in which texture makes a negligible contribution to the overall quality; examples are most beverages and thin soups.

Achieving the desired textural quality of food has important economic considerations. A good example of this is found in beef. Supermarkets in the United States sell cuts of beef that range from less than three dollars per kilo to more than twenty dollars per kilo. The main determinant in this wide range of price is its texture. Beef that is tough or dry either sells for a low price or is made into ground beef or various kinds of sausage, whereas tender beef commands a higher price and is usually sold in the form of roasts and steaks. When one considers the many millions of kilos of beef consumed each year in the United States it becomes abundantly clear that textural quality has major economic importance.

The importance of texture in foods was indirectly pointed out by Schiffman (1977; Schiffman *et al*., 1978), who fed 29 different foods to people who had been blindfolded and asked them to identify the foods based only on flavor. The samples had been pureed by blending and straining in order to eliminate textural clues. Some of the data from Schiffman's work are shown in Table 1.1. It is remarkable to discover how poorly many foods are identified when their texture and color are concealed and flavor is the only attribute that can be used for identification. Young adults of normal weight were able to identify correctly only 40.7% of the foods used in the study. It is surprising to find, for example, that only 4% of the respondents could identify cabbage correctly by flavor only, 15% for pork, 41% for beef, and 51% for carrots.

The importance of texture, relative to other quality factors of foods, may be affected by culture. For example, in a study of food patterns of the United States and Caribbean Blacks, Jerome (1975) stated: 'For Afro-Americans of southern rural origin, the element of primary importance associated with food patterns is *texture*; flavor assumes secondary importance.'

Another indication of the importance of texture in food is the large size of the dental industry in developed countries. This is due primarily to the fact that people do not want to be deprived of the gratifying sensations that arise from eating their food. From the nutritional standpoint it is possible to have a completely adequate diet in the form of fluid foods that require no mastication,

Table 1.1 Percentage of Correct Identification of Pureed Foods[a]

Food	Normal weight (young)	Obese (young)	Normal weight (aged)
Apple	81	87	55
Strawberry	78	62	33
Fish	78	81	59
Lemon	52	25	24
Carrot	51	44	7
Banana	41	69	24
Beef	41	50	27
Rice	22	12	15
Potato	19	69	38
Green pepper	19	25	11
Pork	15	6	7
Cucumber	8	0	0
Lamb	4	6	—
Cabbage	4	0	7
Mean for 29 foods	40.7	50.0	30.4

[a]From Schiffman (1977), Schiffman *et al.* (1978).

but few people are content to live on such a diet. As their tooth function deteriorates with age, they undergo the inconvenience and cost of dental care that restores tooth function and enables them to continue to enjoy the textural sensations that arise from masticating their food.

The deeply ingrained need to chew on things is also found among infants. Growing infants are provided with teething rings and similar objects in order to give them something to satisfy their need for biting and chewing. If the baby is not given something on which it can chew, it will usually satisfy its need to chew on items such as the post of its crib, father's best slipper, or the expensive toy given by a doting grandmother.

Szczesniak and Kahn (1971) conducted in-depth interviews with homemakers and found that texture awareness in the United States is often apparent at a subconscious level and that it is taken more or less for granted; however, when the textural aspects did not come up to expectations, there was a sharp increase in the awareness of the texture and criticism of the textural deficiencies. The authors state that

> If the texture of a food is the way people have learned to expect it to be, and if it is psychologically and physiologically acceptable, then it will scarcely be noticed. If, however, the texture is not as it is expected to be … it becomes a focal point for criticism and rejection of the food. Care must be taken not to underestimate the importance of texture just because it is taken for granted when all is as it should be.

In a widely cited study, Schutz and Wahl (1981) obtained 420 valid returns from a mail ballot to a random group of people living in Sacramento, California, asking them to distribute 10 points on a constant sum scale among the characteristics of appearance, flavor and texture according to the attributes'

importance to the respondent for 94 foods when eaten. The overall means were 2.57 for appearance, 4.92 for flavor and 2.51 for texture which implies that texture is less important than flavor in food acceptability. However, if we assume that the flavor score is equally divided between taste and odor, the overall means become 2.57 for appearance, 2.46 for odor, 2.46 for taste and 2.51 for texture and then texture carries about the same weight as the other acceptability factors for foods.

Some other interesting points about texture importance found in this report by Schutz and Wahl (1981) are as follows. (1) Males and those with a higher education gave significantly higher scores for texture compared with the group as a whole. (2) The 10 foods with the highest texture score were raw bean sprouts, raw celery, white bread, shredded wheat cereal, iceberg lettuce, oatmeal, angel food cake, raw apples, puffed corn cereal and raw carrots. It is surprising to find that this group did not include beef steak as having a high texture score. (3) The 10 items with the lowest texture score were all liquids: coffee, cola soft drinks, red table wine, beer, soy sauce, grape juice, lemon juice, barbecue sauce, apricot nectar and tomato juice. Texture scores ranged from 1.33 for coffee to 2.17 for tomato juice with a mean score of 1.745. As pointed out earlier, texture is of minor importance for most beverages and hence, it is surprising to find in this report that even coffee scored 1.33 points for texture out of a total of ten points for all acceptability factors.

The Vocabulary of Texture

Szczesniak and Kleyn (1963) gave a word association test to 100 people to determine their degree of texture consciousness and the terms they used to describe texture. Seventy-eight descriptive words were used by the participants. These authors concluded that texture is a discernible characteristic, but that it is more evident in some foods than others. Foods that elicited the highest number of texture responses either were bland in flavor or possessed the characteristics of crunchiness or crispness.

Yoshikawa *et al*. (1970a,b,c) conducted tests in Japan that were similar to those conducted by Szczesniak's group in the United States. They asked 140 female college students to describe the texture of 97 foods and collected 406 different words that describe textural characteristics of foods. In a similar study Rohm (1990) asked 208 college students in Austria to describe 50 foods and obtained 105 texture words. Rohm *et al.* (1994) compared texture words (in German) generated by students in Dresden, Hannover and Vienna. These studies showed the importance of textural properties as a factor in food quality and the great variety of textures found in food. The 10 most frequently used words in these three studies are listed in Table 1.2. It is interesting to notice that six of these 10 words are common to all three lists. It is also noteworthy that the Japanese used 406 descriptive words as compared to 78 words in the United States and 105 words in Austria.

Table 1.2 Most Frequently Used Texture Words[a]

United States[b]	Japan[c]	Austria[d]
Crisp	Hard	Crisp
Dry	Soft	Hard
Juicy	Juicy	Soft
Soft	Chewy	Crunchy
Creamy	Greasy	Juicy
Crunchy	Viscous	Sticky
Chewy	Slippery	Creamy
Smooth	Creamy	Fatty
Stringy	Crisp	Watery
Hard	Crunchy	Tough
78 words	406 words	105 words

[a]In descending order of frequency.
[b]Szczesniak and Kleyn (1963).
[c]Yoshikawa *et al.* (1970a).
[d]Rohm (1990).

Perhaps the richer textural vocabulary of the Japanese is due partly to the greater variety of textures presented in Japanese cuisine, making them more sensitive to subtle nuances in textures, and partly to the picturesque Japanese language which uses many onomatopoeic words. For example, Yoshikawa *et al.* (1970a) assign to each of the following expressions the meaning of some form of crispness: *kori-kori*, *pari-pari*, *saku-saku*, *pori-pori*, *gusha-gusha*, *kucha-kucha*, and *shaki-shaki.*

In a second study (Szczesniak, 1971), a word association test was given to 150 respondents and the results were similar to the first study. This test again showed that texture is a discernible characteristic of foods and the awareness of it generally equivalent to that of flavor. This study also found that women and people in the higher economic brackets showed a higher level of awareness of the textural properties of foods than did the general population.

The language used to describe the textural properties of foods is very important, especially in sensory testing and consumer verbalizations of quality. An international standard nomenclature is needed to ensure that research reports from different countries are referring to exactly the same properties. Table 1.2 shows that there can be many similarities between countries but there is not complete unanimity.

Drake (1989) compiled a list of 54 words for textural properties of foods and with the help of over 50 collaborators found their equivalent meanings in 22 other languages ranging from Bahasa to Welsh. One conclusion from this comprehensive compilation is that since every meaning could be found in every language the knowledge and interest in texture is universal and knows no national boundaries. An appendix to Drake's list provided 200 additional English words that sometimes have a textural/rheological meaning.

Lists of texture words in Spanish have been published by Badui (1988), Anzaldúa-Morales (1989), and Pedrero and Pangborn (1989).

Anzaldúa-Morales (1990) pointed out that some words that might appear to translate into another language easily are not always equivalent. For example, the English word 'viscous' might seem to translate into Mexican Spanish 'viscoso' but that is incorrect. The correct Spanish word is 'esposo' meaning thick. 'Viscoso' means slimy like raw egg white or okra.

Lawless *et al*. (1997) compared many sensory texture terms in Finnish and English and reported that the number of terms can be reduced by use of principal component analyses. They also noted that English often gives more than one meaning to a word whereas they are clearly distinguished with no ambiguity about their meaning in Finnish. For example, the word 'thick' in English might refer to dimension ('a thick potato chip') or resistance to flow (maple syrup is thick) whereas in Finnish the word for thick (dimension) is 'paksu' and for thick (viscous) is 'jahmea'. They conclude that the dimensions of texture are consistent across cultures but there are differences in nuance. They also state 'the similarities in texture words and their conceptual groupings are more similar than they are different in these two languages (English and Finnish) having very different linguistic roots'.

Oram (1998) studied the food vocabulary of Australian schoolchildren aged 6–11 years, and adults, using 126 words that might relate to food, 10 non-food words (e.g. jump) and 10 non-words (e.g. frunp). He found that by age 6–7 (grade 1 in school) children already have a limited vocabulary that refers to a wide range of food attributes and this vocabulary then grows as they become older. More than 60% of grade 1 schoolchildren identified as food words, 26 out of the 126 food words presented, and this number increased to 29 for grade 3 schoolchildren, 58 for grade 5 schoolchildren and 68 for adults. More than 75% of respondents in each of the four groups (grade 1, grade 3, grade 5 and adults) considered the following as food words: chewy, creamy, crunchy, fresh, juicy, munchy, watery. The following words were identified as food words by more than 75% of the respondents in three of the four groups: crisp, crumbly, crusty, hot, mashed, saucy, spicy.

Texture and Time of Day

Szczesniak and Kahn (1971) reported that time of day exerted a strong influence on textural awareness and flavor. At breakfast, most people prefer a restricted range of familiar textures that lubricate the mouth, remove the dryness of sleep, and can be swallowed without difficulty. New or unfamiliar textures, and textures that are difficult to chew, are not wanted at breakfast.

People are willing to accept a wider range of textures at the midday meal just so long as it is quick and easy to prepare and not messy to eat. After all, this is a practical meal with a limited time for preparation and consumption.

Texture is most appreciated and enjoyed at the evening meal. This is the time for relaxation, which comes after the day's work and, for most people, is the largest meal of the day when several courses are served and a wide range of textures is expected and relished. The appetizer (nondemanding textures and flavors that stimulate the flow of saliva) is perceived as a preparation for the main meal which follows, and this in turn features a great variety of textures, including some items that require considerable energy to chew. No texture seems to be completely inappropriate for the main course so long as there are several contrasting textures. The same wide range of textures is relished in those cultures in which the main meal of the day is in the early afternoon.

The dessert features textures that require low energy for mastication and restore the mouth to a relaxed and pleasant feeling. This is the time for 'fun' foods that are easy to manipulate and leave a nice feeling in the mouth. Soft, smooth, creamy, or spongy textures are desired. Hard, chewy textures are not wanted at the conclusion of the meal (Szczesniak and Kahn, 1971).

In yet another report, Szczesniak (1972) studied the attitudes of children and teenagers to food texture and found it to be an important aspect of their liking or disliking of specific foods. The young child prefers simple soft textures that can be managed within the limited development of the structures of the mouth. The child extends its range of relished textures as its teeth, jaws, and powers of coordination develop. This study also showed that teenagers have a high degree of texture awareness that sometimes surpasses that of adults, suggesting that perhaps the next generation of adult consumers may be more sophisticated and demanding in terms of textural qualities of the foods that they purchase. The teenagers of 1972 are now mature adult consumers. Perhaps the increasing use of texture descriptors in food advertisements is the response of the food industry to the texture demands of this age group.

Defective Textures

In a survey of consumer attitudes toward product quality conducted by the A. C. Nielsen Co. in 1973, complaints about product quality were recorded (Anonymous, 1973). The results are shown in Table 1.3. Complaints about a broken or crumbled product (a texture defect) headed the list at 51% of respondents. The second item (product freshness) is frequently measured by textural properties such as firmness. These data indicate that there is room for considerable improvement in textural properties of foods that are presently marketed.

This observation was supported by Cardello (1996b) who stated, 'while flavor is commonly found to be the most important sensory factor responsible for the liking of many foods, texture is often cited by consumers as the reason for not liking certain foods. This is especially true for foods the texture of which may be observed as creating a lack of control in the mouth, e.g. foods with sticky, soggy or slimy textures'.

Table 1.3 Consumer Complaints About Product Quality[a]

Type of complaint	Total respondents (%)
Broken or crumbled product	51
Product freshness	47
Contaminated product	28
Incorrect carbonation	23
Bulged can	16
Other	9

[a]From Anonymous (1973).

Lillford (1991) also comments on the role that the expectation of textural quality plays in food acceptance in the following words:

> Preference (acceptability) and texture perception are judgments made by each of us every time we eat, without much conscious thought. … First, eating is not an activity to which a great deal of analytical thought or concentration is normally applied. People behave as if their actions are 'scripted', i.e. they are acting out a process during which a sequence of events is to be expected. Only if the unexpected occurs is any judgment logged. Second, because of the scripted procedures, acceptability of food is dependent on the description or expectation of the properties of the food being eaten. For example, a simple sugar glass can be fabricated into a boiled sweet (hard) or an aerated structure (crunchy). The one is not normally an acceptable form of the other. Fortunately for the confectionery industry, both are acceptable food concepts if properly described.

Bruhn *et al*. (1991) studied the perceptions of quality of six fresh fruits by consumers in California and reported the following levels of dissatisfaction because of texture defects (too hard, too soft or mealy): apricot, 37%; cantaloupe, 20%; peach, 40%; pear, 35%; strawberry, 20%; and tomato, 50%.

The texture of many foods is not static but changes during storage, and these changes usually lower the textural quality. This is a major reason why consumers like to have 'fresh' foods. Examples of some of the textural changes that occur during storage are given in Table 1.4. Preventing, or retarding the deterioration of texture during storage is a major preoccupation of food scientists.

Textural Diversity

There is an enormous range in textural characteristics of foods: the chewiness of bread crust and of meat, the softness of marshmallows, the crispness of celery and potato chips, the juiciness of fresh fruits, the smoothness and melting sensations of ice cream, the soft toughness of bread, the flakiness of fish, the crumbliness of cake, the melting of jelly, the viscosity of thick soup, the fluidity of milk, the thick smoothness of yogurt, the creaminess of pie topping and many others. This great range of types of rheological and textural properties found in foods arises from the human demand for variety in the nature of their food.

Table 1.4 Changes in Food Texture During Storage

Food	Texture change	Cause
Bread, crumb	Firmness increases, springiness decreases	Starch retrogradation, moisture transfer from starch to gluten
Bread, crust	Crispness decreases, toughness increases	Moisture migrates from crumb to crust
Butter and margarine	Firmness and graininess increase, spreadability decreases	Growth of fat crystals, change in crystal form, strengthening of network bonds
Cake	Firmness increases, moist mouthful decreases	Starch retrogradation, moisture migration
Cheese, ripe	Firmness and fracturability increase, springiness decreases	Proteolytic changes
Chocolate	Graininess develops, surface 'bloom'	Change of crystal form, sugar or fat crystallize on surface
Crackers	Loss of crispness	Moisture absorption from air
Eggs, fresh	Viscosity decreases	Loss of CO_2 through shell changes protein
Fruit, fresh	Softening, wilting, loss of crispness, loss of juiciness	Pectin degradation, respiration, bruising, loss of moisture and turgor, weakening of middle lamella
Fruits, dried	Hardening	Loss of moisture
Fish, frozen	Toughening, dryness increases, rubberiness develops	Protein denaturation especially myofibrillar proteins, HCHO generated by trimethylamineoxidase
Ice cream	Coarseness increases, butteriness sandiness crumbliness	Ice crystals enlarge clumping of fat globules crystallization of lactose poor protein hydration
Legume seeds	Lose ability to soften during cooking	Degradation of phytate, lignification, crosslinking of N compounds, loss of microsomal functionality
Mayonnaise	Emulsion breaks	Fat crystallization
Meat, fresh	Toughness increases at first, toughness decreases later	Rigor mortis autolysis
Meat, frozen	Freezer burn, drip	Surface desiccation, reduced water-holding capacity
Meat, freeze dried	Toughness increases, juiciness decreases	Maillard reaction
Milk, powdered	Stickiness	Moisture absorption, lactose changes from glassy to crystalline state
Mustard, prepared	Syneresis	Colloidal aggregation
Pickles	Softening	Degradative enzymes (exogenous or microbial)
Pies	Crust loses crispness, filling becomes dry	Moisture migrates from filling to crust
Shellfish	Softening and mushiness	Proteolysis
Sugar confectionery	Crystallinity, stickiness	Sugars change from amorphous to crystalline state
Tortillas	Increased firmness and brittleness, decreased rollability	Moisture loss to air, retrogradation of starch
Vegetables, fresh	Toughening	(a) lignification, e.g. asparagus, green beans (b) sugar to starch conversion, e.g. green peas, sweet corn
	Softening	Pectin degradation, e.g. tomatoes
	Pitting	Chilling injury, e.g. bell peppers, green beans
	Loss of crispness	Moisture loss and turgor loss, e.g. lettuce, celery
Xixona, turron	Firm to soggy	Phase change in sugars, possible breakdown of emulsion

Much of this table is derived from Szczesniak (1997).

Table 1.5 lists some of the foods that are produced from wheat. It shows the wide range of textures that can be developed from a single raw material by the use of suitable processing technologies. In every case, the processed product has a more tender texture than the wheat grain and it costs much more than the grains from which it was made.

Table 1.5 Textures of Wheat and Wheat-Based Foods

Item	H_2O% (approx)	Form	Texture
Wheat grain	14	Elliptical solid	Very hard, vitreous
Arabic bread		Sheets, sometimes layered	Slightly tough, chewy
Bagels	40	Ring	Tough, chewy
Bread			
Crumb	38	Solid foam	Deformable, chewy, aerated
Crust	8	Sheet	Chewy, tough
Toast, fresh	25	Solid foam	Crisp outside, chewy inside
Melba toast	4	Solid foam	Dry, hard, crunchy
Breakfast cereal, cold	3	Flakes	Crisp, fracturable, tender
Breakfast cereal, hot	80	Paste	Viscous, gummy, sticky
Bulgur (peeled wheat)			
Uncooked	14	Elliptical solid	Hard, semiplastic
Cooked	60	Elliptical solid	Tender, moist, chewy
Cake (chemically leavened)	40	Solid foam	Deformable, tender, moist
Cookies	4	Disks	Some types are hard, crunchy and crumbly, whereas others are soft and chewy, depending on the formulation
Muffins	38	Friable mass	Crumbly, tender, moist
Crackers	4	Flaky disk	Crisp, tender, dry, fracturable
Donuts	24	Ring	Tender, deformable, adhesive
Flour	15	Powder	Not consumed in this form
Pasta			
Uncooked	15	Many shapes	Hard, brittle, dry
Cooked	60	Many shapes	Soft, tender, moist, rubbery, slightly chewy, slippery surface
Pie crust	19	Sheets	Tender, dry
Puffed pastry	15	Layered	Flaky, highly aerated, chewy
Puffed wheat	4	Elliptical solid	Aerated, crisp, dry
Shredded wheat	6	Coarse fibers	Crisp, dry, fibrous

Some anthropologists claim that a large part of success of *Homo sapiens* as a species is due to their ability to learn how to process cereal and legume grains into forms that would not otherwise be consumable or nutritious (Lillford, 1991).

The diversity of relished textures derives from the complexity of the human masticatory apparatus which will be described in the next chapter. Briefly, there are three different types of teeth, each of which performs a different function. The mandible (jaw) can be moved in three planes depending on the nature of the food. The tongue plays an active role in mastication, and for soft-foods such as ice cream and yogurt it is the main agent for developing a swallowable bolus, and the teeth do little work. Saliva plays a major role in preparing many foods for swallowing. People want to use the full potential of the many modes by which mastication can be accomplished, and this requires a diversity of textures. There is no one 'right' texture; many different types of textures are relished and demanded by consumers as described above. However, a 'right' texture is expected for many foods. For example, celery must be crisp and moist, whereas fresh peaches must have a soft, melting,

juicy texture to be considered a high quality product. Although cheeses exhibit many different textures, each type of cheese has its own 'right' texture. A good texture in a cheddar cheese would be considered unacceptable for a brie cheese and vice versa.

An historical example of this human need for variety in food is found in the Old Testament. When the children of Israel made their historic 40-year march from Egypt to Palestine across the great desert, God provided their food in the form of manna, which fell nightly in sufficient quantity to feed daily this migrating nation. Manna was a delicious food to eat; it was known as 'Bread from Heaven,' and is described as being 'crisp and sweet as honey.' We know it provided all the essential nutrients because the people were free from illness during this long period of time. Despite the high quality and excellent sensory characteristics of manna, people became tired of eating it every day and demanded a change. The record says

> and the children of Israel also wept again, and said, Who shall give us flesh to eat? We remember the fish, which we did eat in Egypt freely; the cucumbers, and the melons, and the leeks, and the onions, and the garlick. But now our soul is dried away: There is nothing at all, beside this manna, before our eyes (Numbers 11:4–6).

On another occasion the children of Israel complained about manna, saying 'Our soul loatheth this worthless bread' (Numbers 21:5).

The people of the 21st century are just as insistent in demanding a variety of textures and flavors in their food as were the children of Israel many centuries ago. A large part of the effort of the food industry of our day is directed toward providing both high quality and a wide variety of textures and viscosities in the foods that are provided to the public.

Status of Food Texture Measurements

Of the three main acceptability factors of foods (appearance, flavor, texture), texture was the last to attract considerable research attention. Indeed, for many years texture was considered the overlooked quality attribute of foods. This was reflected in the low proportion of foods whose texture was routinely measured, and the level of satisfaction with those tests that were used. For example, Muller (1969b) reported a survey of food quality measurements made by the food processing industry in the United Kingdom. A total of 125 companies reported on 228 food products with the following results:

- 55% of products used some kind of texture test, but 7% of these were considered to be unsatisfactory;
- 45% used no texture test, but 47% of that number stated they would use a texture test if a good one could be found and 9% had tried using a texture test and abandoned it, presumably because it had been unsatisfactory.

Szczesniak (1990) outlined what she believed were the major reasons for overlooking texture as a quality attribute for so many years (see Table 1.6).

Table 1.6 Reasons Why Texture Was Overlooked as an Attribute and Preference Given to Color and Flavor

1. **Much government money**, because blindness is a national calamity, was spent on biomedical research aimed at elucidating the anatomy and physiology of the eye and the mechanism of color perception. In contrast, the inability to chew and handle various textures in the mouth is not considered a health problem, and no National Institute of Health (NIH) support for research on texture has been available. This, however, may change in the future as the incidence of dysphagia (the inability to swallow certain foods) is increasing among older people and among cancer patients undergoing throat radiation therapy. Another texture-related problem – choking by children on pieces of frankfurters – was brought to the attention of NIH several years ago as a documented and spreading consumer concern.
2. **Texture is usually taken for granted** and consumers do not, as a rule, comment on it unless expectations are seriously violated or unpleasant associations are triggered. These associations may be with inedible objects (such as slime or straw), or with unpleasant events.
3. **Consumers' vocabulary** to describe texture and its parameters has been generally limited; the phrase 'it does not taste good' was often taken in the past as meaning that the food has poor flavor, whereas the consumer might have been referring to poor texture, or to both.
4. **An off-texture does not signal** that the food is unsafe to eat, in contrast to odor, color, and flavor. In extreme cases where putrefaction of protein-based foods leads to the liquification of the originally solid texture, it is the unpleasant odor that is the first indication of the food being potentially dangerous to health. An off-texture usually signifies just poor food quality. Wilted lettuce, soggy potato chips, or hard, dry white bread indicates spoiled food, not in the sense that it is hazardous to one's health, but in the sense that it has suffered a serious loss in acceptability. Low meat quality is reflected in the meat being tough; toughness lowers the market price of meat thus having an important economic impact.
5. **Texture cannot be added** 'from a bottle,' in contrast to aroma, color and taste, which can be formulated and introduced into compounded or processed foods. It must be created through *in situ* reactions, the mechanisms of which are still incompletely understood in most instances. Even the simplest case, that of viscosity increase through the use of starch or gums, involves a reaction mechanism. Viscosity of the medium is increased through immobilization of water by macromolecules with some potential intermolecular bonding. The most distinctive textures are created by nature (fruits, vegetables, meat, etc.).

From Szczesniak (1990). Reprinted from *Food Technology* 44(a), page 88. Copyright by Institute of Food Technologists.

However, with the better understanding of what texture is, the availability of convenient universal testing machines to measure texture, the increasing use of both instrumental and sensory texture profile analysis, and the public's increasing awareness of texture that has occurred over the last three decades has created a much improved awareness of texture and its importance. Much progress has been made since Muller's 1969 survey.

Nevertheless, considerable work still lies ahead if appealing textures are to be provided to the market place at all times. Although adequate procedures exist to measure the texture of many foods, there are still some texture notes for which satisfactory instrumental measurement is not yet available. There is still much to be learned about texture of foods, how to measure all texture notes, and how to manipulate formulation and processing variables to ensure that high textural quality is achieved.

Definitions of Texture

This has been a difficult term to define since it means different things to different people. The dictionary definition of texture is of little help because it relates mainly to textiles and the act or art of weaving and, in general, to 'the disposition or manner of union of particles or smaller constituent parts of

a body or substance, the fine structure.' The dictionary definition that comes closest to the needs of the food technologist states that texture is 'the manner of structure, interrelation of parts, structural quality.' Webster's dictionary gives examples of texture for textiles and fibers, weaving, artistic compositions, music, poetry, petrography (the study of rocks), texture of a bone or plant, but does not even mention foods. In view of this lack of coverage in the dictionary, food technologists have endeavored to produce their own definition of what is meant by texture. These definitions fall into two groups.

Group 1 comprises what might be called 'commodity-oriented' definitions in which the term texture is applied to a particular quality attribute of a given type of food. For example, in ice cream grading, texture means the smoothness of the ice cream but does not include other factors such as hardness and melting properties. In bread grading, texture means uniformity of the crumb and even distribution in size of the gas bubbles but does not include the softness or toughness of the bread.

For example, Coles (1998) states, 'Bread visual texture refers to the pattern of luminance observed in light reflected from the crumb of the leavened bread. In a conventional loaf made of white flour, this patterning is almost entirely due to the variation in brightness caused by contrast between bubbles and their walls'. Coles also states that bread technologists take into account a number of textural features including the number and location of unusually large bubbles, streaking, blind crumb, nonrandom variation of texture within a slice, and longitudinal variation of texture within a loaf.

Ball *et al*. (1957) gives two definitions for texture of meat. The first, which they call a sight definition, is 'texture of meat is the macroscopic appearance of meat tissues from the standpoint of smoothness or fineness of grain.' The second, which they call a feel definition, is 'the texture of cooked meat is the feel of smoothness or fineness of muscle tissue in the mouth.' It is noteworthy that neither of these definitions includes the properties of toughness, moistness or juiciness which most people consider of great importance in the quality of meat.

Davis (1937) defines texture of cheese as

> that which is evident to the eye, excluding color. … Texture varies in meaning in different localities, but is frequently taken to include both closeness (absence of cracks) and shortness or brittleness (easy breaking of a plug).

Davis also defines 'body' as that quality which is perceptible to touch.

Group 2 considers that texture applies to all foods and endeavors to develop definitions that reflect a universal coverage of all foods. Some of these definitions are as follows:

> Texture means those perceptions that constitute the evaluation of a food's physical characteristics by the skin or muscle senses of the buccal cavity, excepting the sensations of temperature or pain (Matz, 1962).

> Texture can be defined as the sensory manifestation of the structure of the food and the manner in which this structure reacts to applied forces, the specific senses involved being vision, kinesthetics and hearing (Szczesniak, 1990).

Texture is the composite of those properties (attributes) which arise from the structural elements of food and the manner in which it registers with the physiological senses (Sherman, 1970).

In its fullest sense the textural experience during chewing is a dynamic integration of mouthfeel, the prior tactile responses while handling the foodstuff, and a psychic anticipatory state arising from the visible perception of the food's overall geometry and surface features. … Texture should be regarded as a human construct. A foodstuff cannot have texture, only particular mechanical (and other) properties which are involved in producing sensory feelings or texture notes for the human being during the act of chewing the foodstuff (Corey, 1970).

(Texture is) the attribute of a substance resulting from a combination of physical properties and perceived by the senses of touch (including kinesthesis and mouthfeel), sight, and hearing. Physical properties may include size, shape, number, nature and conformation of constituent structural elements (Jowitt, 1974).

Texture is that one of the three primary sensory properties of foods that relates entirely to the sense of touch or feel and is, therefore, potentially capable of precise measurement objectively by mechanical means in fundamental units of mass or force (Kramer, 1973).

Texture is the way in which the various constituents and structural elements of a food are arranged and combined in a micro- and macrostructure and the external manifestations of this structure in terms of flow and deformation (deMan, 1975).

(Texture comprises) those properties of a foodstuff, apprehended by the eyes and by the skin and muscle senses in the mouth, including roughness, smoothness, graininess, etc. (Anonymous, 1964).

Texture (*noun*): All the mechanical (geometrical and surface) attributes of a food product perceptible by means of mechanical, tactile and, where appropriate, visual and auditory receptors (International Organization for Standardization, Standard 5492, 1992).

Texture is the human physiological–psychological perception of a number of rheological and other properties of foods and their interactions (McCarthy, 1987).

Texture is the attribute resulting from a combination of physical properties perceived by the senses of kinesthesis, touch (including mouth, feel, sight and hearing). The properties may include size, shape, number, nature, and conformation of constituent structural elements. (British Standards Organization No. 5098).

Although we do not have an entirely satisfactory definition of texture we can say with a high degree of certainty that texture of foods has the following characteristics.

1. It is a group of physical properties that derive from the structure of the food.
2. It belongs under the mechanical or rheological subheading of physical properties. Optical properties, electrical and magnetic properties, and temperature and thermal properties are physical properties that are excluded from the texture definition.
3. It consists of a *group* of properties, not a single property.
4. Texture is sensed primarily by the feeling of touch, usually in the mouth, but other parts of the body may be involved (frequently the hands).
5. It is not related to the chemical senses of taste or odor.
6. Objective measurement is by means of functions of mass, distance, and time only; for example, force has the dimensions MLT^{-2}, work has the dimensions ML^2T^{-2}, and flow has the dimensions L^3T^{-1}.

Since texture consists of a number of different physical sensations, it is preferable to talk about 'textural properties,' which infers a group of related properties,

rather than 'texture,' which infers a single parameter. There are still many people handling foods who talk about the texture of a food as though it were a single property like pH. It is important to realize that texture is a multifaceted group of properties of foods. Table 1.7 lists some relations between textural parameters of foods and popular terms that are used to describe these properties.

These concepts lead to the following definition. *The textural properties of a food are that group of physical characteristics that arise from the structural elements of the food, are sensed primarily by the feeling of touch, are related to the deformation, disintegration, and flow of the food under a force, and are measured objectively by functions of mass, time, and distance.*

Muller (1969a) claims that the term 'texture' should be discarded because it is confusing. In present usage it means both an exact physical property and also a perceived property. He proposes two terms to take the place of the word texture: (1) *rheology*, a branch of physics that describes the physical properties of the food; and (2) *haptaesthesis* (from the Greek words meaning sensation and touch), a branch of psychology that deals with the perception of the mechanical behavior of materials.

Muller compares these two terms with the study of light, which has two distinct branches: (1) *optics*, the study of the physical properties of light, including reflection, refraction, wave theory, etc.; (2) *vision*, the study of the psychological and physiological human responses to light, such as the perception of objects,

Table 1.7 Relations Between Textural Parameters and Popular Nomenclature[a]

Mechanical characteristics		
Primary parameters	Secondary parameters	Popular terms
Hardness		Soft → firm → hard
Cohesiveness	Brittleness	Crumbly → crunchy → brittle
	Chewiness	Tender → chewy → tough
	Gumminess	Short → mealy → pasty → gummy
Viscosity		Thin → viscous
Elasticity		Plastic → elastic
Adhesiveness		Sticky → tacky → gooey
Geometrical characteristics		
Class		Examples
Particle size and shape		Gritty, grainy, coarse, etc.
Particle shape and orientation		Fibrous, cellular, crystalline, etc.
Other characteristics		
Primary parameters	Secondary parameters	Popular terms
Moisture content		Dry → moist → wet → watery
Fat content	Oiliness	Oily
	Greasiness	Greasy

[a]From Szczesniak (1963a); reprinted with permission of Institute of Food Technologists.

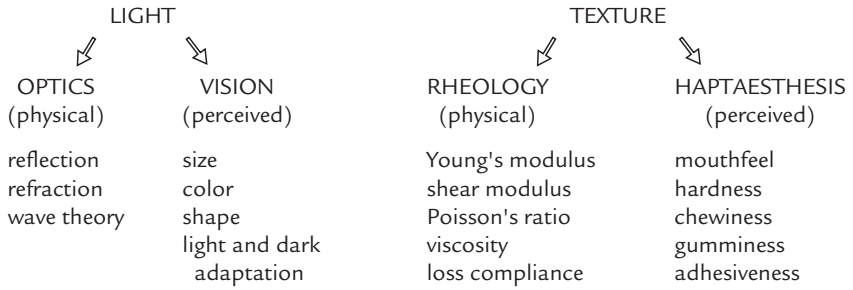


Figure 1.1 Comparison of physical measurement and human perception of light and texture. (After Muller, 1969a.)

perception of color, light and dark adaptations, etc. Figure 1.1 shows schematically the analogy.

Texture-related Concepts and Their Definitions

Some other words that are used in a texture-related sense are:

Kinesthetics. 'Those factors of quality that the consumer evaluates with his sense of feel, especially mouthfeel' (Kramer and Twigg, 1959). This word comes from the Greek words 'kinein' (the muscle sense to move) and 'aesthesis' (perception).

Body. 'The quality of a food or beverage, relating variously to its consistency, compactness of texture, fullness, or richness' (Anonymous, 1964). 'That textural property producing the mouthfeel sensation of substance' (Jowitt, 1974). 'The quality of a food or beverage relating either to its consistency, compactness of texture, fullness, flavor, or to a combination thereof' (American Society for Testing and Materials, Standard E253-78a).

Chewy. 'Tending to remain in the mouth without rapidly breaking up or dissolving. Requiring mastication' (Anonymous, 1964). 'Possessing the textural property manifested by a low resistance to breakdown on mastication' (Jowitt, 1974).

Haptic. 'Pertaining to the skin or to the sense of touch in its broadest sense' (Anonymous, 1964).

Mealy. 'A quality of mouthfeel denoting a starchlike sensation. Friable' (Anonymous, 1964). 'Possessing the textural property manifested by the presence of components of different degrees of firmness or toughness' (Jowitt, 1974).

Mouthfeel. 'The mingled experience deriving from the sensations of the skin in the mouth during and/or after ingestion of a food or beverage. It relates to density, viscosity, surface tension, and other physical properties of the material being sampled' (Anonymous, 1964). 'Those textural characteristics of a food responsible for producing characteristic tactile sensation on the surfaces of the oral cavity; the sensation thus produced' (Jowitt, 1974).

Getaway. 'That textural property perceived as shortness of duration of mouthfeel' (Jowitt, 1974).

The following definitions were all developed by the International Organization for Standardization, Standard 5492/3, 1979:

Consistency. 'All the sensations resulting from stimulation of the mechanical receptors and tactile receptors, especially in the region of the mouth, and varying with the texture of the product.'

Hard (adjective). 'As a texture characteristic, describes a product which displays substantial resistance to deformation or breaking. The corresponding noun is hardness.'

Soft (adjective). 'As a texture characteristic, describes a product which displays slight resistance to deformation. The corresponding noun is softness.'

Tender (adjective). 'As a texture characteristic, describes a product which, during mastication, displays little resistance to breaking. The corresponding noun is tenderness.'

Firm (adjective). 'As a texture characteristic, describes a product which, during mastication, displays moderate resistance to breaking. The corresponding noun is firmness.'

Hardness (noun) is the perceived force required to break the sample into several pieces during the first bite by the molars (Guraya and Toledo, 1988).

Crunchiness (noun) is the perceived cumulative intensity of force required by repeated incremental failures of the product by chewing up to five times with the molars (Guraya and Toledo, 1988).

Texture Versus Viscosity

Viscosity is defined as the internal friction of a fluid or its tendency to resist flow. Both gases and liquids have viscosity but viscosity of gases will not be discussed because there are no gaseous foods. However, some foods contain entrained gases. For example, ice cream is typically 50% air by volume, and apple flesh may contain 25% gas by volume. Some highly extruded crispy snack foods such as corn curls exceed 90% air by volume. Jones *et al*. (2000) showed that in 36 branded ready-to-eat breakfast cereals the volume attributed to pores ranged from 68.2% for flakes made from a mixture of corn, wheat, oats and barley to 99.5% for puffed wheat.

At first sight the distinction between texture and viscosity seems simple – texture applies to solid foods and viscosity applies to fluid foods. Unfortunately, the distinction between solids and liquids is so blurred that it is impossible to clearly demarcate between texture and viscosity. While rock candy can definitely be considered as a solid and milk a liquid, there are many solid foods that exhibit some of the properties of liquids and many liquid foods that exhibit some of the properties of solids. Some apparently solid foods behave like liquids when sufficient stress is applied.

The indistinct separation between solids and liquids results in some confusion in the literature between food texture and viscosity and that confusion is reflected to some extent in this book. The author has followed the arbitrary distinction that foods that are usually considered to be solid or near-solid are discussed in Chapters 4 and 5 and foods that are usually considered to be liquid or near-liquid are discussed in Chapter 6. Some of the tests for solid foods described in Chapters 4 and 5 should really be discussed in Chapter 6 on viscosity, and some of the material in Chapter 6 could have been discussed in Chapters 4 and 5.

The nature of the overlap between solids and liquids should become more clear when the reader reaches the end of Chapter 6. At this point, the reader should be aware that the distinction between solids and liquids is not clearcut and that some inconsistencies in treatment are found because of this problem.

Texture and Food Processing

Much food processing is directed to changing the textural properties of the food, generally in the direction of weakening the structure in order to make it easier to masticate. From the nutritional standpoint wheat could be eaten as whole grains but most people find them too hard to be appealing. Instead, the structure of the wheat kernel is destroyed by grinding it into flour, which is then baked into bread with a completely different texture and structure than the grain of wheat. The texture of leavened bread is much softer and less dense than that of grains of wheat and is a more highly acceptable product, judging by the quantity of bread that is consumed (see Table 1.5, page 10).

The processing that is needed to develop desirable textural properties in foods can be expensive. In the United States the wholesale price of wheat is about 10–20 cents per kilo while the retail price of bread is usually in the range of one dollar to several dollars per kilo. The wide disparity in price between bread and wheat indicates the high cost of conversion of wheat grain into bread and also the price people are prepared to pay to obtain the type of textures they desire. Breakfast cereals made from wheat that has been rolled into flakes cost over $2 per kilo which is another indication of the price that people will pay to convert grains of wheat into a more texturally desirable form. One of the major reasons for cooking most vegetables before consumption is to soften them and make them easier to masticate.

Although much food processing is deliberately designed to modify textural properties, there are some instances where the textural changes are inadvertent, being a side result of processing for some other purpose. These textural changes are frequently undesirable. A good example of this is the extreme softening and severe textural degradation that results from canning, freezing, or irradiation preservation of fruits and vegetables. In some instances the damage to texture is so great that the resultant product is unsalable, in which case that processing method is not used on that commodity. For example, the

dose of about two million rads (20 kilogray) required to sterilize horticultural crops causes such extreme softening of the tissue that it has eliminated the incentive to continue research to resolve questions on the safety of irradiation-sterilized fruit.

Foods might be classed into two groups, depending on the relative ease with which texture can be controlled:

1. *Native foods* are those foods in which the original structure of the agricultural commodity remains essentially intact. With these foods the food technologist has to take what nature provides in the form of fruit, fish, meat, poultry, vegetables, etc., and can only change the texture by processing methods such as heating, cooling, and size reduction. Usually there is almost no direct control over the composition of these foods, although with some of them it is possible to partially control the composition and texture by breeding, time of harvest, and cultural factors.
2. *Formulated foods* are those foods that are processed from a number of ingredients to make a food product that is not found in nature. Many native foods are transformed into ingredients for formulated foods, but in doing so the native plant or animal structure and organization is usually lost. Examples of this type of commodity are bread, ketchup, ice cream, jellies, mayonnaise, candy, cheese, margarine and sausage. With this class of commodity it is possible to change the formulation by the number, amount, and quality of ingredients that are used in addition to processing variables, and hence there are more options available to control the texture of the finished product and to develop specified textures and structures not found in native foods.

A large number of ingredients, called 'texturizing agents' are available to the food technologist to help bring the texture of foods into the range preferred by consumers. The Handbook of Food Additives (Ash and Ash, 1995) is an international guide to more than 7500 substances that are permitted to be added to foods in one or more countries. More than 700 of these substances are described as texturizers, thickeners, viscosity modifiers, bodying agents, gelling agents and stiffening agents. These give the product development specialist a large array of aids to develop the desired textures.

Vincent (1986) estimated that the annual world food production of texturizing agents exceeded one million tons. Starch and modified starches contributed 82% of this amount. Other texturizing agents whose sales exceed 10,000 tons per annum are gum acacia, alginates, carrageenans, carboxymethylcellulose, gelatin, guar gum, locust bean gum, pectin and xanthan gum.

Some texturizing agents are only needed in small amounts. For example, the US Food and Drug Administration permits the addition of 0.4% calcium chloride to processed vegetables to improve their firmness. This effect is achieved by the calcium ions crosslinking the pectin material naturally present in the vegetable by forming salt bridges.

Despite the wide range of options available, food technologists have experienced great difficulty in fabricating foods that closely simulate native foods because of their cellular structure and complex structural organization. The turgor that provides much of the crispness of many fresh fruits and vegetables arises from the physiological activity of the living tissue and is unlikely ever to be duplicated in a fabricated analog.

Textural properties are used as the basis of selection or rejection of certain parts of foods. Many children dislike the texture of bread crust and engage in various subterfuges to avoid eating it. Texture is the main reason why the skin of some fruits and vegetables is eaten whereas that of other fruits and vegetables is not eaten. The skin is usually eaten with the fleshy portion when it is tender or thin, as in the strawberry, cherry, green pea, and green bean. The skin is usually not eaten when it is texturally objectionable because it is thick, hard, tough, hairy, fibrous, or prickly, as in the grapefruit, pumpkin, mango, peach, banana, and pineapple. Of course, there are some borderline cases; some people peel their apples, figs, potatoes, and tomatoes before eating while others do not.

A great deal of attention has been given to 'texturizing' vegetable proteins. Most people enjoy the chewy fibrous texture of muscle meat but this kind of texture is not found in vegetable proteins. Vegetable proteins generally cost less than animal proteins because the biological conversion of vegetable protein into animal protein by the cow, pig, or chicken is inefficient, with, typically, 5–20% of the protein fed to the animal recovered as edible protein food. This inefficient conversion raises the cost of animal protein. In contrast, the direct conversion of vegetable protein into products with a meatlike chewy texture by modern processing technology is usually 70–90% efficient.

Considerable research attention is presently being given to imparting a meat-like texture to vegetable proteins in order to obtain the desirable chewy texture of meat coupled with the lower cost of the vegetable proteins and (for some people) avoidance of cholesterol and other undesirable features of meat. Substantial progress has been made in developing meatlike textures in vegetable proteins but more progress is needed before these products are equal to the meat in their overall textural properties.

The problem of imparting a desirable texture to a food is exemplified in the problems of fish protein concentrate (FPC). The production of FPC makes available for human consumption the protein from many species of fish that are normally not used. The general process is to remove the fat and moisture from the fish and grind the residue into a powder. The problems of developing a bland flavor and absence of fishy flavor, and obtaining stability and good nutritional value of the FPC have been solved, but the problem of utilizing FPC for food has not been satisfactorily solved. FPC is a dry powder and no more a food than is wheat flour a food. It is a food *ingredient* that must be fabricated into a food in much the same way as wheat flour is fabricated into bread, cookies, and similar products and this has proven to be an extremely difficult task. Dry FPC has such poor functional properties that it cannot be

used to develop texture in formulated foods. At the present time the only satisfactory use for FPC is to add it to existing foods at levels that are so low that the textural properties of that food disguise the presence of FPC.

The problem of fabricating vegetable proteins into foods with acceptable texture is extremely difficult. Only those food technologists who have wrestled with this problem know how difficult it is. Several years ago a chemist, writing on future sources of food, wrote:

> The polymer chemist who has produced an almost endless variety of fibers, gels, gums, resins, and plastic products would encounter no major difficulty in incorporating synthetic food materials in products of nearly any desired consistency or texture, and could prepare highly acceptable counterparts of steak, Jell-o, cheese, or seafood.

This scientist should be sentenced to spend 10 years hard labor in the product development laboratory for making such a misleading statement! Acceptable texture has been a limiting factor in the development of many fabricated foods.

Texture and Health

Because obesity has become a major health problem in the industrialized countries the food industry devotes considerable effort to bring low calorie foods and beverages to the market in an effort to alleviate the problems of overweight. Maintaining satisfying textural properties of manufactured foods while reducing or eliminating fat or sugar is a daunting problem.

The Human Nutrition Unit of Sydney University developed a satiety index (SI) as a method to measure the filling powers of different foods. They found that different foods have very different effects on energy production and satiety which is the feeling of fullness that arises after eating (Holt, 1999). High satiety foods tended to have bulky, crunchy, or fibrous textures which makes them relatively more difficult to chew and swallow. Holt (1999) give as examples of high SI foods potatoes, oatmeal porridge, steak, fish, apples, oranges, brown pasta and baked beans. These authors believe that the consumption of low fat, bulky, chewy foods gives a long-lasting feeling of satiety and hence reduces total caloric intake.

Dr Minoru Onozuka and his team at Gifu University School of Medicine in Japan have evidence that chewing stimulates the brain and helps it retain memory (Onozuka *et al*., 1999, 2000). Mice whose molars were extracted to reduce masticatory effectiveness did not perform as well on memory tests as similar mice with teeth. The aged molarless mice showed a significantly reduced learning ability compared with age-matched control mice but there was no difference between control and molarless young adult mice. Onozuka *et al*. suggest there is a link between reduced mastication ability and hippocampal neuron loss as a risk factor for senile impairment of spatial memory. Although these particular experiments were performed on mice, this work supports a small but growing body of evidence that reduced ability to masticate is associated with Alzheimer's dementia. The tentative conclusion is that elderly

people who want to retain their memory and fend off dementia should do more chewing.

Texture and Structure

As pointed out in the definition of texture on pages 12–15 and in a number of other statements, the textures of foods derive from their structure. The structural organization at the molecular level, the microscopic level, and the macroscopic level are major determinants of textural quality. Having noted the importance of structure to texture it must be stated that it is beyond the scope of this book to describe in detail food structures and how they are measured. The reader is referred to the excellent volume "Microstructural Principles of Food Processing and Engineering" by Aguilera and Stanley (2nd edition, 1999) for a full account of the structural basis of texture.

An example of the connection between structure and texture is given in Fig. 1.2 which shows the microstructure of an uncooked hydrated lima bean seed (LHS) and a matching seed boiled in water for 20 min (RHS). In the raw seed the tissue breaks across the cells when stressed because the middle lamella that cements the cells together is stronger than the cell walls. During cooking, the pectic material in the middle lamella is depolymerized, causing it to become weaker than the cell walls, and fracture now occurs through the middle lamella leaving the cells unbroken.

Whether plant tissues break across cell walls or between cells has a great effect on their textural sensations. For example, in the potato it is desirable to keep whole cells, because when the cell walls break, starch grains spill out imparting an undesirable pasty, gummy, sticky texture. In contrast, for apple, it is desirable to break the cell walls to allow the cell sap to spill into the mouth imparting the much relished sensation of juiciness. When the apple flesh fractures between cells no juice is released and that apple has a dry, mealy texture.

Rheology and Texture

Rheology is the study of the deformation and flow of matter. The science of rheology can be applied to any product and in fact was developed by scientists studying printing inks, plastics, rubber, and similar materials. Chapter 3 provides a simple introduction to the basic concepts of rheology.

Food rheology is 'the study of the deformation and flow of the raw materials, the intermediate products, and the final products of the food industry' (White, 1970). In this definition the term 'food industry' should be broadly defined to include the behavior of foods in the home.

Psychophysics is 'the study of the relationship between measurable stimuli and the corresponding responses' (International Organization for Standardization, Standard 5492/1, 1977).

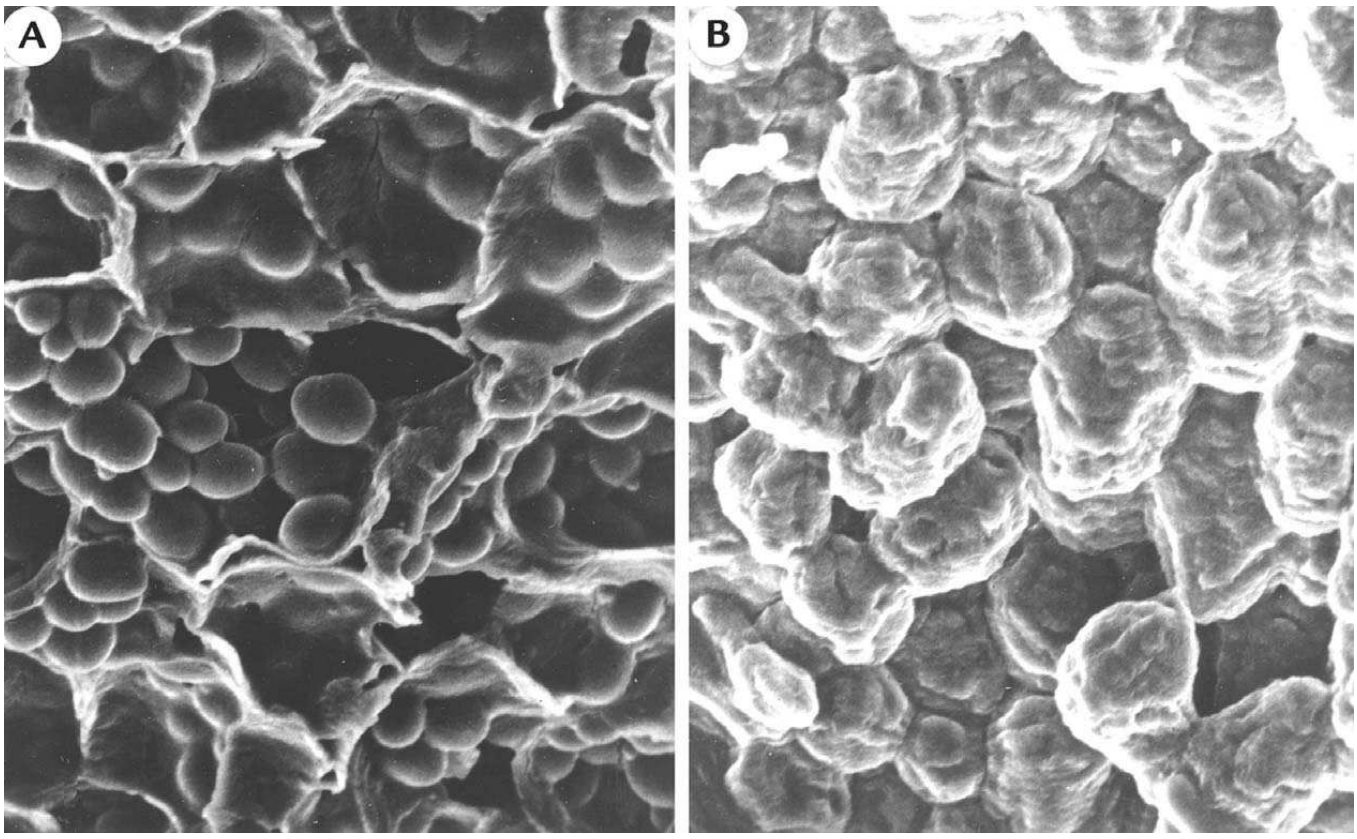


Figure 1.2 Scanning electron micrograph of the fractured surface of a hydrated lima bean seed. LHS, uncooked. Starch grains can be seen inside the broken cells. RHS, boiled for 20 min. The cell walls do not break. Starch granules can be seen pressing against the unbroken flexible cell walls. (From Rockland and Jones, 1974. Reprinted from *J. Food Science* **39**, 344, 1974. Copyright by Institute of Food Technologists.)

Psychorheology. There are two types of definitions given to psychorheology. The first is a scientific definition: (1) psychorheology is a branch of psychophysics dealing with the sensory perception of rheological properties of foods. Another definition, which might be called a people-centered definition, is the following: (2) psychorheology is the relationship between the consumer preferences and rheological properties of foods.

Both of these definitions are meant to bridge the gap between the physical or rheological properties of foods and the sensing of those properties by the human senses (see Fig. 1.1, page 16).

The science of rheology has many applications in the field of food acceptability, food processing, and handling. A number of food processing operations depend heavily upon rheological properties of the product at an intermediate stage of manufacture because this has a profound effect upon the quality of the finished product. For example, the rheology of bread dough, milk curd, and meat emulsions are important aspects in the manufacture of high-quality

bread, cheese, and sausage products. The agricultural engineer is interested in the ability of foods to be handled by machinery and in the creep and recovery of agricultural products that are subjected to stresses, particularly long-term stresses resulting from storage under confined conditions such as the bottom of a bulk container.

Viscosity, especially non-Newtonian viscosity, is an important component of the quality of most fluid and semifluid foods. The food engineer is interested in the ability to pump and mix liquid and semiliquid foods. Plasticity, pseudoplasticity, and the property of shear thinning are important quality factors in foods and the study of these properties is part of the science of rheology. A wide variety of foods, such as butter, margarine, applesauce, tomato catsup, mayonnaise, peanut butter, and many puddings are either plastic or pseudoplastic in nature. They are required to spread and flow easily under a small force but to hold their shape when not subjected to any external force other than gravity. All of these properties fall within the field of rheology.

When celebrating the golden anniversary of the founding of the field of rheology, the then president of the American Society of Rheology singled out for special comment the interesting rheological characteristics of foods in the following words:

> One of the world's greatest rheological laboratories is in the kitchen. Who can cease to wonder at the elasticity of egg white, or of the foam it forms when beaten with air? At the transformation of gelatin from a watery solution to an elastic gel? At the strange flow properties of mayonnaise, ketchup, peanut butter, or starch paste? Or at the way bread dough defies both gravity and centrifugal force as it climbs up the shaft of the beater? (Krieger, 1979).

Rheology is important to the food technologist because it has many applications in the three major categories of food acceptability:

1. *Appearance*. There is a small component of rheology in appearance because certain structural and mechanical properties of some foods can be determined by appearance; for example, we can see how well maple syrup pours from the bottle and covers the pancake.
2. *Flavor.* Rheology has no direct part in this category, although the manner of food breakdown in the mouth can affect the rate of release of flavor compounds.
3. *Touch*. Rheological properties are a major factor in the evaluation of food quality by the sense of touch. We hold foods in the hand and from the sense of deformability and recovery after squeezing frequently obtain some idea of their textural quality. For example, fresh bread is highly deformable whereas stale bread is not; the flesh of fresh fish recovers quickly after squeezing while the stale fish does not. During the process of mastication a number of rheological properties such as the deformation that occurs on the first bite and the flow properties of the bolus (the mass of chewed food with saliva) are sensed in the mouth.

The importance of rheology in foods has been well established in the preceding discussion. However, the science of rheology does not cover all of

the aspects that should be included in the broad definition of food texture. Mastication is a process in which pieces of food are ground into a very fine state, but the process of size reduction (synonyms are comminution, disintegration, pulverization, and trituration) does not belong in the field of rheology. During mastication the size and shape of food particles and their surface roughness are sensed and become important attributes of the overall textural sensation. Brandt *et al*. (1963) described the surface properties of food particles in the sensory terms of powdery, chalky, grainy, gritty, coarse, lumpy, beady, flaky, fibrous, pulpy, cellular, aerated, puffy, and crystalline. They are called 'geometrical properties' or, 'particulate properties' because they relate largely to the mouthfeel of size and shape of particles in the bolus. Bourne (1975a) suggested that the word 'rugosity' or surface roughness is an important attribute of the food particles that are sensed in the mouth.

The ability of the food to wet with saliva and to absorb saliva or to release moisture or lipid are important textural sensations that also do not belong in the field of rheology. Phase changes resulting from temperature changes occurring in the mouth are an important part of the texture sensation of some foods; for example, ice cream, chocolate, and jelly melt in the mouth whereas the oil in hot soup may solidify in the mouth during mastication. These changes are not rheological properties although they are frequently sensed by changes in rheological properties.

From this evidence we have to conclude that the field of food texture falls partly within the field of conventional rheology and partly outside this field. The food technologist certainly needs to define and measure certain rheological properties of foods, but there are many instances where the classical science of rheology is of little help in studies of the textural properties of foods and nonrheological techniques are needed.

Rheology defines and measures *properties* of foods. But the food technologist is also interested in the *process* of mastication and the changes in rheological and other textural properties that occur during mastication. The fact that fundamental rheological measurements usually do not correlate as well with sensory measurements of texture as do empirical tests may result from the incompleteness of the science of rheology to describe all of the changes, or perhaps even the most important changes that are actually sensed in the mouth and are of most interest to the food technologist.

One of the founders of the field of rheology stated,

> The flow of matter is still not understood and since it is not mysterious like electricity, it does not attract the attention of the curious. The properties are ill defined and they are imperfectly measured if at all, and they are in no way organized into a systematic body of knowledge which can be called a science (Bingham, 1930).

Although this comment may not apply today to the field of rheology in general, it is fair to say that it still applies to the subfield of food rheology. Only a small number of research scientists devote their career to food rheology; there is a large volume of empirical information and a small volume of utilizable fundamental concepts. The author hopes that this book will help

systematize the widely scattered body of knowledge in this field and hence promote the development of the field of food rheology into a rigorous scientific discipline.

Early History

It is not easy to decide where to begin citing the work of the early scientists who pioneered the development of the study of the texture and viscosity of foods. Robert Hooke (in England in 1660) enunciated the principle of elastic deformation of solids, giving rise to the descriptive term 'Hookean solid' that is still used today. A contemporary, Isaac Newton (in England in 1687), enunciated the law governing the flow of simple liquids, giving rise to the term 'Newtonian fluid.' However, the findings of these two eminent scientists did not apply specifically to foods.

Possibly, the first person to develop an instrument expressly for testing foods was Lipowitz (1861, Germany), who developed a simple puncture tester for measuring the firmness of jellies (see Fig. 4.2, page 113). Carpi (1884, Italy) also developed a puncture tester for cooled olive oil and other fats. Schwedoff (1889, France) developed a deformation apparatus for jelly based on a torsion test and measured rigidity, viscosity, and relaxation.

Babcock (1886) at the New York State Agricultural Experiment Station (now part of Cornell University) devised a viscometer consisting of a hollow brass cylinder 6.4 cm long that was suspended from a 1.1 m long torsion wire. The cylinder was immersed in milk and caused to oscillate and the degree of damping used to measure the viscosity of milks. Babcock's viscometer design was used by Woll (1895) at the University of Wisconsin who studied the effects of processing milk and cream on their viscosity.

Hogarth (1889, Scotland) obtained a patent for a device that measured the consistency of dough using the same principles as the modern Farinograph. Brabender, in Germany (1901–1980) developed a line of equipment for measuring the rheological properties of flour dough and founded companies in Germany and in the United States that still bear his name. Brabender (1965) recalled that an instrument for dough extensibility was developed in Hungary by Kosutány and Rejtö at the beginning of the last century (Kosutány, 1907). He also pointed out that, in 1905, another Hungarian, Professor Jenö von Hankóczy, designed an apparatus that measured the volume of air that could be blown into a disk of washed wheat gluten before it burst. This device was the forerunner of the Alveograph.

Wood and Parsons (1891, United States) described a puncture test developed for measuring the hardness of butter. Brulle (1893, France) developed an *oléogrammétre* to measure the hardness of solid fats using the puncture principle. Sohn (1893, England), who was independently performing experiments similar to Brulle, felt he had been 'scooped' when Brulle's publication

appeared, and he hurried into print with a description of his apparatus accompanied by a list of seven rules that should be followed to avoid erroneous results. Perkins (1914, United States) continued the work of Brulle and Sohn in developing a puncture test to measure the hardness of fats. Kissling (1893, 1898, Germany) also studied penetration tests on greases and jellies by recording the time for rods of glass, zinc, or brass of various diameters to sink through the sample. Wender (1895, United States) studied the hardness of butter and margarine by measuring the viscosity of chloroform solutions of the fats in a U-shaped capillary viscometer that he called a 'fluidometer.' Lindsay (1901; Lindsay *et al*., 1909; United States) measured the consistency of butter by measuring the depth that a mercury-weighted glass tube penetrated into butter when allowed to fall a standard height. Meyeringh (1911, Netherlands) also used a puncture test while Hunziker *et al*. (1912, United States) used a deformation test to measure butter hardness.

Cobb (1896, Australia) measured the hardness of wheat grains by measuring the force required to cut a grain of wheat in half by a pair of pinchers simulating biting between the front teeth. He defended his objective method against the skeptics by stating, 'If the relative hardness here given differs from preconceived notions, so much the worse for the preconceived notions, unless it is shown that the methods adopted here are fallacious – an unlikely contingency.' Roberts (1910, United States) used similar procedures to measure the hardness of wheat grains.

Waugh (1901, United States) clearly described a sensory deformation test as follows:

> Peaches and apricots are picked as soon as they show the first sign of ripening. The well-trained picker tests each fruit by taking it between his thumb and fingers and feeling it with the ball of his thumb. The fruit is not squeezed or bruised; but if it has the faintest feeling of mellowness its time has come, and the picker transfers it to his basket.

Leick (1904a,b Germany) measured Young's modulus of elasticity of slabs of gelatin gels in tension and compression and showed that the modulus is approximately proportional to the square of the gelatin concentration. How to measure the firmness of jellies was a matter of interest to a number of early researchers, including Alexander (1906), who was awarded a United States patent (Alexander, 1908) for his apparatus; E. S. Smith (1909), who was also awarded a United States patent; Valenta (1909); Hulbert (1913); Sindall and Bacon (1914); Low (1920); C. R. Smith (1920); Sheppard *et al.* (1920); Oakes and Davis (1922); Freundlich and Seifriz (1923); Sheppard and Sweet (1923); Poole (1925); and Tracy (1928). Bloom (1925) was awarded a United States patent for a 'machine for testing jelly strength of glues, gelatins and the like.' This became the Bloom Gelometer, which is still used by the gelatin industry to measure the jelly grade of gelatins. Tarr (1926, United States) developed the Tarr–Baker Jelly Tester, a puncture test that measured the firmness of pectin jellies. Sucharipa (1923, United States) attempted to measure the firmness of pectin jellies by means of compressed air.

Goldthwaite (1909, 1911, United States) described the texture of a fruit jelly as follows:

> The ideal fruit jelly … will quiver, not flow, when removed from its mold; a product with texture so tender that it cuts easily with a spoon, and yet so firm that the angles thus produced retain their shape; a clear product that is neither syrupy, gummy, sticky, nor tough; neither is it brittle and yet it will break, and does this with a distinct beautiful cleavage which leaves sparkling characteristic faces.

It is clear from this description that Goldthwaite understood the multifaceted nature of texture.

Washburn (1910, United States) also struggled to define differences in textural properties, going to some effort to distinguish between 'body' and 'texture' of ice cream. Lehmann (1907a, Germany) devised an apparatus called the 'Dexometer' to measure the toughness of meat and used the same instrument to measure the softening of vegetables during cooking (Lehmann, 1907b). This was probably the first objective test to measure meat toughness. Willard and Shaw (1909, United States) give results from a puncture test that was used to measure the strength of egg shells but did not describe the equipment.

Professor Morris of Washington State University developed the first puncture tester for measuring the firmness of fruit in 1917 but did not publish his results for several years (Morris, 1925). In the meantime, other workers became aware of his work and developed their own designs of fruit pressure testers, sometimes publishing before Morris (e.g., Lewis *et al*., 1919; Murneek, 1921; Magness and Taylor, 1925).

A graduate student at Kansas State College by the name of Lyman Bratzler was assigned by his advisor, Professor Warner, a research problem involving toughness of meat. He developed a mechanical shearing device whose principle of operation is well known today as the Warner–Bratzler Shear (Warner, 1928; Bratzler, 1932, 1949). Tressler (1894–1981), who has made numerous contributions to the field of food technology, developed a tenderness test for meat based on the puncture principle, which he considered to be superior to the Warner–Bratzler Shear (Tressler *et al*., 1932; Tressler and Murray, 1932). He called the Warner–Bratzler Shear 'the mousetrap,' possibly because of the manner in which it snaps back into place when a tough piece of meat finally shears. Pitman (1930) developed a shear test somewhat similar to the Warner–Bratzler Shear for measuring the firmness of almonds. Tauti *et al*. (1931, Japan) developed a physical test for measuring the firmness of raw fish.

Bingham (1914) developed a U-tube viscometer with applied air pressure that he called a 'plastometer.' This apparatus was used by Herschel and Bergquist (1921) to measure the consistency of starch pastes, and by Porst and Moskowitz (1922) for processed corn products.

Davis (1921, United States) devised the three parallel bar test for measuring the breaking strength or shortness of cookies, calling it a 'shortometer.' This was later improved by Fisher (1933). Hill (1923, 1933, United States) developed the Hill Curd Tester for measuring the firmness of cheese curd; Babcock (1922, United States) developed the falling plummet test for measuring the

firmness of whipped cream; Vas (1928, Netherlands) developed a penetrometer for measuring the firmness of cheese curd; and Knaysi (1927) developed a falling-ball viscometer to measure the viscosity of buttermilk.

Stewart (1923) found that the volume of popped popcorn correlates well with popcorn quality. Sayre and Morris (1931, 1932) measured the volume of juice that could be expressed from sweet corn and concluded that it was a satisfactory test for physical quality of sweet corn. This procedure eventually developed into the Succulometer test (Kramer and Smith, 1946).

One person who must be singled out for special mention is Dr George W. Scott Blair (1902–1987). Dr Scott Blair, an Englishman, and one of the founders of the science of rheology, is world renowned for his pioneering contributions to food rheology and also the rheology of soils, plastics, and biological fluids. He authored over 250 publications on rheology and is author or editor of seven books. Because of his early work on flour (Scott Blair *et al*., 1927) and later on dairy products and psychorheology in the 1930s to 1950s, he is considered to be the 'father' of food rheology. In 1929, while on a sabbatic leave at Cornell University he attended a meeting in Washington, DC, that resulted in the official adoption of the term 'rheology' and the formation of the (American) Society of Rheology. He was also a founding member and president of the British Society of Rheology. A special issue of *Journal of Texture Studies* (Vol. 4, No. 1, 1973) took the form of a festschrift honoring Dr Scott Blair on his seventieth birthday.

A number of contemporary or near-contemporary scientists have made major impacts on the development of texture science and technology. Some of those who have retired or are recently deceased are listed below. Dr Amihud Kramer (1913–1981), Professor of Horticulture at the University of Maryland, made significant advances in our understanding of texture as a quality attribute of fruits and vegetables and led the team that developed what is popularly known as the 'Kramer Shear Press,' an instrument still widely used today. Laurie Lynch (1900–1974) in Australia developed the multi-pin puncture tester named the Maturometer for measuring texture and maturity of green peas and quantified the relationship between texture, maturity, and chemical composition of peas. Dr Toshimaro Sone (1925–1984) in Japan pioneered the use of fundamental rheological methods to characterize the texture of dairy products and related these properties to their internal structure. Dr Birger Drake, in Sweden, made a number of important contributions to our understanding of texture including showing how the analysis of food sounds was an important component of textural quality, especially in crispy and crunchy foods. Dr Alina S. Szczesniak (now retired), a Principal Scientist at General Foods Corporation (now part of Kraft Foods), pointed out the multidimensional nature of texture and its importance to the consumer and developed the principles of texture profile analysis for both instrumental and sensory methods. She was a Founding Editor of *Journal of Texture Studies* in 1969 and served in that capacity for 10 years. A Festschrift honoring her achievements was published in *J. Texture Studies* Vol. 12 issue 2, 1981. Both Professor Kramer and Dr Szczesniak received the Nicholas Appert Award (in 1976 and 1985,

respectively), the highest award given to members of the Institute of Food Technologists. Dr Szczesniak was appointed a Fellow of the International Academy of Food Science and Technology (IAFoST) in 1999 in recognition of her outstanding contributions to the field of food texture. Peter Voisey (now retired), an engineer with Canada Agriculture applied new technologies and engineering principles to modernize and improve many popular empirical testing instruments and developed the Ottawa Texturometer and numerous attachments for performing different tests with just one machine. He stressed the need for dimensional standardization and proper calibration of texture-measuring instruments. Dr Philip Sherman (now Emeritus Professor of Food Rheology at King's College, University of London, England) and Founding Editor of *J. Texture Studies*, a position he held for 24 years, greatly strengthened the rheological aspects of texture measurement and performed the classical experiment that established the shear rates normally engendered in the mouth. A Festschrift honoring his work was published in *J. Texture Studies* Vol. 26 issue 4, 1995. Professor Sherman was appointed a Fellow of the International Academy of Food Science and Technology in 1999 in recognition of his work on food rheology and in extending that work to other countries. Dr Donald Hamann (1933–1996), Professor of Food Science at North Carolina State University who conducted pioneering work on torsion, compression and tensile testing and developed the torsion gelometer and theoretical principles of fracture properties of food gels. Dr David Stanley (now Emeritus Professor of Food Science), University of Guelph, Canada, highlighted the structural and microstructural basis of food texture. Dr John de Man (also an Emeritus Professor of Food Science), University of Guelph, Canada, made many contributions to the field, especially in texture and structure of fats and fat-based foods. The author has had the privilege of personally knowing every person named in this paragraph. Most of this group also played a less visible role in developing the field by serving on the Editorial Board of *Journal of Texture Studies*.

All of the above made notable contributions to the field of food texture and most of those who are still living maintain an active interest in the field. The number of scientists in the texture field continued to multiply in the 1980s and 1990s; their names are referenced throughout the pages of this book. Their number can be expected to increase well into the 21st century due to the increasing recognition of the importance of texture as a quality affecting food acceptance, value, and utilization.

Suggestions for Further Reading

The *Journal of Texture Studies* published bimonthly by Food and Nutrition Press, 6527 Main Street, PO Box 374, Trumbull, Connecticut, 06611, USA publishes original research, reviews, and discussion papers on rheology, psychorheology, physical testing and sensory testing of foods. It is the best

single source of information on developments in the field of food texture, food rheology and food viscosity.

The following books and articles contain much useful information. The older publications will be useful for those who want to trace the development of texture technology.

Aguilera, I. M. and D. W. Stanley. 1999. "Microstructural Principles of Food Processing and Engineering," Second Edition, Aspen Publishers, Gaithersburg, Maryland.

Barnes, H. A., J. F. Hutton, and K. Walters. 1989. "An Introduction to Rheology," Elsevier, New York.

Blanshard, J. M. V. and P. Lillford, eds. 1987. "Food Structure and Behaviour," Academic Press, London.

Blanshard, J. M. V. and R. J. Mitchell, eds. 1988. "Food Structure – Its Creation and Evaluation," Butterworths, London.

Borwanker, R. P. 1992. "Rheology of Foods," Elsevier Applied Science, New York.

Brennan, J. G. 1980. Food texture measurement. *In* "Development in Food Analysis Techniques, Vol. 2" (R. D. King, ed.), pp. 1–78. Appl. Sci., London.

deMan, J. M., P. W. Voisey, V. F. Rasper, and D. W. Stanley. 1976. "Rheology and Texture in Food Quality," Avi, Westport, Connecticut.

Escher, F. 1986. "Textur, Rheologie und Struktur in der Lebensmitteltechnologie," Juris, Zürick.

Faridi, H. and J. M. Faubion, eds. 1990. "Dough Rheology and Baked Product Texture," van Nostrand Reinhold, New York.

Hartel, R. W. 2001. "Crystallization in Foods," Asper Publishers, Gaithersburg.

Kramer, A. and A. S. Szczesniak, eds. 1973. "Texture Measurements of Foods," Reidel Publ., Dordrecht, Netherlands.

Lawless, H. T. and H. Heyman. 1999. "Sensory Evaluation of Food – Principles and Practices," Aspen Publishers, Gaithersburg, Maryland.

Lewis, M. J. 1996. "Physical Properties of Foods and Food Processing Systems," Woodhead Publishing Ltd, Cambridge.

Matz, S. A. 1962. "Food Texture," Avi, Westport, Connecticut.

Meilgaard, M., G. V. Civille, and B. T. Carr. 1999. "Sensory Evaluation Techniques," Third Edition, CRC Press, Boca Raton, Florida.

Meiselman, H. L. and H. J. H. MacFie, eds. 1996. "Food Choice, Acceptance and Consumption," Blackie Academic and Professional, London.

Mohsenin, N. N. 1986. "Physical Properties of Plant and Animal Materials," Gordon & Breach, New York, Second Edition.

Moskowitz, H. R., ed. 1987. "Food Texture. Instrumental and Sensory Measurement," Marcel Dekker, New York.

Muller, H. 1973. "An Introduction to Food Rheology," Crane Russak, New York.

Peleg, M. and E. B. Bagley, eds. 1983. "Physical Properties of Foods," Avi Publishing Co., Westport, Connecticut.

Prentice, J. H. 1984. "Measurements in the Rheology of Foodstuffs," Elsevier Applied Science, London.

Rao, M. A. and J. F. Steffe. 1992. "Viscoelastic Properties of Foods," Elsevier Applied Science, New York.

Rha, C. H., ed. 1974. "Theory, Determination, and Control of Physical Properties of Food Materials," Reidel Publ., Dordrecht, Netherlands.

Rosenthal, A. J., ed. 1999. "Food Texture, Measurement and Perception," Aspen Publishers Inc., Gaithersburg, Maryland.
Scott Blair, G. W., ed. 1953. "Foodstuffs: Their Plasticity, Fluidity, and Consistency," Wiley (Interscience), New York.
Scott Blair, G. W. 1958. Rheology in food research. *Adv. Food Res.* **8**, 1–61.
Sherman, P. 1970. "Industrial Rheology with Particular Reference to Foods, Pharmaceuticals, and Cosmetics," Academic Press, New York.
Sherman, P., ed. 1979. "Food Texture and Rheology," Academic Press, New York.
Society of Chemical Industry. 1960. "Texture in Foods," Monograph No. 7, Soc. Chem. Ind., London.
Society of Chemical Industry. 1968. "Rheology and Texture of Foodstuffs," Monograph No. 27, Soc. Chem. Ind., London.
Sone, T. 1973. "Consistency of Foodstuffs," Reidel Publ., Dordrecht, Netherlands.
Van Wazer, J. R., J. W. Lyons, K. Y. Kim, and R. E. Colwell. 1963. "Viscosity and Flow Measurement. A Laboratory Handbook of Rheology," Wiley (Interscience), New York.
Vincent, J. F. V. and P. J. Lillford, eds. 1991. "Feeding and the Texture of Food," Cambridge University Press, Cambridge.

Body–Texture Interactions

CHAPTER 2

Introduction

The properties of texture and viscosity are perceived by the human senses. Hence, in order to understand texture and viscosity it is necessary to know something about how the human body interacts with food. Most people are well aware of the structure and function of the teeth, and everybody is familiar with the process of mastication and how to squeeze food gently in the hand. Nevertheless, a brief review of these topics is needed to introduce the discussion of the sensing of texture and viscosity.

Mastication is a process in which pieces of food are ground into a fine state, mixed with saliva, and brought to approximately body temperature in readiness for transfer to the stomach where most of the digestion occurs. After some residence time in the stomach the food passes to the small intestine where digestion continues and from whence the nutrients are absorbed into the bloodstream and distributed throughout the body. Pulverization of food is the main function of mastication, but it also imparts pleasurable sensations that fill a basic human need. Table 2.1 summarizes the degree of size reduction that must occur before food can be absorbed and utilized by the body. The process of mastication is an early step in the process of size reduction to small molecules. Mastication usually reduces particle size by two to three orders of magnitude before passing to the stomach where another approximately 20 orders of magnitude of size reduction are accomplished by chemical and biochemical action. If food cannot be reduced to particles of the order of a few multiples of 10^{-22} g, it is not absorbed and utilized but is excreted.

Other parts of the body, principally the hands, often interact with food before it reaches the mouth. The interaction may be by direct contact between the food and the hand, or through some implement such as knife, spoon or fork held in the hand. While mastication is a highly destructive process as

Table 2.1 Steps in the Comminution of Food Before Absorption by the Body

State	Approx. particle mass (g)	Process	Location	Implement
Large cookie				
Whole cookie	20	Biting off	Mouth	Incisors
Mouthsize portion	5	Grinding, crushing	Mouth	Molars
Swallowable paste (bolus)	1×10^{-2}	Biochemical attack	Stomach, intestine	Acid, enzymes
Hexose sugar molecules	3×10^{-22}	Absorption	Intestines	—
Whole dressed steer				
Whole carcass	3×10^{5}	Sawing and cutting	Butcher shop	Saw, knives
Cooked steak	3×10^{2}	Cutting	Plate	Knife and fork
Mouthsize portion	5	Shearing, grinding	Mouth	Teeth
Swallowable paste	1×10^{-2}	Biochemical attack	Stomach, intestines	Acid, enzymes
Amino acid molecules	2×10^{-22}	Absorption	Intestines	—

described above, the squeezing of the food in the hand is nondestructive and yet it often provides important clues to the textural quality of the food.

This chapter will give a simple description of the human masticatory apparatus and follow this with a description of the hand. Since texture is perceived by the human senses, one needs to understand how the body interacts with different foods because this is the foundation on which is built an understanding of what is needed in objective and subjective tests for texture.

Importance of the Tactile Sense

The sensation of texture is perceived primarily by the sense of touch, how the food feels in the hand, and in the mouth. The sense of sight is used to assess the thickness of foods by observing the flow rate of liquids or the degree of slump of semisolids. The sense of sound perceived by ears is an important factor in determining the degree of crispness or crunchiness in foods. But the tactile sense is the one used more than all the other senses combined to perceive the textural properties of foods.

To touch and be touched are basic human needs. All five of the human senses (sight, hearing, taste, odor, touch) are important and have been, and continue to be the subject of considerable research effort. However, in comparison with the other four senses the sense of touch seems to have been slighted by the research community judging by the amount of published literature on each of the senses.

Four of the senses can be deceived fairly easily but it is difficult to deceive the sense of touch. For example, artificial flowers can be made so skillfully that it becomes difficult to tell whether they are real or artificial by looking at them, but a moment's touch with the fingers positively identifies which flower is real and which is artificial. Another example of the remarkable sensitivity

of the tactile sense is found in that frequent human experience of turning the page of the book, magazine or newspaper; one can immediately tell whether one or two pages are held between the forefinger and thumb even though a single sheet of paper is only 0.04–0.14 mm thick.

Sachs (1988) called touch 'the intimate sense' and described its importance in the following words.

> Throughout the first few days of life, the baby continues to be most affected by the things that touch her: a soft blanket, warm breast, a firm bed. Even after she has begun to favor sight, she relies heavily on this most intimate of senses to gather information about her environment. If she spies, say, an alphabet block in her crib, she will pick it up, turn it over in her hands, then put it in her mouth – not, as one might think, to taste the block but to touch it with her lips and tongue, regions of the body that are particularly sensitive to tactile stimuli. She uses her sense of touch, which is not easily fooled, to confirm her sense of sight, which, even when fully mature, is subject to all manner of illusions. The fundamental nature of touch is even more apparent when the sense is deprived of stimulation. Being unable to hear or see does not prevent one from attaining a happy and fruitful existence. … But an existence devoid of tactile sensation is another matter: sustained physical contact with other humans is a prerequisite for healthy relationships and successful engagement with the rest of one's environment. … And among humans, denial of physical contact during the first years of life can cause virtually irreversible states of withdrawal. Touch, in short, is the core of sentience, the foundation for communication with the world around us, and probably the single sense that is as old as life itself.

Some Definitions

Masticate. To chew, grind, or crush with the teeth and prepare for swallowing and digestion. Note: Mastication is a *process*.

Bolus. A mixture of chewed food and saliva in the mouth.

Deglutition. The act or process of swallowing food. Deglutition tips the food into the esophagus (gullet), the tube which leads down to the stomach. Deglutition ends the voluntary portion of the digestive process. The rest of the digestive process is involuntary and automatic.

Since textural properties of foods are perceived primarily in the mouth there is a need to know something about the structure of the organs and tissues of the mouth and the actions that occur during mastication.

1. *Teeth (dentes)* are the main agent for masticating foods and breaking them into small pieces. They also play an important role in clear speech and facial structure and appearance. Crooked, decayed, or missing teeth reduce masticatory efficiency and cause disfigurement and sometimes self-consciousness. From the external viewpoint teeth consist of two parts: (1) the *crown* is that part that protrudes above the gums and is visible in the mouth and (2) the *root* is that portion that is not visible in the mouth but is buried in the gums and serves to anchor the teeth in the jawbone.

A cross-sectional cut through a tooth shows that it is composed of several layers of tissues (Fig. 2.1). The enamel is the very hard external layer that covers the crown of the tooth and contacts the food during mastication. Underneath the enamel is the dentin, which is hard tissue forming the body of the tooth and which constitutes the principal mass of the tooth. The cementum

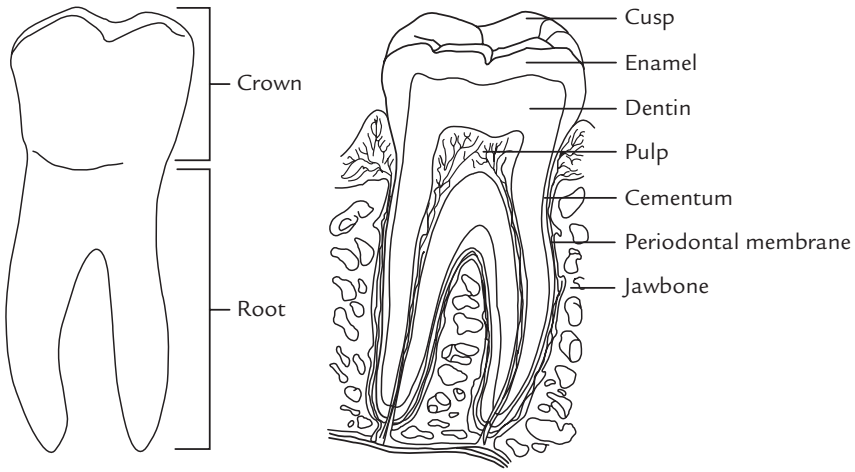


Figure 2.1 Cross-section of a tooth. (Copyright by the American Dental Association, reprinted with permission.)

is a bonelike tissue that covers the root. The pulp is a soft tissue that occupies the central portion of the tooth called the pulp chamber. It contains nerves, arteries, veins, and lymph vessels. These vessels enter the tooth through small openings at the tip of the root. The periodontal ligament (membrane) is the layer of connective tissue that lies between the cementum and the jawbone and helps to hold or support the tooth in its place. Small elastic fibers are connected to the tooth via the cementum along the entire surface of the root. A cusp is a pointed or rounded surface on the crown of the tooth and is the main contact surface for breaking up the food. It is a prominence on the chewing surface of a tooth. Cusps wear flat over years of chewing and are progressively flattened as one gets older. The teeth are composed principally of calcium phosphate. Teeth are not bones; they are much harder and more dense than bones.

Teeth may be classified according to their shape and the function they perform (Fig. 2.2). The incisors, located in the center front of the mouth, are wedge-shaped and have a sharp flat edge which is used to cut or incise foods. The cuspids, which are located at the corners of the mouth, have a long heavy root and a crown with a single pointed cusp. They are often called the ‘eye’ teeth or canines. These are used to tear foods. The premolars (bicuspids) are located behind or in back of the cuspids and have two cusps and one or two roots. They are used to both tear and crush foods. The molars are located at the back of the mouth. Each molar has two or three roots and several cusps that occlude with the opposing molars. Their broad crowns are used to grind and crush the food with a grinding millstone-type of action.

A child in full dentition has 20 teeth (Fig. 2.3). The 10 teeth in each jaw comprise two central incisors, two lateral incisors, two cuspids, two first molars, and two second molars. These primary (deciduous, milk, or ‘baby’) teeth appear between 6 and 24 months in the average child and are shed between 6 and 12 years to be replaced by the adult or permanent teeth as the jaw increases in size sufficient to accommodate the larger size and increased number of adult teeth.

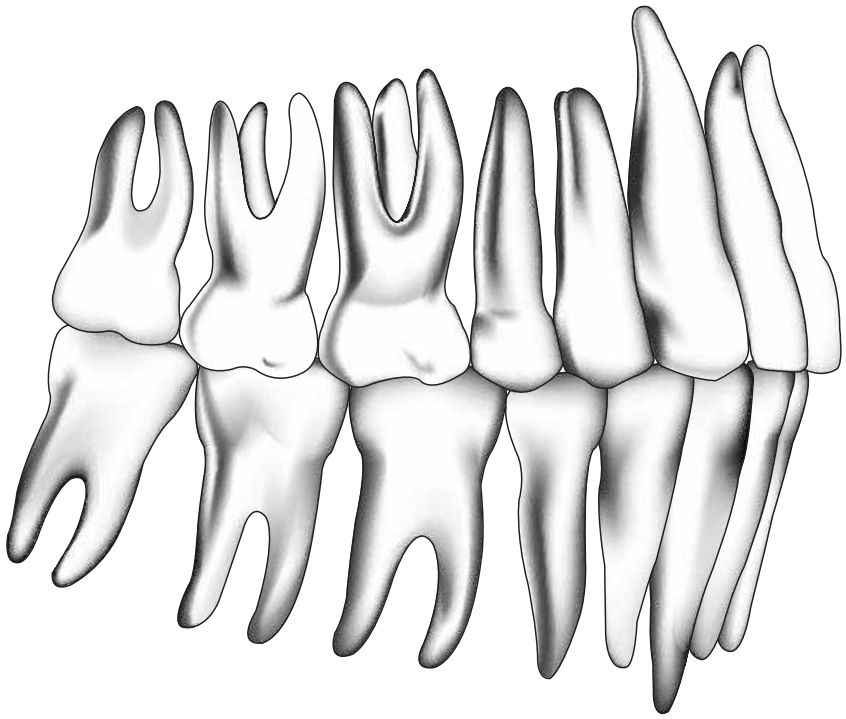
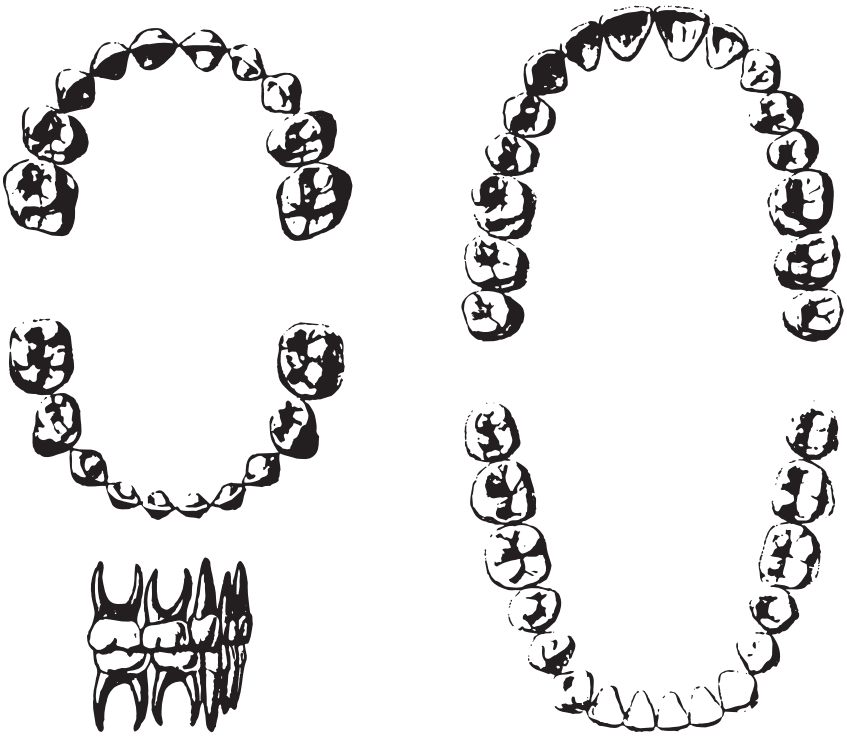


Figure 2.2 Normal occlusion of permanent teeth. In order from left to right: third molars; second molars; first molars; second bicuspids; first bicuspids; cuspids; lateral incisors; central incisors. (Copyright by the American Dental Association, reprinted by permission.)



a b

Figure 2.3 (a) Eruption and shedding of the primary teeth. (b) Eruption of the permanent teeth. (Copyright by the American Dental Association, reprinted by permission.)

Full dentition in the adult consists of 32 teeth, 16 in each jaw (Fig. 2.3). Each jaw contains two central incisors, two lateral incisors, two cuspids, two first bicuspids, two second bicuspids, two first molars, two second molars, and two third molars. These teeth erupt from the age of approximately 6 to

Table 2.2 Eruption and Shedding of Human Teeth

Primary teeth			Permanent teeth	
	Eruption (months)	Shedding (years)		Eruption (years)
Upper			Upper	
Central incisor	7½	7½	Central incisor	7–8
Lateral incisor	9	8	Lateral incisor	8–9
Cuspid	18	11½	Cuspid	11–12
First molar	14	10½	First bicuspid	10–11
Second molar	24	10½	Second bicuspid	10–12
			First molar	6–7
			Second molar	12–13
			Third molar	17–21
Lower			Lower	
Central incisor	6	6	Central incisor	6–7
Lateral incisor	7	7	Lateral incisor	7–8
Cuspid	16	9½	Cuspid	9–10
First molar	12	10	First bicuspid	10–12
Second molar	20	11	Second bicuspid	11–12
			First molar	6–7
			Second molar	11–13
			Third molar	17–21

21 years. The third molars (wisdom teeth) generally appear in the late teens or early twenties and complete full dentition in the adult. The normal times for eruption and shedding of teeth are shown in Table 2.2.

Partial or full dentures (artificial teeth) may be fitted to offset the loss of natural teeth, but they do not perform as well as healthy natural teeth (see Tables 2.4 and 2.6, pages 47, 51). People with reduced masticatory efficiency caused by incomplete dentition or dentures often compensate for the deficiency by selecting foods that are easier to chew and present less challenge to masticatory function.

2. The *lips (labia oris)* are the two highly mobile fleshy folds that surround the orifice of the mouth and admit food and liquid into the oral cavity. The lips also prevent the loss of food from the mouth between masticatory strokes. They have a variety of sensory receptors that can judge the temperature and some of the textural properties of foods. The lips have a high acuity to touch; they are even more sensitive than the tips of the fingers.

3. *Cheeks (buccae)* form the sides (lateral walls) of the mouth and face and are continuous with the lips. They consist of outer layers of skin, pads of subcutaneous fat, muscles associated with chewing and facial expression, and inner linings of stratified squamous epithelium. The cheeks keep the food within the oral cavity and return the food between the teeth between bites.

4. The *tongue (lingua)* is a strong, mobile, muscular organ with its base and central part attached to the floor of the mouth. It occupies much of the oral

Table 2.3 Size Threshold Between Smooth and Grainy Texture

Food	Particle size (μm)	Reference
Chocolate	13	Cook, 1982
Chocolate	20	Rostagno, 1969
Chocolate	25	Hinton, 1970
Fondant (sugar crystals)	20–25	Woodruff and Gilder, 1931
Ice cream (ice crystals)	55	Fukushima and Kimura, 1992
Margarine (fat crystals)	22	Vaisey-Genser *et al*., 1989
Sweetened condensed milk (lactose crystals)	10–12	Sakurai *et al*., 1993
Tofu (soy particles)	24	Numata *et al*., 1997

space when the mouth is closed. It is a very active organ during the act of mastication, working in close proximity to the teeth but seldom caught between the teeth. Skillful coordinated neuromuscular functions between the tongue and teeth are required for painless mastication. It returns food between the teeth between chews and is actively involved in mixing the bolus with saliva and in moving the bolus toward the pharynx during swallowing. It is used to break up soft foods against the hard palate without the help of the teeth and is the organ most responsible for sensing the surface or geometrical properties of foods because of its ability to perceive minute differences in particle size, shape, firmness, and roughness. The tongue demonstrates a more acute tactile sensibility than any other part of the body. Two-point sensibility is the shortest distance between two points that can be perceived as two separate stimuli. For the tongue this is 1.4 mm, for the fingertip 2 mm, and for the nape of the neck 36.2 mm. The tongue is also the principal organ of taste and an important organ of speech.

The presence of particles can affect textural sensations and contribute to the liking or disliking of foods. The feeling of the size, shape, and roughness of discrete particles in the mouth is called ‘geometrical properties’ by Brandt *et al*. (1963) and ‘particulate properties’ by Hutchings and Lillford (1988). Particles are detected by the tongue and hard palate, especially near the incisors. A description of the most frequently sensed particles together with examples of foods that exemplify them is given in Table 7.9, page 267. It is remarkable to find just how small a particle can be detected by the tongue. For example, Imai *et al*. (1999) showed that a sensory panel could detect particles as small as 6 μm in food.

Imai *et al*. (1999) noted that graininess is a desirable feature of bean paste when the starch cells are 100–150 μm across, and of pounded rice cakes when the rice flour particles are 75–105 μm across. They also point out that graininess is undesirable in smooth foods and cite figures showing how small particles must be to avoid being detected as discrete particles in the mouth (see Table 2.3).

5. The *palate* (roof of the mouth) consists of two sections. To the front of the mouth (anterior) lies the hard palate (*palatum durum*), which consists of a bony

skeleton covered with a thin layer of soft tissue. It separates the oral cavity from the nasal cavity and presents a hard surface against which foods can be pressed by the tongue to break them up, spread them out, or mix with saliva.

The soft palate (*palatum molle*), which lies at the back of the mouth (posterior), consists of a thick fold of muscular membrane containing muscles, vessels, nerves, lymphoid tissues, and mucous glands. During swallowing or sucking it is elevated to close the opening to the nasal cavity, thus preventing food from entering the nasal cavity from the oral cavity.

6. The *gums (gingivae)* are composed of dense fibrous tissue that surround the teeth and help anchor them. Healthy gingivae effect a cuff creating a barrier round the teeth to stop egress from the mouth down the sides of the teeth.

7. *Salivary glands* provide the saliva that hydrates foods, lubricates the bolus, and begins the digestion of carbohydrates. There are three pairs of salivary glands: the *sublingual* (beneath the tongue), *submandibular* (beneath the jaw), and *parotid* (beneath the ear). Secretions from the salivary glands enter the oral cavity through narrow tubes called salivary ducts.

8. The *upper jaw (maxilla)* serves to anchor the upper teeth and is fairly immobile during mastication. The teeth in the maxilla can be likened to the anvil against which the food is pressed to break and crush it by the lower teeth. The maxilla can move rhythmically during mastication thus contributing to separation of the jaws.

9. The *lower jaw (mandible)* is a horseshoe-shaped bone that anchors the lower teeth and articulates (moves) primarily in a reciprocating vertical motion with approximate sinusoidal speed. A variable amount of lateral (sideways) motion is also present, depending on the nature of the food. Foods that are easily crushed (e.g., snack foods such as potato chips) require little lateral motion whereas foods that are tough (such as meat and bread crust) require a rather large amount of lateral motion to masticate the food. The mandible translates forward to bring the upper and lower incisors into alignment during biting off.

A number of muscles are responsible for articulating the mandible. The most powerful of these is the masseter muscle, which is capable of generating high compressive forces aided by two other powerful muscles, the temporal and medial pterygoid. Lateral and protrusive movements of the mandible are largely controlled by the lateral pterygoid and suprahyoid muscles. The jaws are operated by the most complex muscular system in the body; five different movements are available, most of them generating high forces.

Articulation of the mandible occurs about a highly specialized and complex composite joint called the temperomandibular joint, which allows five different movements – far more than any other joint in the body. The joint contains two compartments. During normal chewing action it acts as a hinge joint in which the mandible rotates in a vertical direction in the first compartment (Fig. 2.4). When the jaw is opened very wide or protruded forward, the mandible glides out of the first compartment into the second compartment, which is a movable sliding socket. The mandible can be moved laterally when

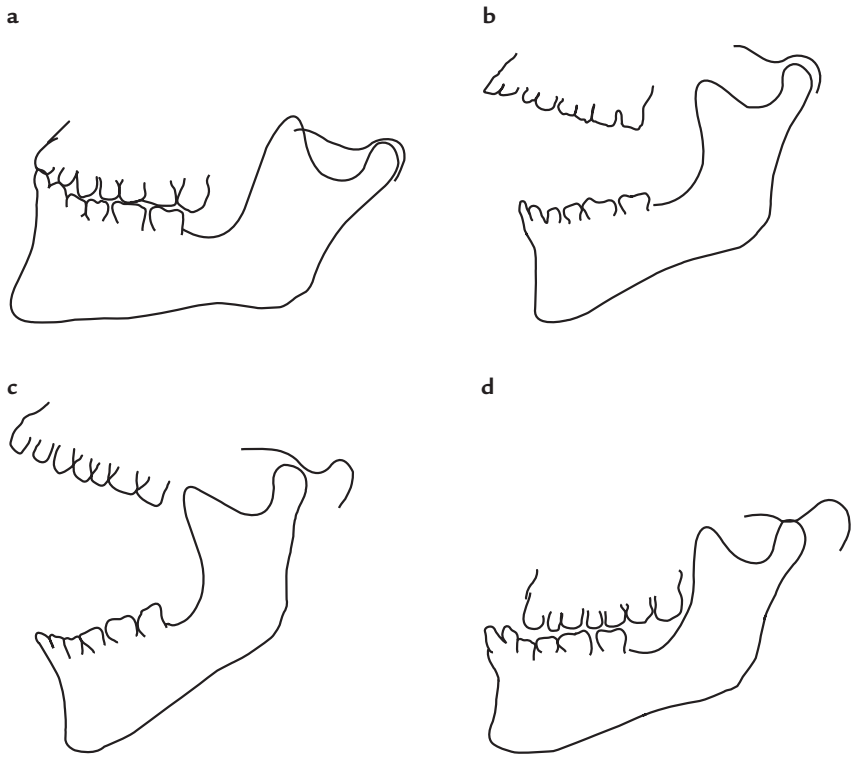


Figure 2.4 The tempero-mandibular joint. (a) In occluded position; (b) Opened in pure hinge position; (c) Opened as wide as possible; (d) In protruded position. Notice how the mandible slips out of its cup in positions c and d.

in either compartment, although the extent of the sideways movement is limited by the temperomandibular ligaments. From a position in which the incisors are in contact, the mandible may be moved downward to open the jaw, laterally for a sideways swing, forward in protrusion, and backward in retrusion. The temperomandibular joint is remarkable in its flexibility and in the variety of movements it can accomplish with great force. It is the key to the various chewing modes that are available to masticate foods with widely differing combinations of physical properties.

Many people can feel the temperomandibular joint move by lightly placing the tips of the fingers on the jaw just in front of the ears. The hinge action can be felt by opening and closing the jaw to a moderate degree and the lateral motion can be felt by swinging the jaw sideways. When the jaw is protruded or opened very wide, one can feel the joint glide forward from the pure hinge compartment into the socket compartment.

The vertical articulation of the mandible is bilaterally symmetrical because the mandible is a single bone and movement in one temperomandibular joint cannot occur without a similar coordinating movement in the corresponding joint on the opposite side of the mouth.

Temperomandibular joint (TMJ) diseases and disorders are diverse chronic painful conditions affecting the area where the mandible joins the skull at the articular fossa. Symptoms include pain in the face or jaw joint area, headaches, limited ability to open the mouth, locking of the jaw, and clicking, or grating sounds on opening or closing the jaw. According to the US National Institutes of Health, more than ten million people are affected by TMJ disease

in the US, most of them being premenopausal women. The descriptive term 'temperomandibular joint disease' is being rapidly replaced in the dental field by the term 'cranio-mandibular pain dysfunction syndrome.'

10. The *oral cavity (cavium oris proprium)* is the space bounded by the lips and cheeks, by the palate above, and the muscular floor below. It contains the teeth and tongue.

11. The *pharynx* is the cavity at the back of the mouth that connects the nasal and oral cavities with the larynx (voice box) and the esophagus (tubular passageway to the stomach). When the bolus is pushed into the pharynx by the tongue, the swallowing reflex is initiated and the following responses occur in rapid succession:

a. The soft palate is raised, preventing the bolus from entering the nasal cavity.
b. The larynx is elevated to prevent the bolus from entering the trachea (windpipe).
c. The tongue presses up against the soft palate, sealing off the oral cavity from the pharynx while the pharynx moves upward toward the bolus.
d. The muscles at the lower end of the pharynx relax and open the esophagus.
e. The muscles of the upper end of the pharynx contract, forcing the bolus into the esophagus. Peristalsis (alternate contractions and relaxation of the muscles along the esophagus that cause a contraction ring to move along the esophagus) moves the bolus down the esophagus to the stomach. When the peristaltic waves reach the stomach, the muscles that guard its entrance relax and allow the bolus to enter. These muscles contract after the bolus has entered the stomach, closing off the entrance and preventing regurgitation of the acid stomach contents into the esophagus.
f. The muscles and organs return to their normal position.

12. *Other*. The arm, neck, and shoulder muscles may be brought into use at times, especially when biting off a piece of tough food.

Occlusion refers to the manner in which the upper and lower teeth meet and fit together as the jaw is closed. In good occlusion the cusp surfaces of the upper teeth fit closely to the lower teeth. The medial occlusal position (or intercuspal position) is that position in which the mandible returns when the jaws are snapped shut automatically from a wide opening when no food is in the mouth. In this position the upper and lower molars and cuspids are in direct contact and the cusps fit together to give an uneven line while the upper incisors lie in front of, and partially cover the lower incisors (see Fig. 2.2, page 37).

From the medial occlusal position the jaw can be protruded (moved forward after slight opening) so that the upper and lower incisors meet in readiness for biting off; in this position the molars do not contact each other. The mandible

can be protruded even farther forward by pressing the temperomandibular joint forward into its second compartment. It can also be retruded until the lower incisors are well behind the upper incisors. From the medial occlusal position the lower jaw can also be pulled sideways to the right or left (lateral movement). The ability of the mandible to be moved in all directions from the medial occlusal position allows a wide range of chewing techniques to be employed.

Malocclusion (bad closing) occurs when the cusps of the upper and lower teeth do not fit well when the mandible is in the closed position. This is a problem to which dentists devote much attention.

Mastication refers to the entire complex of processes that occurs as the food is chewed and brought into a condition ready to be swallowed. It may be a voluntary or involuntary act. This is an extremely complex set of processes that is generally not well understood or appreciated. Mastication is a biting–chewing–swallowing action that is a complex stimulation–motor feedback process in which a constant stream of stimuli travels from mouth to brain and a corresponding stream of instructions travels from the brain to the mouth instructing it how to proceed (Fig. 2.5). This complexity has been well described by Yurkstas (1965) as follows:

> We sometimes fail to appreciate the complexity of the chewing apparatus. It is truly remarkable that most people perform this function daily, with little or no forethought. Mastication involves the use of forces that sometimes exceed 100 lb and pressures that are probably 10,000 lbs in^{-2}. One hundred blows per minute are often delivered for periods of one-half to one hour at a time. These blows are automatically controlled and are precise to within a few hundredths of an inch, since a mistimed blow or misguided stroke can cause intense pain or result in considerable damage.

The Sequence of Mastication

The time devoted to masticating a food, number of chews, and type of chewing motion varies considerably from person to person, and from one food to another. The sequence below is the most common sequence found with the majority of foods.

(1) Bite off a piece of food with the incisors (initial breakage phase). Soft foods are usually wiped off the spoon with the lips instead of using the incisors.
(2) Cut into small pieces with the incisors when necessary.
(3) Puncture or tear apart with cuspids and bicuspids as necessary.
(4) Grind into small particles with the molars, simultaneously mixing the food into a paste with the saliva using both tongue and teeth. Soft, smooth foods are manipulated by the tongue more than by the teeth. This process is mainly one of mixing the food with saliva when there are no hard pieces to be broken down by the teeth (mush phase).
(5) Swallow the liquid portion and fine particles, retaining the insufficiently chewed portion in the mouth.

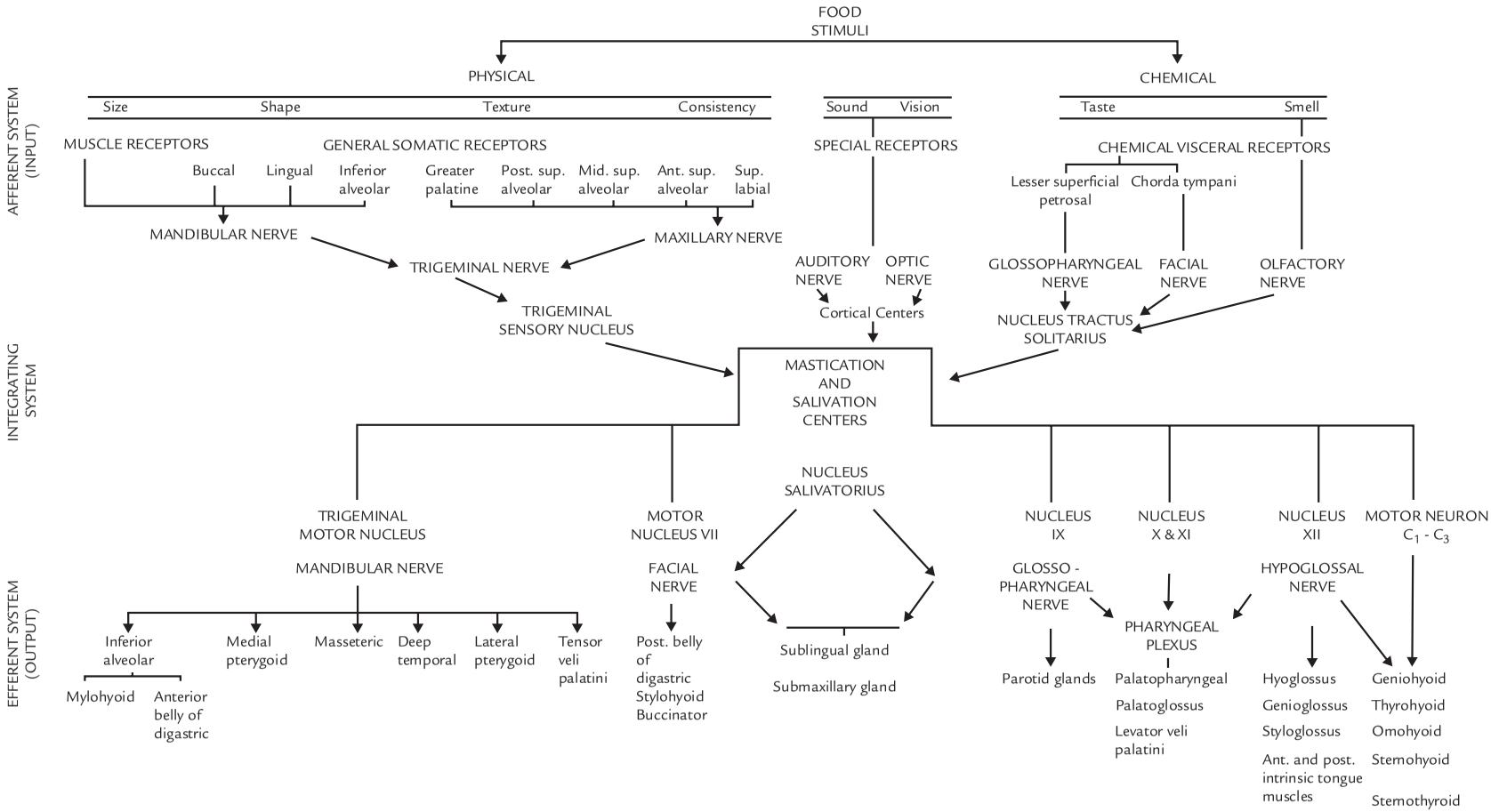


Figure 2.5 The complex neuromuscular mechanism involved in the act of chewing food. The senses of sound, vision, taste and smell participate indirectly in chewing through their influence on the salivary secretion. (From Kapur *et al.*, 1966; reprinted with permission of W.B. Saunders Co.)

(6) Continue the grinding, mixing, and swallowing sequence until the bolus has disappeared and the mouth is empty and ready to bite off the next piece (clearance phase). Pierson and LeMagnen (1970) showed that there is only one deglutition for very soft and liquid foods and that the number of deglutitions increased as the hardness, dryness, or compactness of the food increased. Hiiemae and Palmer (1999) showed that deglutition of liquids occurs sooner than for triturated foods, and they developed a model for a bolus formation and deglutition.

Methods and Processes Used for Disintegration of Food

Different mastication processes and combinations of processes are used for preparing foods for swallowing. The main processes are described below.

(1) Mechanical disintegration. The teeth do most of the work and saliva plays a minor role, e.g. meat and most fruits and vegetables. For foods that release much liquid (for example, oranges and juicy meat) some swallowing of the expressed liquid may be needed before serious chewing begins.
(2) Softening by absorption of saliva or a beverage that is consumed with dry foods, e.g. crackers, dry cookies, potato chips, popcorn. Saliva (or beverage) plays a major role and its softening effect may be more important than the mechanical disintegration accomplished by the teeth. For some foods saliva absorption may be the rate-determining process that prepares the food for deglutition. Some foods are presoftened by absorption of a liquid before placing the food in the mouth. For example, some people dunk their cookies in tea or milk because they prefer a softer texture. On the other hand, the softening of dry crisp breakfast cereals in milk is usually considered undesirable.
(3) Melting is caused by a phase change from solid to liquid as food is warmed in the mouth, e.g. ice cream and gelatin gels. The cocoa butter that provides most of the textural sensations of chocolate is noteworthy for having a narrow melting point range just a few degrees below body temperature. Its rapid conversion from a hard snappy solid into a viscous flavorful liquid provides delightful sensations. Chocolate substitutes using fats that do not have the same sharp melting characteristic as cocoa butter usually do not melt completely at body temperature and leave an unpleasant waxy feel in the mouth.

    Since viscosity decreases as the temperature increases, cold liquids become thinner as they warm up in the mouth even when there is no phase change.
(4) Hardening caused by a phase change from liquid to solid as hot foods are cooled in the mouth, e.g. the oil in hot soup may solidify as it is

cooled in the mouth changing from an oily mouth feel to a fatty mouth feel.

(5) Thinning caused by dilution with saliva, e.g. thick beverages such as milk shakes and cream soups. The teeth are not used or hardly used. The product is stirred around in the mouth by the tongue until sufficient saliva has been absorbed to render the bolus thin enough to be swallowed easily.

(6) Thinning caused by stirring. Some semiliquid foods exhibit what is known as 'shear thinning' behavior, that is, the viscosity is decreased by the mechanical stirring imparted by the tongue and shearing as the tongue compresses the food against the hard palate (Kokini *et al*., 1977; Kokini and Dickie, 1982). Shear thinning behavior is described in Chapter 3.

(7) Solution. Hard sugar candies may be licked or sucked until they simply dissolve in the saliva. However, there are people who chew them (mechanical disintegration) in order to get a shorter but more intense burst of flavor release.

(8) No disintegration. Thin liquids such as coffee, tea and carbonated beverages are simply swallowed with virtually no assistance from teeth, tongue or saliva. Slippery foods such as oysters and some Oriental noodles are sometimes swallowed whole with no interaction from the teeth or saliva and little assistance from the tongue.

Hutchings and Lillford (1988) postulate characteristic 'breakdown pathways' for different foods as they are prepared for swallowing and that two planes must both be penetrated before swallowing begins.

Plane 1 is the degree of structure plane. Particle size must be reduced below a certain level before swallowing can begin.

Plane 2 is the degree of lubrication plane. A certain degree of lubrication must be exceeded before swallowing begins. The lubrication may come from free moisture initially present in the mouth, flow of saliva, or juice expressed from the food. In some foods it may come from the release of oil or fats.

The first few chews on a piece of food are generally slow as one manipulates the piece within the mouth to soften it with saliva or cut it into smaller pieces with the incisors. When the bolus reaches a consistency that can be readily managed, the chewing rate is stepped up to the normal chewing rate, which then remains fairly constant for the remainder of that chewing cycle.

The size of the pieces of food that are swallowed is known as the 'swallowing threshold.' Yurkstas (1965) studied this and concluded:

The results show that the swallowing threshold was directly related to masticatory performance, the correlation coefficient being significant to the 1% level. Thus, people with superior masticatory ability attained a finer degree of food pulverization at the swallowing threshold than did people who possessed dentitions that were less efficient. The person with the diminished ability to chew compensated for his dental handicap by swallowing larger particles of food. … People

Table 2.4 Effect of Missing Teeth on Masticatory Performance

	Chewing efficiency[a]	
	Mean	Range
Complete dentition	88	75–97
Third molar missing	78	45–92
Third and one other molar missing	55	17–83
Dentures	35	9–57

[a]Chewing efficiency is defined as the percentage of food passing through a 20-mesh screen after 20 chews. Data from Yurkstas (1965).

Table 2.5 Chewing Rates on Sticks of Chewing Gum

	Chews per minute			
Year	Mean	Maximum	Minimum	Number of respondents
1973	64.5	98	45	34
1975	54.8	105	27	23
1977	60.4	84	38	20
1979	70.3	105	48	28
1981	65.5	100	24	30

who had poor dentitions did not compensate for their dental handicap by chewing for a longer period of time or by increasing the number of masticatory strokes.'

Table 2.4 shows the effect of missing teeth on masticatory performance.

Kapur *et al.* (1964) showed that the chewing process by natural teeth is preferential; that is, the coarse particles are ground more rapidly than fine particles as chewing proceeds, whereas mastication in subjects with complete dentures is nonpreferential – all particles are pulverized at random.

It should be noted that the forces exerted by the teeth provide the *stress* on the food while the movement of the jaw provides the *strain* on the food during mastication. (These two terms are defined in the next chapter.)

The rate at which people chew depends partly on the food and partly on the person. Each time the author teaches his class in food rheology he gives the students sticks of a well-known brand of chewing gum and asks them to measure their chewing rate once the gum has been brought to a 'steady-state' condition. In this classroom situation the mean chewing rate is approximately 60 chews per minute with a range of 24–105 chews per minute (Table 2.5). Using informal tests on a number of people on sticks of the same brand of chewing gum the author has found a chewing rate as low as 26 chews per minute to a high of 132 chews per minute (Bourne, 1977).

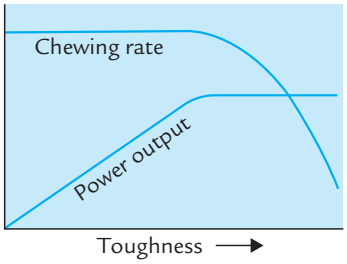


Figure 2.6 Schematic representation of the relationship between chewing rate and power output on foods of increasing toughness.

The effect of the food on the chewing rate follows a complex pattern. What seems to happen is demonstrated schematically in Fig. 2.6. The chewing rate remains approximately constant as one moves from foods of low toughness to foods of moderate toughness. This constancy is achieved by increasing the power output of the jaw (power is the rate of doing work). As the food continues to increase in toughness the limit of comfortable power output is reached. Beyond this point the power output remains approximately constant, and this is achieved by slowing the rate of mastication. One chews tough meat and chewy caramels more slowly than foods that require less energy for mastication.

The chewing pattern is completely changed with extremely hard foods such as rock candy and nuts in the shell. These foods are usually placed carefully between the molars where the maximum leverage is available and the force is steadily increased until the food cracks or shatters. In these cases the compression rate before breaking is almost zero. The chewing mode is that of constant rate of increase in force application. This is a stress-dependent type of mastication in contrast to the usual strain-dependent type.

Rate of Compression between the Teeth

The rate of compression between the teeth varies over a wide range and is affected by several factors. Table 2.5 indicates the wide range of chewing speeds from person to person on a standard product. It has been noted above that the first few chews on a piece of food are frequently slower than the regular chewing rate and that tough foods are masticated more slowly than tender foods.

How widely the jaw is opened affects the compression speed. Some people make short strokes of the jaws whereas others make longer strokes. People who make long strokes will have a higher compression rate if they use the same number of chews per minute because the average compression speed is the product of the number of chews per minute by twice the distance between the teeth at the point of maximum opening.

The mandible articulates in approximately the arc of a circle around the temperomandibular joint. The teeth that are closer to this joint move a smaller distance than the teeth that are farther from the joint. The incisors are the farthest from the joint and move at about twice the speed of the molars. Even among the molars the first molar moves at a faster rate than the third molar because of its greater distance from the temperomandibular joint.

The rate of movement of the jaw follows approximately a sine curve. The actual rate of compression will vary continuously throughout each masticatory stroke, reaching a maximum speed at approximately midstroke and falling to zero at the end of the stoke.

If we assume 60 chews per minute as the average chewing rate, and an average stroke length of 10 mm, then the average compression rate is 1200 mm min^{-1}, or 20 mm s^{-1}. As noted above, there will be substantial variations from this 'average' figure.

Soothing Effect of Mastication

Mastication has been found to have a pronounced soothing effect. Chewing 'soothes the nerves.' Fidgeting activities such as finger tapping, leg swinging, pipe smoking, adjusting the hair or mustache, etc., greatly decline in frequency when mastication is taking place. The sucking and chewing that a fretful baby gives to its thumb or a pacifier is another example of the soothing effect of mastication. Chewing gum is a harmless way to use the soothing effect of mastication to relieve tension. For this reason it would be desirable to allow students to chew gum during examinations!

Saliva

The flow of saliva that is generated by the salivary glands (see item 7, page 40) lubricates the bolus, softens dry foods, flushes away small food particles, absorbs juices, initiates the first phase of digestion through its ptyalin content, and aids deglutition. The act of chewing stimulates the flow of saliva. One study found that the mean saliva flow among a group of people at times of nonstimulation was 26 ml h^{-1} with a range of 2.5–110 ml h^{-1} (Jenkins, 1978). When the saliva flow was stimulated in the same people by giving them flavored wax to chew, the saliva flow increased to 46–249 ml h^{-1}. It should be noted that factors other than mastication can stimulate the flow of saliva; for example, the smell or sight of food or talking about food. There is the classical example of Pavlov's dogs that were conditioned to salivate at the sounding of a bell (Pavlov, 1927).

Saliva generally consists of approximately 99.5% water and 0.5% solids, but these figures can vary widely from person to person and from day to day within the same person. The main constituent of saliva is a glycoprotein called *mucin* which imparts a slimy mucus character to the saliva, thus assisting in the lubrication of the bolus. Saliva contains the enzyme ptyalin (an amylase) which assists in the biochemical breakdown of the food. The parotid gland secretion is rich in ptyalin but watery because it is low in mucin. The submandibular gland secretion is viscous because it is rich in mucin but is low in ptyalin. The secretion from the sublingual gland is mixed, containing both ptyalin and mucin. Total ash is approximately 0.25%. In a study of 3400 people it was found that the pH of saliva ranged from 5.6 to 7.6 with a mean of 6.75 (Jenkins, 1978).

Van der Reijden *et al*. (1994) reported that during the day the pH of the oral fluid in the human mouth changes continuously between pH 6.5 to pH 7.5 due to the intake of food and subsequent acid production by microbial fermentation. Prinz and Lucas (2000) showed that pooled saliva from healthy people is shear thinning in behavior (see Fig. 2.7) but that certain diseases caused a substantial decrease in degree of shear thinning. The term 'shear thinning' is explained in the next chapter.

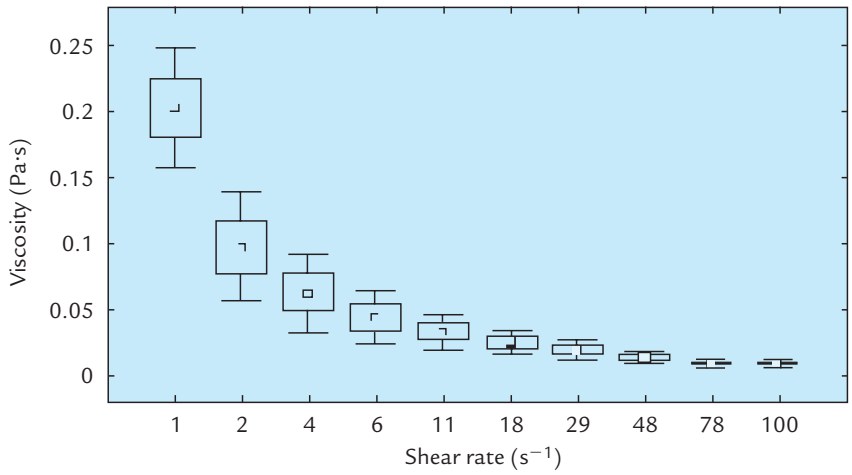


Figure 2.7 Viscosity versus shear rate of pure saliva. (From Prinz and Lucas, 2000. Reprinted from *J. Oral Rehabilitation* 27, page 993. Copyright by Blackwell Science Ltd.)

Forces Generated between the Teeth and Palate

In general the maximum force exerted between the teeth is 15 kg between the incisors, 30 kg between the cuspids, and 50–80 kg between the molars. This range in readings is undoubtedly due to the leverage effect – the molars are much closer to the fulcrum of the mandible than are the incisors.

Oldfield (1960) noted that Borelli measured the total force exerted by the jaw in 1681 by hanging weights on the lower jaw, and found that the maximum weight that could be supported was about 100 lb. Table 2.6 shows the maximum forces that can be exerted between the teeth among Eskimos and Americans. The wide differences between the two tribes shown in this table are undoubtedly due to the fact that the Eskimos eat a great amount of tough, hard foods and they chew on animal skins to improve the quality of the pelt, which develops the masseter and other muscles of the jaw, whereas Americans, eating mostly soft foods, are never required to develop the muscular strength of the Eskimos. It is interesting to notice that the mean value of 200 lb for female Eskimos is equal to the maximum value of 200 lb for the American male. The author leaves his readers to draw whatever conclusions they want from these figures!

Another national difference in chewing ability is shown in Table 2.7, where the number of chews required to bring food to the point of deglutition is shown for a trained American texture panel and a trained Filipino texture panel. In each case the Filipinos required more chews than the Americans for the same type of food. This difference is probably due to the fact that the Filipino diet is basically cooked rice, which is soft, requires little mastication and never calls for strong jaw muscles. Other foods that are used in the Filipino diet are generally cut into small pieces before being brought to the table so that the diet on the whole is not challenging or demanding from the textural standpoint.

Table 2.6 Forces Exerted Between Teeth (in Pounds)[a]

	Male		Female	
Subject	**Mean**	**Maximum**	**Mean**	**Maximum**
Eskimo	270	348	200	326
American (natural teeth)	120	200	85	165
American (dentures)		~60		

[a]Data taken from Waugh (1937) and Klatsky (1942).

Table 2.7 Average Chew Counts on Selected Foods

	US-trained panel[a]	Filipino-trained panel[b]
Frankfurter	17.1	22.1
Jelly beans	25.0	34.0
Steak	31.8	56.6
Caramels	37.3	61.6

[a]Unpublished data from A. S. Szczesniak.
[b]Unpublished data from M. C. Bourne.

Table 2.8 Average Force per Tooth during Mastication[a]

Food	Force (kg)	Food	Force (kg)
French roll	1.8	Ham on white bread	1.0
Tender steak	1.4	Lobster	0.8
Pear (hard)	1.4	Apple (Macintosh)	0.7
Celery (raw)	1.3	Cucumber (raw)	0.7
Carrot (raw)	1.3	Raised doughnut	0.7
Bologna on roll	1.2	Broccoli	0.6
White bread (with crusts)	1.1	Potato (boiled)	0.6
Tomato	1.1	Crabmeat	0.5
Hard rye bread	1.0	Tuna fish	0.5
Hamburger (broiled)	1.0	Shrimp	0.5
Coleslaw	1.0	Cake	0.5
Lettuce	1.0	Cabbage (boiled)	0.4
Orange section	1.0	Carrot (boiled)	0.4
French roll (with liquid)	1.0	Beets (boiled)	0.3

[a]Data from Yurkstas and Curby (1953).

Table 2.8 shows the average force *per tooth* required to masticate some common foods by two wearers of full upper and lower dentures. These data show a sixfold range from 0.3 kg for boiled beets to 1.8 kg for a French roll. It would be interesting to see whether the same force levels were exerted by persons possessing their natural teeth.

Table 2.9 Percentage Force Distribution on Three Teeth During Mastication[a]

Food	First bicuspid (tooth no. 4)	Second bicuspid (tooth no. 5)	First molar (tooth no. 6)
Hard rolls	30	40	30
Rolls plus liquid	24	45	32
Raw vegetables (tough)	41	33	26
Raw vegetables (soft)	37	31	32
Cooked vegetables	15	39	46
Breads	32	26	43
Bread plus liquid	20	27	58
Tough meat	19	48	33
Tender meat	19	29	52
Fish	28	39	33

[a]Data from Yurkstas and Curby (1953).

The distribution of forces that were applied to three teeth by two denture wearers fitted with full upper and lower dentures is shown in Table 2.9. The authors of this report (Yurkstas and Curby, 1953) state that

> Mastication of hard rolls resulted in almost equal force distribution among the three teeth studied. This was due to the fact that initially the rolls were masticated in the first and second bicuspid area, and, as they were softened, the molar area was utilized to a greater degree. The ingestion of liquids with rolls resulted in a slight posterior distribution of force. The raw vegetables studied were divided into soft and hard categories. Softer raw vegetables showed relatively equal force distribution on all three teeth, while tougher ones such as carrots were masticated in the first bicuspid area. The cooked vegetables showed a definite trend toward the posterior area. When liquids were ingested simultaneously with bread, there was a definite shift towards the first molar area in preference for mastication. Softer meats such as hamburger were definitely masticated in the molar area, whereas steaks were generally chewed in the bicuspid region.

Takahashi and Nakazawa (1991a) embedded three pressure transducers in a palatal retainer made of thin acrylic resin that fitted the upper dental arch of two adult females with normal oral and dental structure. These measured the pressure exerted as they ate gels made with varying concentrations of gelatin. They found that mean palatal pressure increased from about $100\,g\,cm^{-2}$ for 1% gelatin up to about $250\,g\,cm^{-2}$ for 5% gelatin, and then progressively decreased for 6% and 7% gelatin gels. They attributed this decrease to the subjects transferring the gels to the teeth because they were too hard to break up with the tongue.

In a later study, Takahashi and Nakazawa (1992) using gelatin and agar gels of varying concentrations, concluded that the oral action was primarily crushing of the gel against the hard palate up to a gel strength of $7–10 \times 10^5\,dyne\,cm^{-2}$ which changed to biting by the teeth when the required force exceeded this value.

Takahashi and Nakazawa (1991b) also studied the effect of changing the viscosity of liquids on palatal pressure by dissolving various levels of carboxymethylcellulose in orange juice to give apparent viscosities measured at $20\,s^{-1}$ ranging from 3.4 to 2300 m Pa·s. They found that the palatal pressure

almost doubled as the viscosity increased 676-fold and attributed the relative insensitivity of palatal pressure to changes in viscosity to two factors: (1) low viscosity juices were swallowed in a single deglutition whereas high viscosity juices were swallowed in several smaller portions; (2) shear thinning of the thickened juices caused by stirring with the tongue, dilution with saliva, and warming towards mouth temperature.

Tracking Food Movement Within the Mouth

Lee and Camps (1991) used a computer-based procedure to track the location of food samples within the mouth in real time. An outline of a human maxilla complete with teeth was shown on the computer screen. Subjects were given various foods and used a mouse to move a cursor on the screen to show where they felt the sample was located in the mouth at any point in time and the data were stored in the form of X and Y coordinates. Figure 2.8 shows some of these evaluations. Water showed a brief residence time (two $\times$ 0.5 s movements) whereas honey required four $\times$ 1 s movements and both showed no utilization of teeth which means that only the tongue was used for manipulating the product. Solid foods showed considerable utilization of the teeth, especially the molars. The harder foods showed longer residence times, for example, the hard candy was moved between the molars and cuspids on both sides of the jaw in about 16 $\times$ 3 s movements and fresh potato chip showed one $\times$ 1 s movements on the cuspids followed by three $\times$ 1 s movements on the molars.

Reasons for Masticating Food

It is worth noting why food is masticated. The major reasons are as follows.

(1) *Gratification*. Chewing is an enjoyable sensory experience that gives great satisfaction. It is one of the few sensory pleasures that lasts from the cradle to the grave. This point is especially significant for the older person for whom many other sources of pleasure are diminishing. Foods should be selected for the elderly that will give them the maximum masticatory pleasure while satisfying their nutritional needs, and yet not go beyond the limits set by their reduced chewing ability. As pointed out on page 2, maintaining the gratification that comes from chewing has led to a large dental industry.
(2) *Comminution.* Breaking the food into smaller pieces makes swallowing possible.
(3) *Mix with saliva*. This lubricates the bolus and softens many hard, dry foods, making them easier to swallow. The enzymes in the saliva start digestion of starches.
(4) *Temperature adjustment*. The human race likes to consume much of its food and drink in a cold or hot condition. The mouth seems to be able

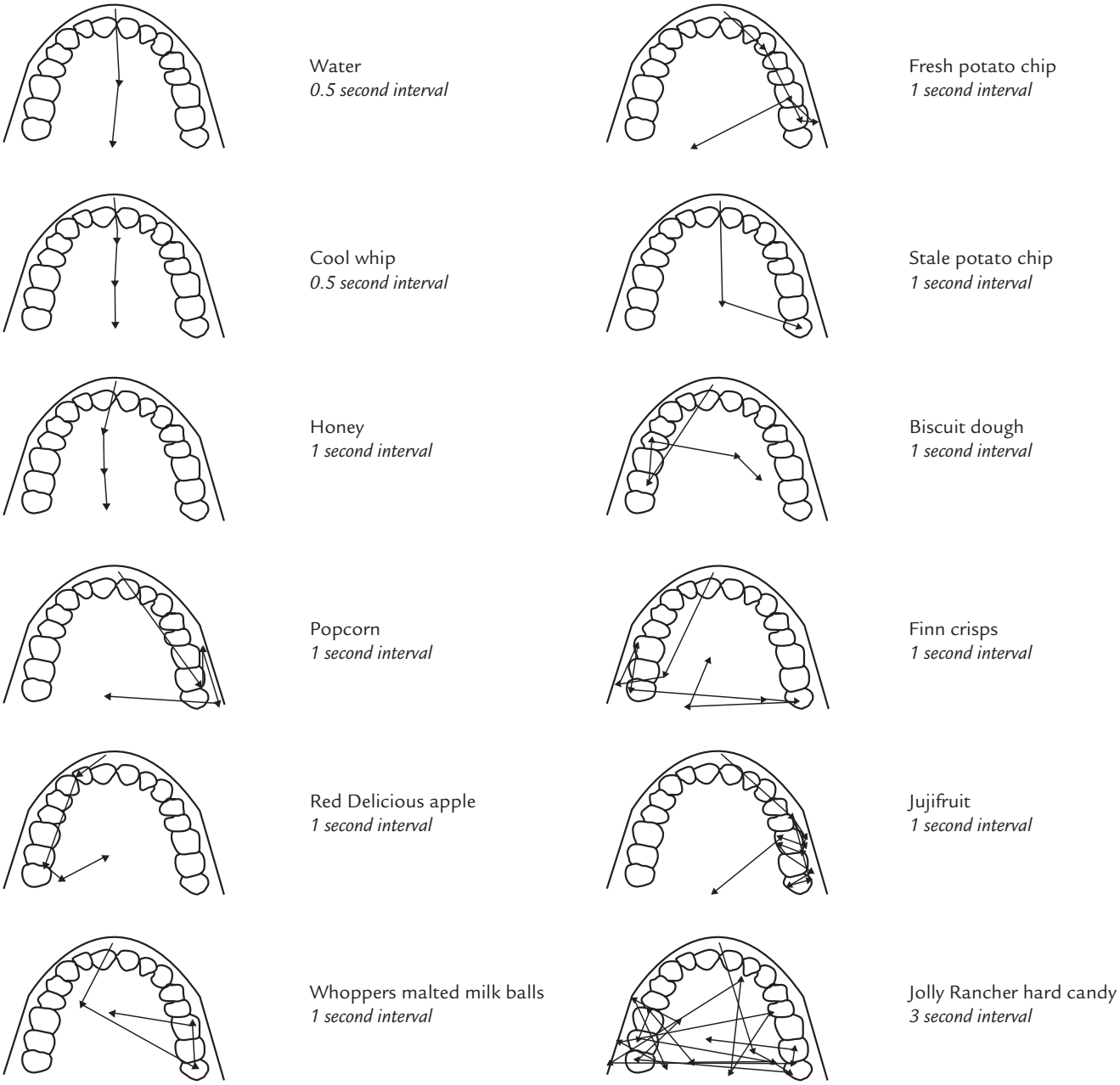


Figure 2.8 Tracking foods in the mouth. (From Lee and Camps, 1991.) Reprinted from *J. Texture Studies* 22, pages 280, 281. Copyright by Food and Nutrition Press Inc.

to withstand a wider temperature range than most other parts of the body and the residence time during mastication brings the food close to normal body temperature before sending it on to the stomach.

(5) *Release flavor*. Many substances responsible for odor and taste sensations are released as the food is pulverized, causing a stronger stimulus to the chemical receptors in the oral and nasal cavities.

(6) *Increase surface area*. The chemical and biochemical attack on the food in the stomach occurs at the surface of each food particle.

Mastication greatly increases the surface area available to digestion and also decreases the thickness of each food particle, thus promoting rapid digestion.

Nonoral Methods for Sensing Texture

Although most of the sensing of texture occurs in the mouth and with the lips, it is possible to measure textural properties outside the mouth, most commonly with the fingers and the hand. It is a common practice to hold and squeeze foods in the hand, and this frequently gives a good method for assessing the textural quality of the food. The food may be squeezed between the forefinger and the opposed thumb or between two, three, or four fingers and the opposed thumb. It may be squeezed by pressing with the whole palm on top of the food which is resting on a firm surface such as a table, or the two palms may be placed at opposite ends of the food and squeezed. The size of the object frequently determines the method that is used. The forefinger and opposed thumb are generally used for small objects whereas the entire hand or two hands are used on large objects such as a loaf of bread. While the hand is usually used to touch foods, it is possible to use other parts of the anatomy such as cheeks, elbows, and feet to obtain some index of the textural qualities of foods.

The Hand

Two prominent surgeons (Burton and Rockwell, 1994) describe the unique combination of incredible strength, sensitivity, and versatility of the hand as follows:

> The philosophic exaltation of the hand by scholars of antiquity is equaled by the profound regard for its complexity and versatility held today by functional anatomists and surgeons. The hand is composed of material of dexterity, strength, sensitivity, and refinement – all in the most complex array and condensed into a unit weighing significantly less than 1 kg. With this amazing tool we implement the desires of the human brain, whether requiring the speed and precision of the fingering hand of a concert violinist or the brute power grasp needed to wield a sledgehammer. With the hands the laborer supports a family, the parent loves and cares for a baby, the musician plays a sonata, the blind 'read' and the deaf 'talk'.

The hand is a wonderfully complex manipulative tool. Much of our technology, music and art derive from the wide range of purposeful actions that can be performed by the human hand as directed by the brain. The hand is a sensory organ, as well as a manipulative tool, gathering information on touch and temperature and feeding this back to the brain.

The hand, as a sensory organ, is the main focus of interest for the texture technologist. A simple description of the structure and operation of the hand follows.

The hand (*manus*) begins at the wrist (*carpus*) extending through the palm (*metacarpus*) to the five fingers (*digits*): thumb (*pollex*), index finger (*digitus*

indicus), middle finger (*digitus medius*), ring finger (*digitus anularis*) and little finger (*digitus minimus*).

The skeleton of the palm is composed of five thin, long bones (*metacarpals*). The metacarpals are identified by Latin numerals from metacarpal I (leading to the thumb) through metacarpal V (leading to the little finger). The palm is filled by loose connective tissue containing some fat in which are embedded the long flexor tendons, small lumbrical muscles, nerves and blood vessels.

Each of the four fingers contain three phalanx bones connected end to end. The top of the finger holds the *distal phalanx*, which abuts the *middle phalanx* which abuts the *proximal phalanx* which abuts the metacarpal bones of the palm. The thumb has only two bones, the *distal phalanx* and *proximal phalanx*. The distal phalanx (end bones) in the fingers and thumb are somewhat flattened (tuberosity). The fingernail covers the dorsal sides (back) of the distal phalanx, while the front side (anterior) is covered with a fatty pad in which are embedded many nerve endings that provide the acute sense of touch detected by the balls of the fingertips. These nerve fibers connect to corpuscular receptors that respond to pressure, temperature, pain and itch. The high degree of sensory innervation in the fingertips allows many intricate tasks to be performed including the 'handfeel' of foods.

The muscles located within the fingers and palm (intrinsic muscles) are small and relatively weak, the main ones being the *lumbrical* muscles that surround the knuckles and cause the fingers to spread apart or close together.

The strong clenching motion that is achieved by closing the fingers down towards the palm is mainly achieved by two powerful muscles (extrinsic muscles) located in the front (anterior) of the forearm beginning near the elbow and continuing about half way to the wrist. These muscles are the *flexor digitorum profundus* and *flexor digitorum superficialis*. The opening of the fingers away from the palm is achieved mainly by two less powerful muscles that lie in the back (posterior) of the forearm, *flexor carpi radialis* and *flexor retinaculum*.

It is remarkable that the strong clenching motion of the hand is not powered by muscles within the hand but by a large mass of muscles concentrated in the upper forearm some 20–40 cm distant from the fingertips. Long tendons attach to the powerful muscles in the middle forearm and extend through the carpal tunnel in the wrist to the fingertips in a manner suggestive of a rope and pulley system. The tendons that close the fingers (flexor) are deeply embedded in the palm while the tendons that straighten them lie just under the skin in the back of the hand. Most people can see the extensor tendons move when the fingers are bent and straightened.

The long flexor tendons that cause the fingers to close are surrounded by synovial sheaths from the wrist up to the last finger joint. These sheaths lubricate the tendons and allow them to move easily with little friction. Most people can see the long flexor tendons moving just above the wrist when they clench the hand. They can also see and feel the strong flexor muscles that power this movement tighten up just below the elbow.

The thumb is opposable. In contrast to the fingers, the major muscle that closes the thumb (*abductor pollicis brevis*) stretches from the first joint in the thumb across the lower palm to about the middle of the wrist. Its motion is aided by another intrinsic muscle (*flexor pollicis*). The extrinsic muscles in the forearm that help move the thumb are one flexor (*flexor pollicis longus*) and two extensors (*extensor pollicis longus* and *extensor pollicis brevis*).

The movements of the hand are complex biomechanical operations involving all joints at the same time but they can be broken down into two basic acts:

(1) *Power grip*. The fingers form one side of a clamp and the palm the other side while the thumb is wrapped around the index finger. These movements are used to hold the steering wheel of the car, the handle of a suitcase, and the handles of tools. This grip can exert very strong forces.
(2) *Precision grip*. The ball of the thumb presses against the balls of one or more fingers (oppositive) exposing the sensory surfaces to the product. This grip can be controlled within short movements and is the one used to feel items such as foods. It is also the grip used for writing, painting, sewing and other delicate tasks.

Sight

A visual manifestation of texture can be found according to the rate and degree that foods slump or spread when unrestrained (see pages 161, 216 and 224). For example, a firm jelly holds its shape well whereas a soft jelly sags to a greater degree. One observes the viscosity of a liquid or semiliquid food by watching the rate of flow as it pours from a container or flows across the food or the plate (Shama *et al*., 1973).

Sound

Crisp and crunchy foods generate characteristic sounds when masticated. One person can stand behind a screen out of sight of a second person and chew on various foods and the second person can quickly decide when a crispy food is being chewed just by listening to the sounds being generated. This subject is discussed more fully on page 171.

This Page Intentionally Left Blank

Physics and Texture

CHAPTER 3

Introduction

This chapter introduces the reader to the branches of physics that are relevant to texture, mainly rheology and physical properties of materials. The concept of food rheology was introduced in Chapter 1, pages 22–26. Physics is a branch of science that can quickly become complicated and very mathematical. For example, Table 3.1 shows the nomenclature for rheological functions in steady simple shear and linear viscoelasticity recommended by the Society of Rheology. The Society has two more tables giving recommended nomenclature for nonlinear viscoelasticity in shear and nonlinear viscoelasticity in extension. One glance at Table 3.1 demonstrates how complex this branch of physics can become. Fortunately, many of the rheological functions listed in Table 3.1 probably have little relevance to food.

This account of food physics is introductory and uses the minimum of mathematics. The reader should consult one or more of the references listed at the end of this chapter for a more comprehensive description of the principles of physics.

Rheology is defined as 'the study of the deformation and flow of matter'. Its principles can be applied to any kind of material ranging from mobile fluids such as water, to plastics, blood, paints, cosmetics, soils, glasses, rubber, lubricants, ceramic materials, rocks, and of course, foods and beverages. The Society of Rheology, which has its headquarters in the United States of America, was founded in 1929 and now has a membership exceeding 1600 members. Other countries, including Australia, Japan and the United Kingdom have their own national societies of rheology. With this large number of practising rheologists, it is not surprising to find that the field of rheology is well developed and thriving. It needs to be remembered that most of the rheological concepts and instruments were developed for nonfood products, e.g. plastics, and the food rheologist, while borrowing freely from conventional rheological theory and

Table 3.1 Society of Rheology Nomenclature

Quantity	Symbol	SI units
Steady simple shear		
Direction of flow	x_1 or x	m
Direction of velocity gradient	x_2 or y	m
Neutral direction	x_3 or z	m
Shear stress	σ	Pa
Shear strain	γ	—
Shear rate	$\dot{\gamma}$	s^{-1}
Viscosity	η	Pa·s
First normal stress function	N_1	Pa
Second normal stress function	N_2	Pa
First normal stress coefficient	ψ_1	$Pa·s^2$
Second normal stress coefficient	ψ_2	$Pa·s^2$
Limiting viscosity at zero shear rate	η_0	Pa·s
Limiting viscosity at infinite shear rate	η_∞	Pa·s
Viscosity of solvent or of continuous medium	η_s	Pa·s
Relative viscosity (η/η_s)	η_r	—
Specific viscosity ($\eta_r - 1$)	η_{sp}	—
Intrinsic viscosity	$[\eta]$	$m^3\ kg^{-1}$
Linear viscoelasticity		
Simple shear		
Shear strain	γ	—
Shear modulus (modulus of rigidity)	G	Pa
Shear relaxation modulus	$G(t)$	Pa
Shear compliance	J	Pa^{-1}
Shear creep compliance	$J(t)$	Pa^{-1}
Equilibrium shear compliance	J_e	Pa^{-1}
Steady-state shear compliance	J_s^0	Pa^{-1}
Complex viscosity	$\eta^*(\omega)$	Pa·s
Dynamic viscosity	$\eta'(\omega)$	Pa·s
Out-of-phase component of η^*	$\eta''(\omega)$	Pa·s
Complex shear modulus	$G^*(\omega)$	Pa
Shear storage modulus	$G'(\omega)$	Pa
Shear loss modulus	$G''(\omega)$	Pa
Complex shear compliance	$J^*(\omega)$	Pa^{-1}
Shear storage compliance	$J'(\omega)$	Pa^{-1}
Shear loss compliance	$J''(\omega)$	Pa^{-1}
Tensile extension		
Strain (True strain)	ϵ	—
Young's modulus	E	Pa
Tensile relaxation modulus	$E(t)$	Pa
Tensile compliance	D	Pa^{-1}
Tensile creep compliance	$D(t)$	Pa^{-1}

Source: Adapted from Dealy (1994). Reprinted from *J. Rheology* **38**, pages 179, 180. Copyright by Society of Rheology.

practice, needs to be alert to the possibility that some of this theory may not be applicable to foods. As pointed out on page 17, most people have a clear understanding of the differences between solids and liquids. However, there are many substances, including numerous foods, that simultaneously possess

some of the properties of both solids and liquids, and measuring and specifying their properties is sometimes difficult.

The classical definition of rheology divides into two parts.

(1) Deformation usually applies to materials that are predominantly solid-like in nature.
(2) Flow usually applies to materials that are predominantly fluid-like in nature.

The most important elements in both deformation and flow are the fundamental quantities of distance, time and mass.

Distance, symbol l, is measured in meters (m)
Time, symbol t, is measured in seconds (s)
Mass, symbol m, is measured in kilograms, (kg)

A description of these quantities is given in Table 3.13, page 104. A number of other quantities such as area, volume, force, etc. are derived from various combinations of the above three fundamental elements.

Deformation

This section begins by defining the most common units used for measuring and defining deformation. The term 'displacement' is sometimes used in place of deformation.

Force, symbol F, has the dimensions mass $\times$ length $\times$ time^{-2} (mlt^{-2}). The conventional unit of force is the newton, symbol N, named after the British physicist, Sir Isaac Newton (1642–1727). The word 'load' is sometimes used instead of 'force.'

Stress is the force per unit area, symbol σ (Greek lower case sigma). It has the dimensions mlt^{-2}/l^2 = ml^{-1}t^{-2}. It is expressed in units of pascals (symbol Pa) and named after the French physicist Blaise Pascal (1623–1662) and has the units newtons per square meter (N m^{-2}). An earlier and now obsolete unit of stress is the dyne-cm^{-2}. The equation describing stress is simply:

$$\sigma = F/A$$

where σ is the stress achieved when a force F is applied uniformly to a body with area A.

Figure 3.1 explains the difference between force and stress. Suppose a material of uniform composition is fashioned into two pieces of the same height with one piece 1 cm $\times$ 1 cm square and the other 5 cm $\times$ 5 cm square. Now suppose a steady force of 100 N is uniformly applied to each piece. The force (or load) is 100 N on both pieces, but in the first piece the stress is 100/1 = 100 N cm^{-2} whereas in the second piece it is 100/25 = 4 N cm^{-2}. It is necessary to know both the force and the area of the specimen to calculate stress.

If the sample is uniform in shape and composition and the deformation is small, it is generally assumed that the stress is evenly distributed throughout

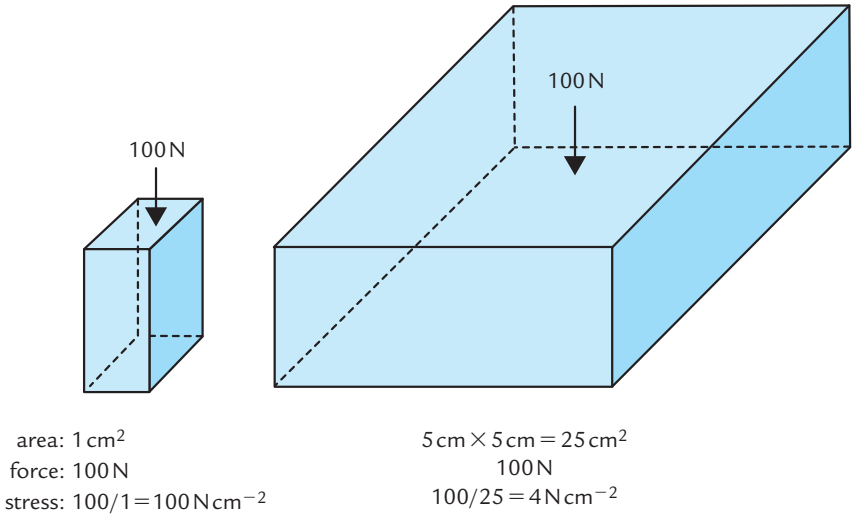


Figure 3.1 Stress is dependent on both force and area.

the sample, but when the sample does not present a flat surface to receive the force, e.g. a sphere such as an orange, or if the sample is nonuniform in structure or composition, e.g. a bread roll, or if the vehicle applying the force has an uneven surface, e.g. the cusp of a molar, the stress is unevenly distributed throughout the sample. Also, if the deformation is large, or if the material splits, crumbles or breaks the stress is unevenly distributed. In these cases, which are frequent in foods, it becomes very difficult, and often impossible to map the distribution of stress throughout the sample.

Stress is most commonly applied to foods in compression but it can also be applied in tension or shear (sideways or lateral).

Strain refers to the change in size or shape of a material when it is subjected to a stress. It is denoted by the Greek letter ε (epsilon) and may be described in several ways:

(1) Dimensional units, e.g. 'the strain is x mm', i.e. the change in height Δl.
(2) Simple ratio: Cauchy strain also called 'engineering strain'

$$\varepsilon = \frac{l_0 - l}{l_0} = \frac{\Delta l}{l_0} \quad \text{for compression}$$

$$\varepsilon = \frac{l - l_0}{l_0} = \frac{\Delta l}{l_0} \quad \text{for tension}$$

where l_0 is the height or length of the unstressed specimen and l after the stress has been applied and Δl is the change in height (x).

(3) Logarithmic ratio: Hencky strain, also called 'true strain' or 'natural strain.'

$$\varepsilon = \ln \frac{l}{l_0}$$

where ln is the natural logarithm of the ratio of the stressed/unstressed heights.

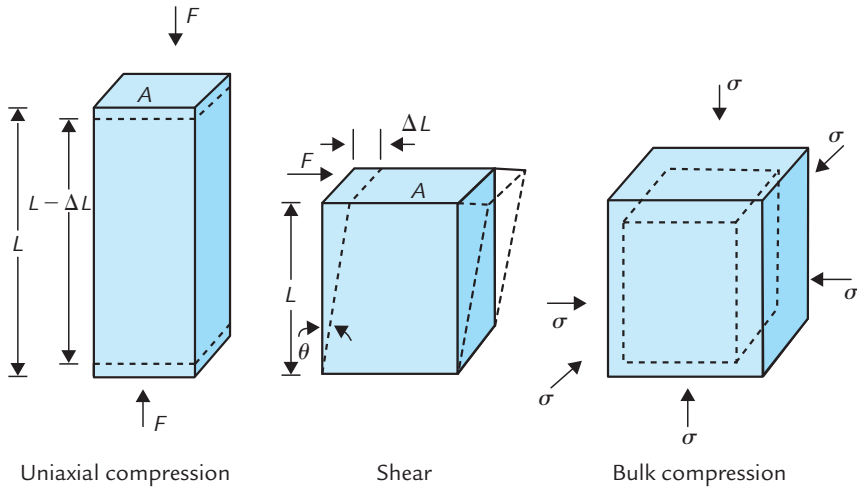


Figure 3.2 Uniaxial compression, shear, and isotropic (bulk) compression of an elastic solid. In shear the angle θ equals the shear strain γ. (Reprinted from Rao and Rizvi 1986. Engineering Properties of Foods, Figure 5.1 by courtesy of Marcel Dekker Inc.)

A suffix is often used to distinguish Cauchy strain (ε_c) from Hencky strain (ε_h). When one of these strains is known, the other can be calculated from it by using the conversion equation:

$$\varepsilon_h = \ln (1 - \varepsilon_c)$$

Note that both Cauchy and Hencky strains are ratio measurements and, therefore, dimensionless. There are other methods for calculating strain including Swainger's strain (ε_S), Almansi's strain (ε_A) and Green's strain (ε_G) (Peleg, 1985). All these methods of expressing strain are about the same at small displacements but their values increasingly diverge at larger displacements.

Also note that stress is always a force measurement and strain is always based on measurement of a distance. The colloquial use of stress and strain as interchangeable entities ('the stress and strain of life') has no place in physics.

Uniaxial compression is simply compression in one plane. It is the simplest and most widely used mode of testing food texture and is the type of compression that is used in the universal testing machines that are now present in most food laboratories.

Bulk compression compresses the product in all three dimensions. It is usually accomplished by hydrostatic pressure, and because of the complex apparatus required is rarely used for food texture measurements.

Shear occurs when a force is applied laterally (sideways) to a solid body whose lower face is locked and stationary. The change in angle of the vertical face (γ) is the shear. $\tan \gamma = \Delta l/h$. For small deformations the angle of shear in radians equals the shear strain, in which case $\tan \gamma = \gamma$.

The difference between uniaxial compression, bulk compression and shear is illustrated in Fig. 3.2.

Linear elastic describes those materials in which the strain is directly proportional to the stress, and the strain returns to zero when the stress is removed. For most foods, stresses and strains must be very small to comply with linear

Table 3.2 Strain Limits for Linear Viscoelastic Behavior

Food	Strain limit (%)	Reference
Alginate gel	5 to 8	Mancini *et al*. (1999)
Cornstarch gel, fried	4	Rovedo *et al*. (1999)
Dulce de Leche		
confectionery type	9	Navarro *et al*. (1999)
common type	3.5	Navarro *et al*. (1999)
low calorie	3.5	Navarro *et al*. (1999)
Frankfurters	1.5 to 3	Mohsenin and Mittal (1977)
Frankfurters	3.8	Skinner and Rao (1986)
Fruits, fresh	1.5 to 3	Mohsenin and Mittal (1977)
Meat	0.5	Mathevon *et al*. (1995)

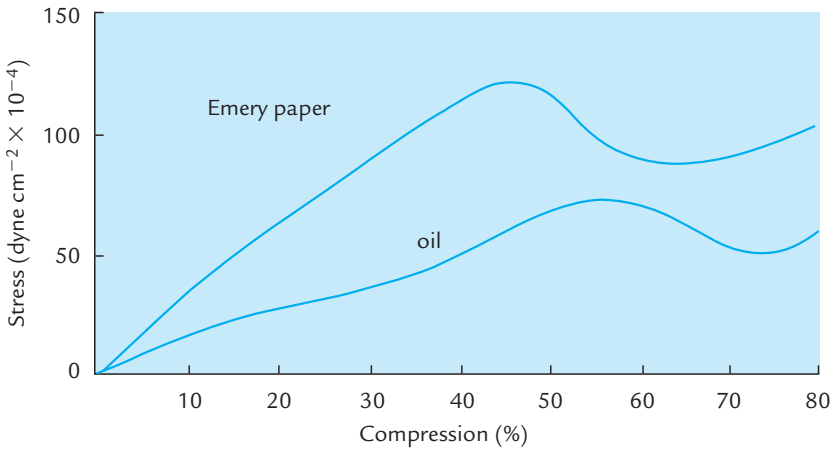


Figure 3.3 Influence of mineral oil and emery paper on the true surface stress–compression behavior of Gouda cheese samples 25 mm high and 25 mm diameter tested at a crosshead speed of 500 mm min^{-1}. (Reprinted from Culioli and Sherman, 1976. *J. Texture Studies* **7**, page 356. Copyright by Food and Nutrition Press Inc.)

elastic behavior as shown in Table 3.2. Most texture tests on solid foods use large strains that are well beyond the linear elastic range.

Effect of Lubrication

In a series of papers, Professor Sherman's group at the University of London showed that lubrication, or lack of lubrication, of the contact surface between the food and compressing platen affects the force required to reach a given degree of compression (Culioli and Sherman 1976; Abu-Shakra and Sherman, 1984; Atkin and Sherman, 1984; Goh and Sherman, 1987). A nonlubricated surface requires a higher force than a lubricated surface for the same degree of compression (see Fig. 3.3). On theoretical grounds it was shown that when a cylinder of food is compressed it should assume an hour-glass shape. However, friction between the surface of the food and the contact surface of the compressing platen prevents the lateral movement of the food needed to assume the hour-glass shape and the food bulges in the middle, assuming a barrel

shape. When samples of cheese were lubricated with a thin film of oil they assumed an hour-glass shape when compressed, but without the oil they assumed a barrel shape. The barrel shape was even more noticeable when emery paper was inserted between the cheese and the metal compression plates. Others have noted differences in compression force between lubricated and nonlubricated (bonded) compression (e.g. Montejano *et al.*, 1983a,b; Casiraghi *et al.*, 1985; Chu and Peleg, 1985; Nussinovitch *et al.*, 1992). Therefore, the surface needs to be lubricated if one is to get correct rheological data from compression tests.

However, Brennan and Bourne (1994) pointed out that two influences are present when food is compressed between the molars: (1) saliva acts as a lubricant; (2) the cusps of the molars act as anchors to hold the surface and prevent lateral movement. In compression tests on cylinders of Provolone cheese and chicken frankfurter between molars mounted on a TA.XT2 Texture Analyzer, and with human subjects when they compressed them between their molars they found that the samples assumed a barrel shape showing that the anchoring effect of the cusps prevailed over the lubrication provided by the saliva. In other words, compression between the molars in the mouth gives the equivalent of nonlubricated compression even though it is conducted in a well-lubricated environment. The conclusion from this experiment is that if one is looking for true rheological data, the surface should be lubricated, but if one wants to duplicate what happens in the mouth there should be no lubrication in compression tests.

Time Aspects of Deformation

Suppose an article of food of uniform cross-sectional area is resting on a rigid surface with a weightless rigid plate resting on the upper side (Fig. 3.4). Suppose now that a weight is placed on the plate and that some mechanism is available to measure the change in height of the food under this constant compressing force.

Figure 3.5 illustrates what happens when the material is perfectly elastic. When the weight is placed on the food, there is an immediate deformation called ‘instantaneous elastic deformation’ and no further change with time. When the weight is removed, the sample instantaneously and completely recovers its original height.

Few foods are perfectly elastic. Most foods possess flow properties in addition to elasticity, most frequently ‘plastic’ and ‘viscoelastic.’ The behavior of a viscoelastic food under these conditions is demonstrated in Fig. 3.6. When the weight is placed on the food, there is an immediate compression of the food which is the instantaneous elastic deformation. This is followed by a prolonged, continuous but decelerating rate of deformation called ‘creep’ or ‘retarded deformation.’ The deformation continuously increases with time and theoretically never stops; the slope of the line never becomes perfectly horizontal.

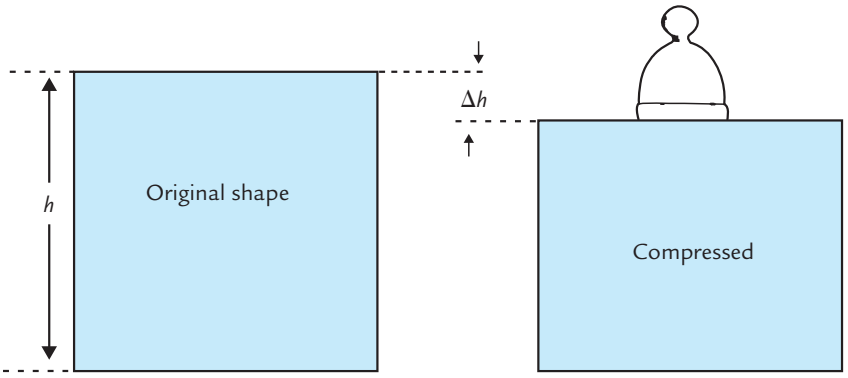


Figure 3.4 Schematic of uniaxial deformation of a solid under a constant force.

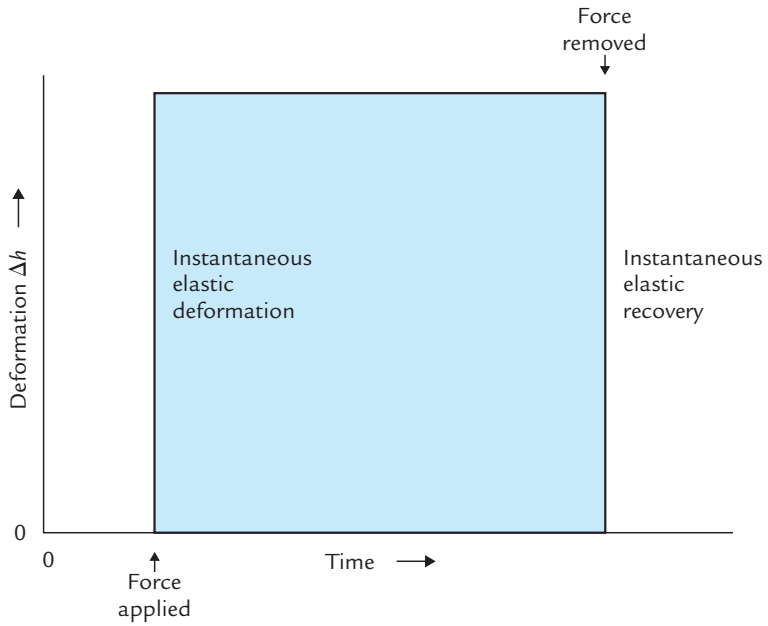


Figure 3.5 Deformation–time relationship for an elastic body under constant stress.

When the weight is removed, there is an instantaneous partial elastic recovery followed by further recovery with respect to time called 'retarded recovery,' or 'creep recovery.' Again, this line theoretically never becomes horizontal. With these products the commodity does not return to its original height; it is permanently and irreversibly compressed. This is known as irreversible or 'permanent deformation,' or 'set.'

The viscoelasticity of foods varies widely. A food that is mostly elastic and slightly viscoelastic will give a deformation–time response behavior similar to that shown in Fig. 3.5, whereas a highly viscoelastic product will exhibit behavior as shown in Fig. 3.6.

Creep and recovery are probably a minor part of the deformation that is normally sensed in the hand because of the short time duration of the squeeze. Sometimes it is important; for example, in bread doughs, which are highly viscoelastic. The irreversible deformation that results from viscoelasticity is found, for example, in grapefruit that have been tightly packed in a shipping carton; after being placed on the table where they are free to resume their

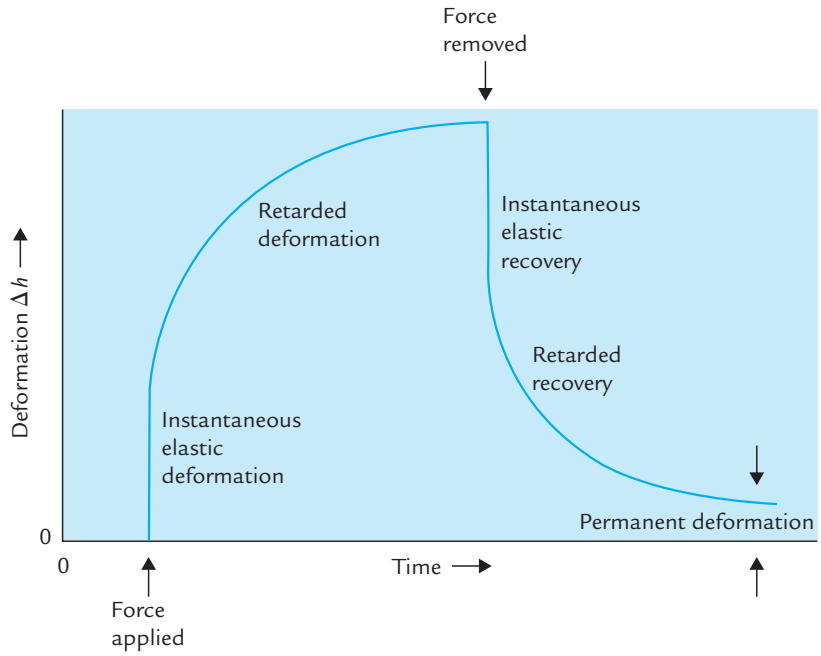


Figure 3.6 Deformation–time relationship for a viscoelastic body under constant force.

spherical shape, they will retain flat compression faces for many days, demonstrating the permanent deformation that has occurred.

The above discussion relates to the change in height with respect to time under a constant deforming force. Another way of measuring the time aspects of deformation is to measure the change in force over a period of time at a constant level of deformation; that is, the product is compressed to a certain height and held at that compression while changes in force are measured. This is a test that is easily performed in the Instron and similar instruments (Bourne *et al*., 1966). A typical curve for a viscoelastic solid is shown in Fig. 3.7. The force increases steeply and almost linearly from O to A when the commodity is compressed. At point A the compression is stopped and the product is held at a constant height. The force declines, rapidly at first and then more slowly as the product continues to deform under the force. This decay of stress under a constant strain is known as 'stress relaxation.' At point B the product is partially decompressed by raising the compression plate a short distance and stopping it again at C. As the product is held with less compression the force will increase again as the product slowly recovers its original shape. This is known as 'recovery.' An elastic solid gives almost the same compression from O to A as the viscoelastic solid, but when compression is stopped at A the force does not change but gives a horizontal line until the solid is decompressed.

The relaxation time is the time required for the stress at constant strain to decrease to $1/e$ of its original value, where e is the base of natural logarithms (2.7183). Since $1/e = 0.3678$, the relaxation time is the time required for the force to decay to 36.8% of its original value. This can be measured on instruments such as the Instron where a constant compressive strain can be maintained and the change in force with respect to time is measured. In some cases

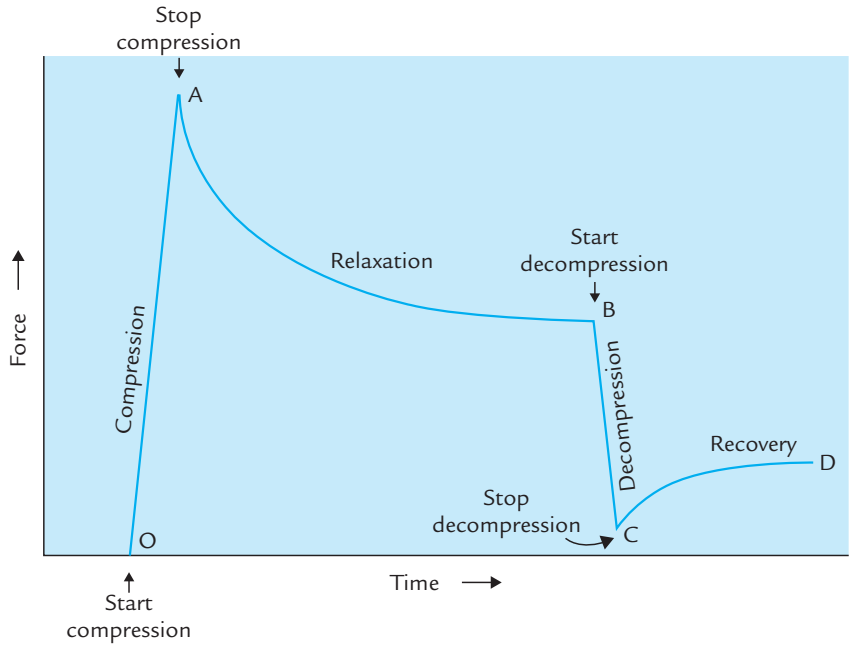


Figure 3.7 Force–time relationship for a viscoelastic body under constant deformation.

the time to relax to l/*e* is excessive, in which case some lower value is taken as an arbitrary relaxation time.

Materials Science

It is now time to introduce some fundamental tests that are widely used in the theory and practice of materials science.

Young's Modulus

Young's modulus of elasticity is the ratio of stress to strain when an elastic solid material is compressed or extended. It is a measure of stiffness and was developed by Thomas Young, an English physicist (1773–1829) and it is described by the equation:

$$E = \frac{\text{stress}}{\text{strain}} = \frac{F/A}{\Delta L/L}$$

where E is Young's modulus, F is the applied force perpendicular to the area defined by the stress, A is the cross-sectional area of the test material, L is the length or height of the test specimen and ΔL the change in length resulting from the application of force F. Young's modulus is equal to the slope of the stress–strain curve. The prefix 'Young's' is sometimes omitted, making this term 'modulus of elasticity.'

Theoretically, Young's modulus of elasticity should only be used to describe elastic materials. Since most foods are viscoelastic in nature, and many are of nonuniform shape, size and structure, it is questionable whether this term should be used for foods. Mohsenin and Mittal (1977) pointed out the importance of

Table 3.3 Values for the Modulus of Deformability of Some Foods

Food	Apparent Young's Modulus (Pa)
Apple, raw	60–140
Banana, fresh	8–30
Bread	0.1–0.3
Carrot, raw	200–400
Gelatin gel	2
Peach, fresh	20–200
Pear, raw	120–300
Potato, raw	60–140

(Data from Finney, page 39 in Texture Measurements of Foods 1973. eds A. Kramer and A. S. Szczesniak with kind permission of Kluwer Academic Publishers.)

maintaining the purity of rheological terms, using them only when measurements and definitions are in accordance with accepted rheological definitions. They stated, 'Rheological terms as used by rheologists are firmly established terms defining the mechanical behavior of a material under stress and strain conditions, and they should not be employed where mechanical behavior of the food is neither well defined nor understood.' As an example of this approach, they suggested that the term *modulus of deformability* should be substituted in research with food materials for the term *modulus of elasticity*, in order to maintain the purity of the well-established and precise meaning of the latter term. It is hoped that the term 'modulus of deformability' will be used in the future instead of 'Young's modulus of elasticity' for most foods. Table 3.3 lists values for the modulus of deformability (apparent Young's modulus) for a number of food items spanning a wide range of firmness.

Shear Modulus

Shear modulus is the ratio of shearing stress to shearing strain and is described by the equation:

$$G = \frac{\text{shearing stress}}{\text{shearing strain}} = \frac{F/A}{\gamma/L}$$

where G is the shear modulus, F is the applied force parallel to the area defined by the stress, γ is the greatest distance of movement in the test material, and L is the length. This is sometimes called 'modulus of rigidity' but still uses the symbol 'G.'

Bulk Modulus

Bulk modulus is the ratio of the stress to the change in volume:

$$K = \frac{\text{hydrostatic pressure}}{\text{volumetric strain}} = \frac{P}{\Delta V/V}$$

Table 3.4 Apparent Poisson Ratio of Selected Foods at Different Levels of Hencky Strain

	Apparent Poisson's Ratio				
Sample	$\varepsilon_H = 0.05$	$\varepsilon_H = 0.12$	$\varepsilon_H = 0.30$	$\varepsilon_H = 0.65$	$\varepsilon_H = 0.90$
Apple					
Red Delicious	0.21	0.25	f		
Jonagold	0.17	0.22	f		
Idared	0.24	0.24	f		
Bread					
Rye	0.28	0.22	0.21	0.19	0.20
White	0.17	0.14	0.11	0.07	0.07
Butter	0.42	0.44	0.43	f	
Potato					
Raw	0.38	0.43	0.46	f	
Steamed	0.40	0.42	f		

Reprinted from Rohm, Jaros and de Haan, 1997, *J. Texture Studies* **28**, page 252. Copyright by Food and Nutrition Press Inc.
f, product fractured.

where K is the bulk modulus, P the force per unit area (pressure) applied from all directions (isotropically), V is the original volume of the unstressed material and ΔV the change in volume resulting from the application of pressure P.

Poisson's Ratio

Poisson's ratio is named after the French physicist Siméon Denis Poisson (1781–1840) and is described by the equation:

$$\mu = \frac{\text{lateral strain}}{\text{axial strain}} = \frac{\text{change in width per unit width}}{\text{change in length per unit length}} = \frac{\Delta D/D}{\Delta L/L}$$

where μ is Poisson's ratio, D is the width of the test specimen and L its length or height, ΔD and ΔL the changes caused by the application of a stress.

If the volume is unchanged when the stress is applied, Poisson's ratio is 0.5. It is less than 0.5 if the volume changes. Since water is essentially incompressible, those foods that contain a high water content such as fruits and vegetables have a Poisson's ratio close to 0.5 unless they also contain gas. Highly compressible products such as fresh bread crumb have a very low apparent Poisson's ratio. Table 3.4 lists the apparent Poisson's ratio for several foods at different levels of Hencky strain. Individual cereal grains usually have a Poisson's ratio between 0.25 and 0.4. Researchers often assume a ratio of 0.3 for cereal grains if the actual Poisson's ratio is not known (Borgale and Irudayaraj, 1995).

Interrelations Between Moduli

E, G, K and μ are called 'material constants' because they are inherent to the material and their values should not be affected by the size and shape of the

Table 3.5 Numerical Values for Rheological Moduli

Substance	Modulus	Value	
		Measured	Calculated
Steel	Shear	8×10^{10}	10.1×10^{10}
Steel	Young's	25×10^{10}	19.2×10^{10}
Steel	Bulk	16×10^{10}	17.3×10^{10}
Glass	Young's	7×10^{10}	4.96×10^{10}
Rubber	Shear	2.9×10^{10}	2.68×10^{5}
Rubber	Young's	8×10^{5}	11.4×10^{5}
Rubber	Bulk	1.9×10^{7}	8.9×10^{4}

Calculated from data listed by Muller (1973).

test specimen or by the rate of loading or the machine used to make the measurement. However, as will become evident later in this chapter, this is an ideal concept. There are often substantial deviations from the ideal in practice, especially when large strains are applied.

Figure 3.2 (page 63) illustrates the difference between compression, shear and bulk compression.

Rheological theory shows that for elastic materials these four moduli are interrelated as follows:

$$G = 3EK/(9K - E)$$
$$K = E/3(1 - 2\mu) = EG/(9G - 3E) = G[2(1 + \mu)]/3(1 - 2\mu)$$
$$E = 9GK/(3K + G) = 2G(1 + \mu) = 3K(1 - 2\mu)$$
$$\mu = (E - 2G)/2G = (1 - E/3K)/2$$

These equations seem to hold well for materials of construction. Table 3.5 compares the experimentally measured values with the values calculated from the three other moduli. For steel and glass there is good agreement between the measured and calculated values but for rubber there are major differences, amounting to as much as five orders of magnitude for shear modulus. It is obvious that these conversion equations are ineffective for rubber. Since most foods are more like rubber than steel it is likely that these equations will be of little use for most foods.

Creep Compliance

The increase in deformation or strain as a function of time is called 'creep' and the ratio of the strain at time t to the constant load is called 'creep compliance.' A typical creep compliance curve can generally be divided into three sections as shown in Fig. 3.8.

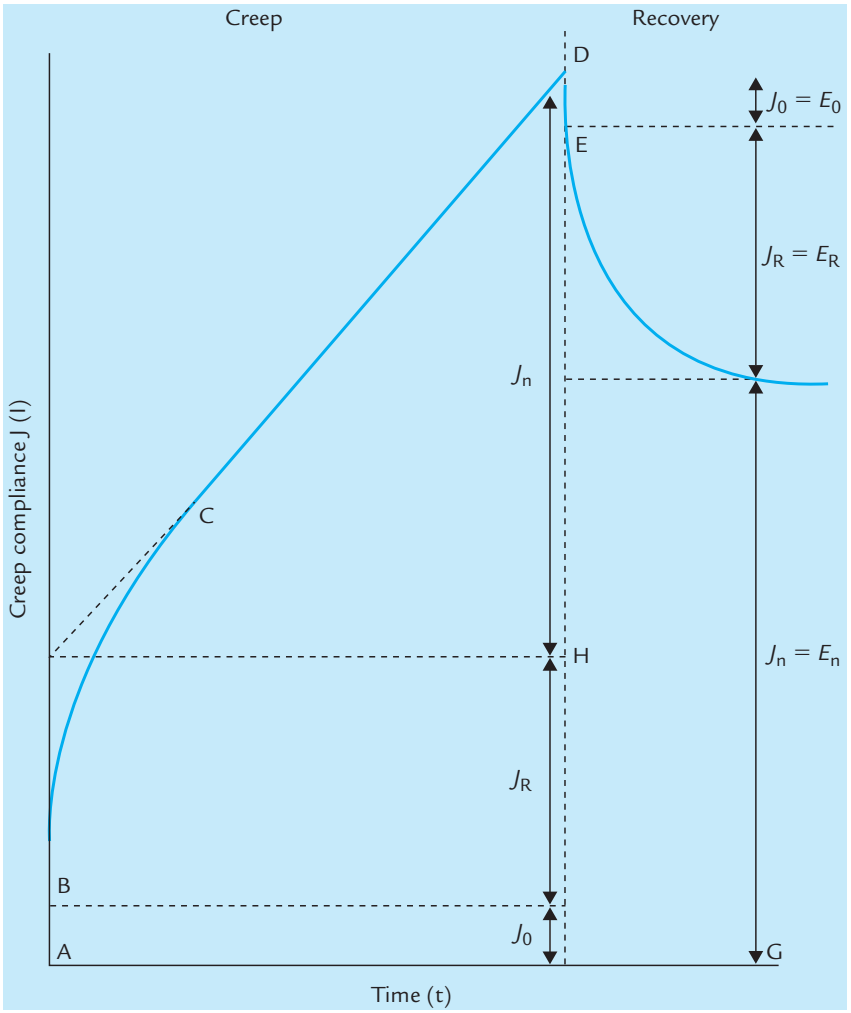


Figure 3.8 Model creep curve. (Reprinted from Sherman, Figure 1.9 in Texture Measurements of Foods 1973, eds. A. Kramer and A. S. Szczesniak with kind permission of Kluwer Academic Publishers.)

Section 1: Instantaneous compliance is denoted by region A and the symbol J_0 in Fig. 3.8.

$$J_0 = \frac{1}{E_0}$$

where E_0 is the instantaneous elastic modulus (Young's Modulus) and E_0 (t) is the instantaneous strain (i.e. t is almost zero).

Section 2: Time dependent retarded elastic region denoted by B–C and the symbol J_R

$$J_R = J_m\,[1 - \exp(-t/\tau m)]$$

where J_R is the retarded elastic compliance, J_m is the mean elastic compliance and τm is the mean retardation time.

Section 3: A linear region of elastic compliance denoted by the region C–D and the symbol J_n, where J_n is the newtonian compliance.

When the load is removed there can be an instantaneous elastic recovery from D to E and a retarded elastic recovery from E to F.

A graphical procedure has been developed to solve for all the symbols in the above equations (for example, see Chen and Fridley, 1972). Jackman and Stanley (1995) give a useful report on the use of creep–recovery compliance measurements to study the viscoelastic properties of fresh tomatoes.

Viscosity

Everybody is aware that some liquids flow more easily than others. The poet Lucretius (96–55 BC) wrote,

We see how quickly through the colander,
The wines will flow; on the other hand,
The sluggish olive oil delays; no doubt,
Because 'tis wrought of elements more large,
Or else more crooked and intertangled.
(cited by Markovitz, 1985).

The tendency of a fluid to flow easily or with difficulty has been a subject of great practical and intellectual importance to mankind for centuries. The famous English physicist Sir Isaac Newton (1642–1727) was one of the earliest researchers to study the flow of fluids. In his *Principia*, the section entitled 'On the Circular Motion of Liquids,' he stated the hypothesis that 'the resistance which arises from the lack of slipperiness of the parts of the liquid, other things being equal, is proportional to the velocity with which the parts of the liquid are separated from one another.' This principle, that the flow of fluid is directly proportional to the force that is applied, is used to describe the class of liquids known as 'Newtonian fluids.' Water is the best-known Newtonian fluid.

Other scientists have studied more complex liquids; for example, Schlubler in an 1828 paper on 'The Fatty Oils of Germany' included within the physical constants a 'fluidity ratio' using an instrument that is similar to some of the simple instruments that are currently used. Poiseuille (1797–1869) performed an elegant study of the flow of fluids in capillary tubes and may be considered as one of the founders of modern viscometry. Sir George Gabriel Stokes (1819–1903), who was president of the Royal Society from 1885 to 1892, studied the flow of liquids through an orifice and can be considered the founder of the efflux type of viscometer.

Some important definitions in viscometry are set out below.

Laminar Flow and Turbulent Flow

Laminar flow is streamline flow in a fluid. Turbulent flow is fluid flow in which the velocity varies erratically in magnitude and direction.

The difference between laminar flow and turbulent flow is illustrated in Fig. 3.9. Suppose a fluid is being pumped through a pipe at a constant rate and a thin thread of colored solution is injected into the flowing stream. If laminar flow is occurring, the thread of colored solution will move straight down the tube. In the case of turbulent flow there are many eddies and currents, which

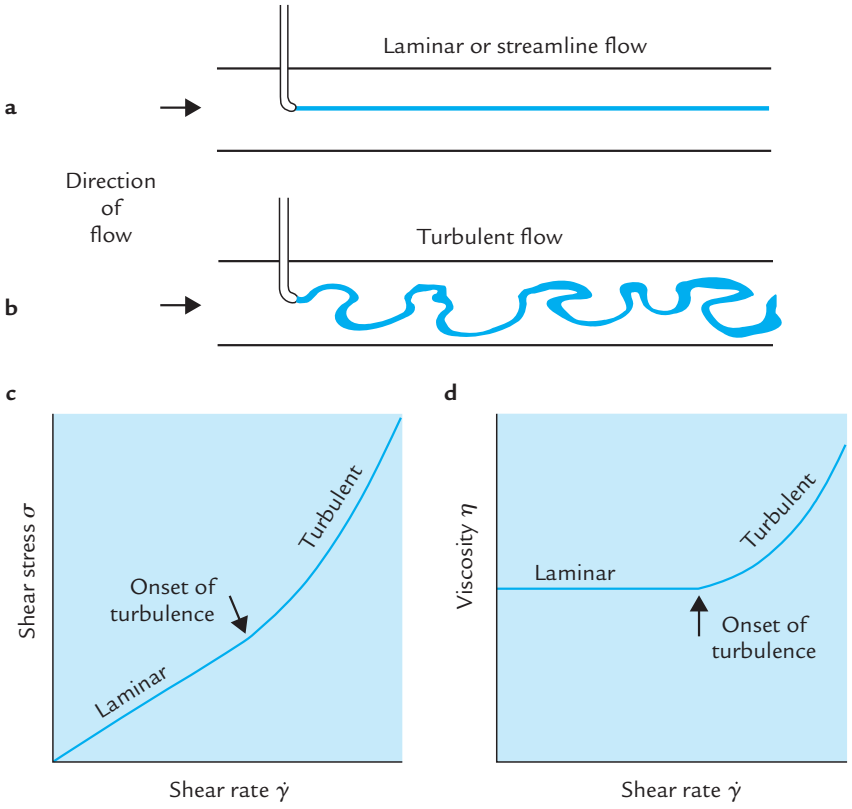


Figure 3.9 The difference between (a) laminar and (b) turbulent flow; (c) shear stress versus shear rate for a Newtonian fluid in the laminar and turbulent flow range; (d) viscosity versus shear rate for a Newtonian fluid in the laminar and turbulent flow range.

are shown by the line of colored solution breaking up and forming eddies and vortices as it moves down the pipe. Laminar flow occurs at slow rates of flow and turbulent flow occurs at high rates of flow.

The Reynolds number (Reynolds, 1883) is a dimensionless number defined by an equation that can take several forms, one of which is the following:

$$\mathrm{Re} = 2\rho Q/\pi r\eta$$

where Re is the Reynolds number (a dimensionless number); ρ, the density of liquid; Q, the rate of flow; r, the radius of pipe; and η, the viscosity. The point at which the onset of turbulence occurs is known as the critical Reynolds number, Rc. The critical value of Reynolds number denotes the rate of flow at which the flow changes from laminar to turbulent flow. For pipe flow this occurs at approximately Rc = 2200 and is shown schematically in Fig. 3.9c,d. Newtonian flow only occurs in the laminar region. Even a Newtonian fluid will lose its Newtonian behavior when turbulent flow begins. This critical Reynolds number determines the lowest velocity at which turbulent flow can take place, but it does not determine the highest velocity for the appearance of laminar flow. It is possible to obtain a laminar flow above the critical Reynolds number, particularly if the fluid is free of colloidal or suspended material and the pipe is very smooth, giving a metastable region that is somewhat analogous to supercooling and superheating effects that can be found when heating or cooling pure liquids. The point to remember is that a Newtonian fluid appears to be non-Newtonian when the shear rate is very high.

Table 3.6 Units of Measurement of Viscosity

	Old system (metric)		New system (SI)
Shear stress			
symbol	τ (Greek tau)		σ (Greek sigma)
unit	dyne cm^{-2}		pascal (Pa)
dimensions	dyne cm^{-2}		newton $meter^{-2}$ (Nm^{-2})
conversion		1 N = 10^5 dyne	
		1 m^2 = 10^4 cm^2	
		1 Pa = 10 dyne cm^{-2}	
Shear rate			
symbol	$\dot{\gamma}$		$\dot{\gamma}$ (Greek gamma dot)
unit	s^{-1}		s^{-1}
Viscosity			
symbol	η		η (Greek eta)
unit	poise (P)		pascal second (Pa·s)
conversion		10.00 P = 1.00 Pa·s	
		1.00 cP = 1.00 mPa·s	
Kinematic viscosity			
symbol	ν		ν (Greek nu)
unit	stoke (St)		m^2 s^{-1}
	centistoke (cSt)		mm^2 s^{-1}
conversion		1cSt = 1 mm^2 s^{-1}	

Note that the viscosity of water at 20°C is 1.00 centipoise or 1.00 millipascal second.

Dynamic Viscosity

Dynamic viscosity which is frequently called 'viscosity,' or 'absolute viscosity,' is the internal friction of a liquid or its tendency to resist flow. It is usually denoted by η and is defined by the equation

$$\eta = \sigma/\dot{\gamma}$$

where η is the viscosity; σ, the shear stress; and $\dot{\gamma}$, the shear rate.

According to the International Organization for Standardization (ISO) the unit of measurement for dynamic viscosity is the pascal second (Pa·s). Since the pascal second is a large unit of measurement, a more common unit for low viscosity fluids is the millipascal second (mPa·s) where 1000 mPa·s ≡ 1 Pa·s.

An obsolete, but still widely used unit of viscosity, is the poise (P) named after the French scientist Poiseuille (1846). Since this is a large unit of measurement, the centipoise is widely used for low viscosity liquids (100 cP = 1 P). The reader is encouraged to use the SI system of Pa·s or mPa·s but should know how to convert poise and centipoise into SI units because most of the older literature, and some of the more recent literature, expresses viscosity in poise. Table 3.6 lists the units of measurement of viscosity in the metric system (now obsolete) and the International System of Units (SI) that were officially adopted in 1960. The conversion factors that convert metric units to SI units are also given in Table 3.6 to help the reader convert data in the older literature into SI units.

Table 3.7 Some Typical Viscosities

Substance	Viscosity (cP or mPa·s)
Air	1.86×10^{-4}
Water (0°C)	1.7921
Water (20°C)	1.000
Water (100°C)	0.2838
20% Sucrose solution (20°C)	1.967
40% Sucrose solution (20°C)	6.223
60% Sucrose solution (20°C)	56.7
80% Sucrose solution (20°C)	40,000
Diethyl ether (20°C)	0.23
Glycerol (20°C)	1759

Table 3.7 shows viscosities of some well-known liquids. It is worth noting that water at 20°C has a viscosity of 1.0 mPa·s ≡ 1 cP.

Fluidity

Fluidity is the reciprocal of dynamic viscosity. It is occasionally used in place of viscosity. It is denoted by ϕ, and is defined by the equation

$$\phi = \dot{\gamma} / \sigma$$

Kinematic Viscosity

This is defined as the absolute viscosity divided by the density of the fluid. It is usually denoted by ν:

$$\nu = \eta/\rho = \sigma/\rho\dot{\gamma}$$

where ν is the kinematic viscosity, η is the absolute viscosity and ρ is the density in grams per cubic centimeter. The SI unit for kinematic viscosity is the meter-square-second.

An obsolete unit of kinematic viscosity is the stoke (after Stokes, 1819–1903). It has the dimensions M^2T^{-1}. One centistoke equals 0.01 stoke.

Kinematic viscosity is measured in efflux viscometers because the rate of flow in this type of viscometer is proportional to density as well as viscosity. Kinematic viscosity is widely used in the petroleum industry where the specific gravity of liquid hydrocarbons does not vary widely. Kinematic viscosity is not used in the food industry to the same extent because a wide range of densities can be encountered, which compresses the kinematic viscosity into a smaller range than the absolute viscosity. This is exemplified in Table 3.8, which shows the absolute viscosity and kinematic viscosity of sucrose solutions. The absolute viscosity changes from 1.0 mPa·s for water to 480.6 mPa·s for 70% syrup, whereas over the same range the kinematic viscosity changes from 1.0 to 357.4 $mm^2\ s^{-1}$.

Relative Viscosity

This is sometimes called the 'viscosity ratio,' which is the ratio of the viscosity of a solution to the viscosity of the pure solvent and is defined by

Table 3.8 Viscosity and Density of Aqueous Sucrose Solutions at 20°C

% Sucrose	Specific gravity	Absolute viscosity η (mPa·s)	Kinematic viscosity ν ($mm^2\,s^{-1}$)
0	1.00	1.00	1.00
20	1.083	1.97	1.82
40	1.179	6.22	5.28
60	1.289	56.7	44.0
70	1.350	480.6	357.4
74	1.375	1628	1188

the equation

$$\eta_{rel} = \eta/\eta_s$$

where η_{rel} is the relative viscosity; η, the viscosity of solution; and η_s, the viscosity of solvent.

Apparent Viscosity

This is the viscosity of a non-Newtonian fluid expressed as though it were a Newtonian fluid. It is a coefficient calculated from empirical data as if the fluid obeyed Newton's law. This concept will be discussed in more detail on p. 83. The symbol η_a is used to denote apparent viscosity.

Shear Stress

Shear stress is the stress component applied tangential to the plane on which the force acts. It is expressed in units of force per unit area. It is a force vector that possesses both magnitude and direction. The SI unit for shear stress is the pascal (Pa) with units of newton meter^{-2} ($N\,m^{-2}$).

The nomenclature committee of the Society of Rheology recommends that σ be used to denote shear stress in simple steady shear flow and that τ be used to denote relaxation time or retardation time [*Rheol. Bull.* **43**(2), 6 (1974)]. In accordance with this convention, σ will be used to denote shear stress in this chapter. However, the reader is cautioned that the older literature and many rheologists continue to use τ to denote shear stress (for example, see Figs 3.17 and 3.22, pages 85 and 92 respectively).

Shear Rate

Shear rate is the velocity gradient established in a fluid as a result of an applied shear stress. It is expressed in units of reciprocal seconds (s^{-1}).

The nomenclature committee of the Society of Rheology (see above) recommends that $\dot{\gamma}$ be used to denote shear rate and that γ be used to denote shear strain. The use of γ to denote shear rate is conventional among rheologists and will be used in this chapter.

Krumel and Sahar (1975) give some useful guidelines that enable one to think in practical terms of what various shear rates mean when related to well-known phenomena. A shear rate of $0.1\,s^{-1}$ approximates rate of film sag, or flow of film over a vertical plate; $0.1–10\,s^{-1}$approximates the rate of flow of

a normal Brookfield reading; 50 s^{-1} approximates the shear rate in the mouth; 10–100 s^{-1} approximates the shear rate in tumbling or pouring; 100–1000 s^{-1} approximates the shear rate in most home mixers; >1000 s^{-1} approximates the shear rate in a blender.

Van Wazer *et al*. (1963) noted the sensitivity of the eye in judging viscosities of Newtonian liquids between about 0.1 Pa·s (1 P) and 10 Pa·s (100 P) by their rate of flow. Below about 0.01 Pa·s (0.1 P) and above about 100 Pa·s (1000 P) the eye cannot distinguish differences in viscosity.

Factors Affecting Viscosity

Temperature

There is usually an inverse relationship between viscosity and temperature. Typical data are shown in Fig. 3.10 which plots the viscosity of water and

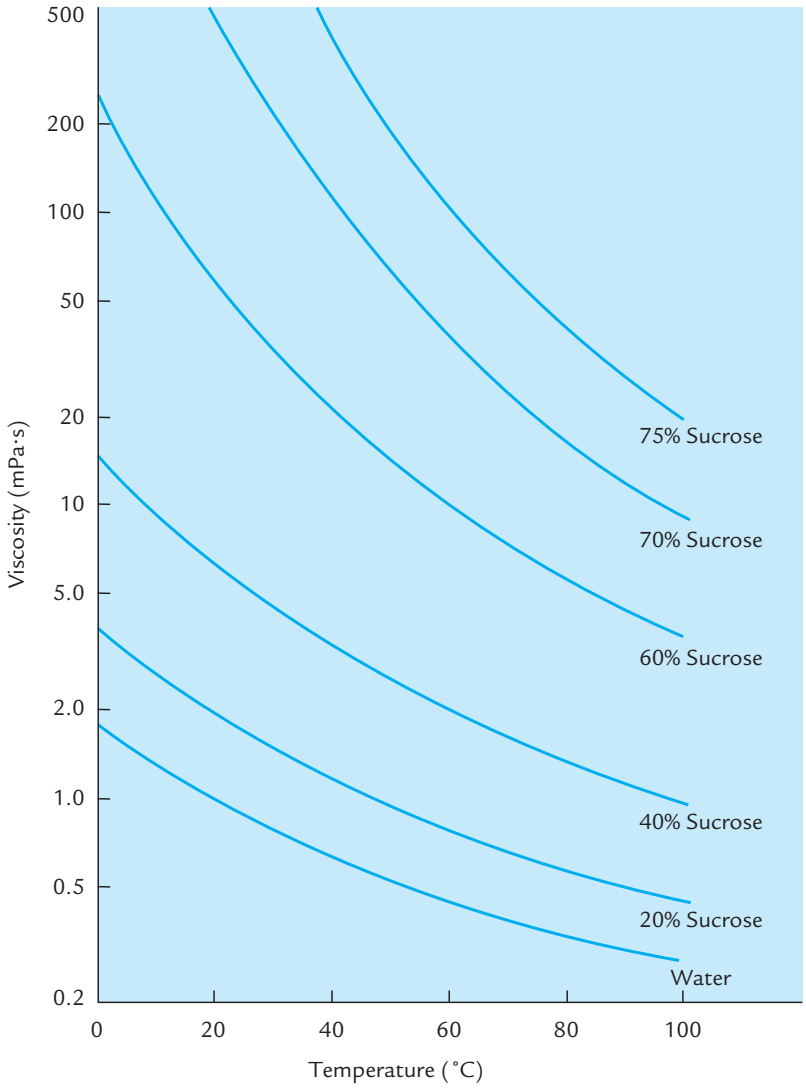


Figure 3.10 Viscosity of water and sucrose solutions as a function of temperature.

some sucrose solutions as a function of temperature. Note also from Table 3.7 that the viscosity of water at 0°C is 1.79 mPa·s falling steadily to 0.28 mPa·s at 100°C.

Concentration of Solute

There is usually a direct nonlinear relationship between the concentration of a solute and viscosity at constant temperature. Figure 3.11 shows the viscosity–concentration behavior of salt solution and sucrose solutions at constant temperatures. It is typical of the concentration effect on viscosity. Table 3.7 also shows this phenomenon: water at 20°C has a viscosity of 1 mPa·s, whereas 80% sucrose solution has a viscosity of approximately 40,000 mPa·s.

The concentration may also determine the type of flow behavior. For example, Velez-Ruiz and Barbosa-Canovas (1998) showed that concentrated milks showed Newtonian flow up to 22.3% solids, power-law flow from 22.3% to 30.5% solids, and Herschel–Bulkley flow above 42.4% solids.

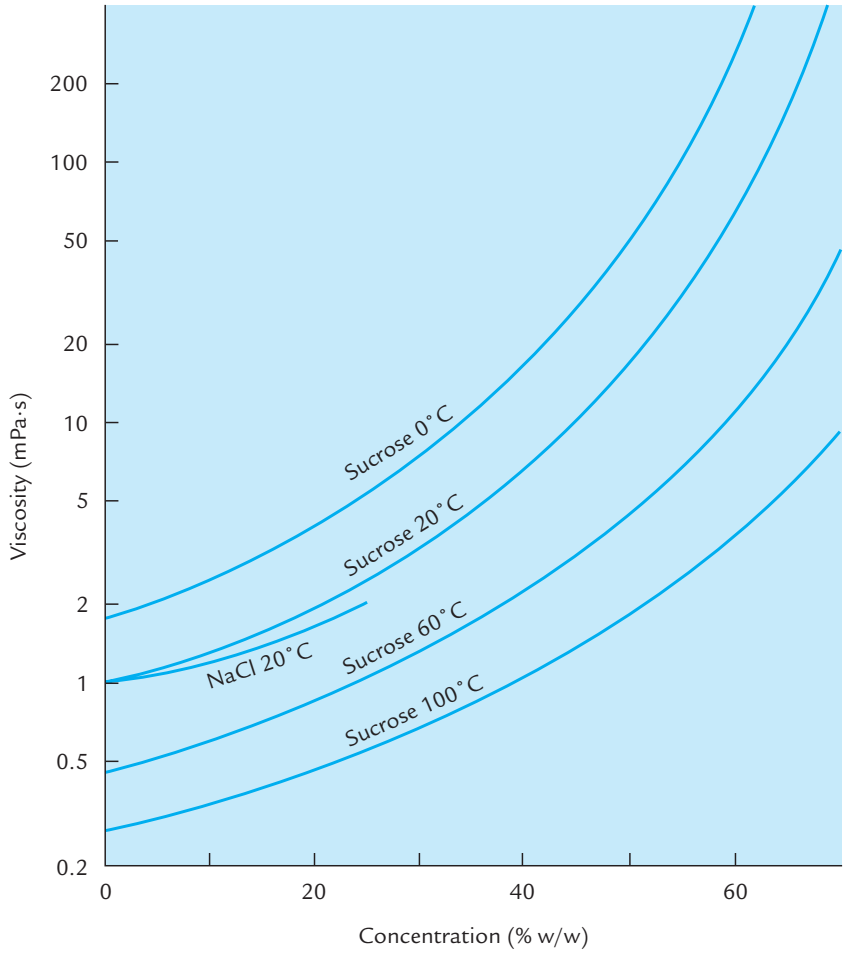


Figure 3.11 Viscosity as a function of concentration of sucrose solutions at four temperatures and sodium chloride.

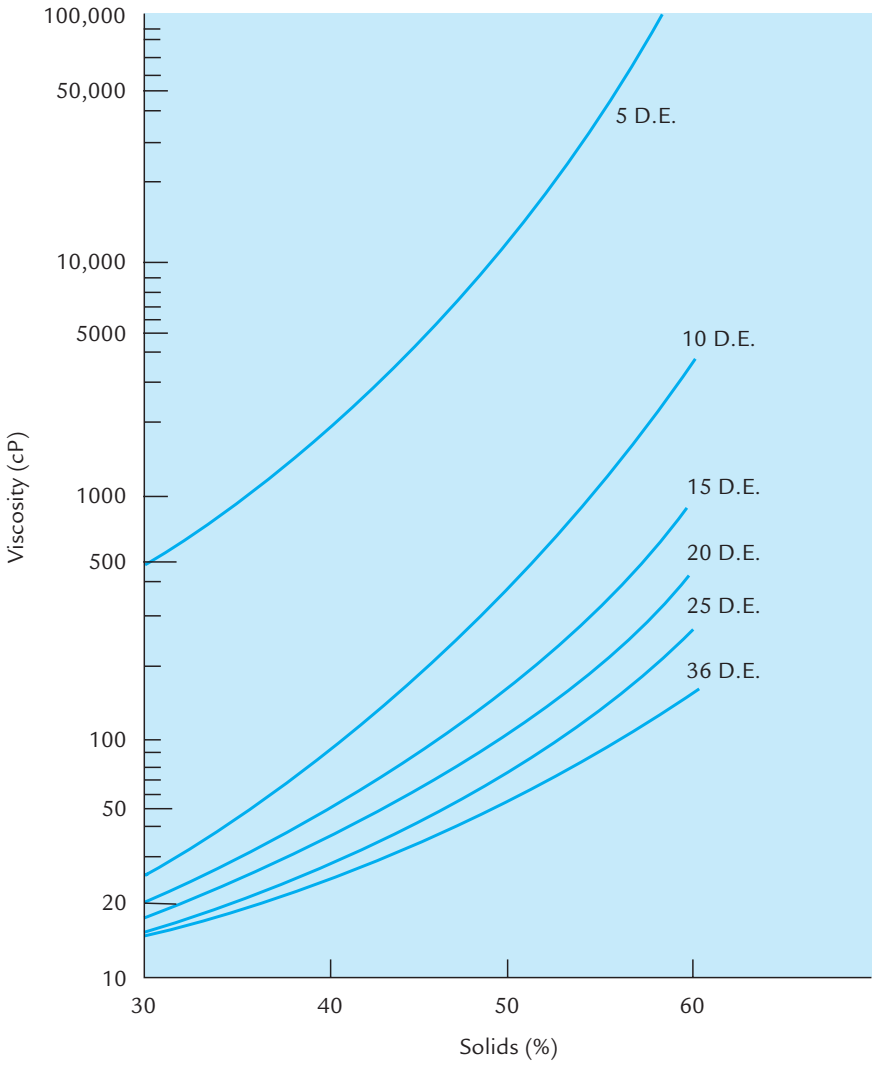


Figure 3.12 Viscosity–concentration–molecular weight relationships for hydrolyzed cornstarch syrups. (From Murray and Luft, 1973; courtesy of Grain Processing Corp. Reprinted from *Food Technol*. **27**, 33. Copyright by Institute of Food Technologists.)

Molecular Weight of Solute

There is usually a nonlinear relationship between the molecular weight of the solute and the viscosity of the solution at equal concentrations. Figure 3.12, shows the viscosity of corn syrups as a function of molecular weight. Corn syrup is made by hydrolyzing by degrees high-molecular-weight starch into dextrose, a simple hexose monosaccharide. The abbreviation D.E. refers to 'dextrose equivalent' and means the equivalent reducing activity of pure dextrose. A '36-D.E.' syrup means that 100 g of corn syrup solids has the same chemical reducing capacity as 36 g of pure dextrose. A low D.E. means a long chain length and high-molecular-weight oligosaccharide. Figure 3.12 shows that 5-D.E. corn syrup (consisting principally of long-chain oligosaccharides) has a much higher viscosity at the same solids concentration than lower average molecular weight corn syrups of equal concentration.

Pressure

The viscosity of most liquids is essentially constant over a pressure range of 0–100 atm. Hence the pressure effect can usually be ignored for foods.

Suspended Matter

This usually increases the viscosity slightly when in low concentrations, but high concentrations of suspended matter can cause substantial increases because of entanglement between the particles. High concentrations of suspended matter usually render the product non-Newtonian and can lead to plastic flow or dilatant flow (see pages 82–87). A number of foods are composed of two phase systems. One of the best examples is fruit and vegetable juices, purees and concentrates in which insoluble cell wall material and fibers are suspended in a serum containing water-soluble materials such as sugars, acids, and salts. The concentration of the insoluble suspended matter has a profound effect on the viscosity and the type of viscous flow. Another example is emulsions such as mayonnaise and salad dressings where the volume concentration of the discontinuous phase (oil droplets) also has a profound effect on the viscosity and the type of viscous flow.

Types of Viscous Behavior

Newtonian

This is true viscous flow. The shear rate is directly proportional to the shear stress and the viscosity is independent of the shear rate within the laminar flow range. The viscosity is given by the slope of the shear stress–shear rate curve (see Fig. 3.13). Typical Newtonian fluids are water, and watery beverages such as tea, coffee, beer, and carbonated beverages, sugar syrups, most honeys, edible oils, filtered juices, and milk. A Newtonian fluid possesses the simplest type of flow properties. The characteristics of this type of flow are adequately described by the equation given above ($\eta = \sigma/\dot{\gamma}$). A fluid with high viscosity is called ‘viscous’ whereas a fluid with low viscosity is called ‘mobile.’

Many fluid foods are not Newtonian, in fact, they deviate very substantially from Newtonian flow. And yet there often seems to be a mental fixation on Newtonian-type flow. Some instruments that satisfactorily measure Newtonian flow are far from satisfactory for measuring the flow properties of non-Newtonian fluids, yet one often sees food scientists using equipment designed for Newtonian fluids to measure viscous properties of non-Newtonian fluids. Much confusion is found in the literature because the viscous properties of non-Newtonian fluids have been measured by instruments that are only applicable to Newtonian fluids and the data are erroneously interpreted using the concepts of Newtonian fluids.

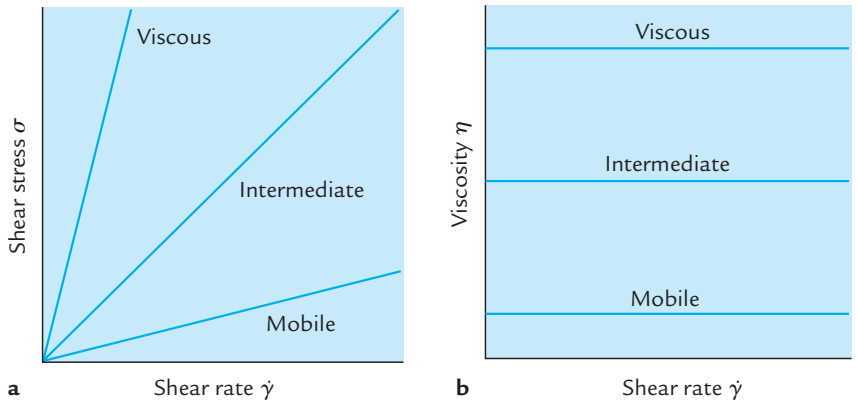


Figure 3.13 Newtonian flow: (a) shear stress versus shear rate (note that the straight lines begin at the origin); (b) viscosity versus shear rate (the viscosity remains constant with changing shear rate).

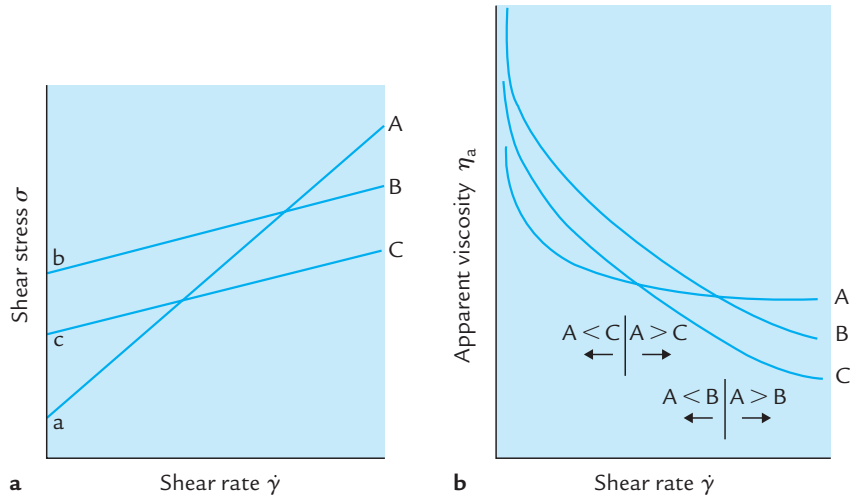


Figure 3.14 Plastic flow for three foods A, B, and C. (a) Shear stress versus shear rate. Note that the lines do not begin at the origin. There is always an intercept ("yield stress") on the vertical axis. (b) Apparent viscosity versus shear rate for same three foods. The apparent viscosity decreases with increasing shear rate. Note that the apparent viscosity of fluid A may be greater or less than that of fluids B and C, depending on the shear rate at which the measurement is taken.

Non-Newtonian Fluids

Most fluid and semifluid foods fall into one of several classes of non-Newtonian fluids.

Plastic (or Bingham)

A minimum shear stress known as the 'yield stress' must be exceeded before flow begins. This type of flow is often found in foods. Typical examples of this type of flow are tomato catsup, mayonnaise, whipped cream, whipped egg white, and margarine. This type of flow is named after Bingham (1922), who studied the flow properties of printing inks and discovered the important principle that no flow occurs at low stress. He identified the point at which flow begins as the 'yield stress.' The term 'plastic' refers to materials that exhibit this yield stress; it does not refer to synthetic plastics.

Figure 3.14 shows the characteristics of plastic flow for three fluid foods. Fluid A has a low yield stress; the rate of flow (shear rate) is directly proportional to the shear stress after the yield stress has been exceeded. Fluids B and C have a higher yield stress than A. The rate of flow of fluids B and C is also

Table 3.9 Values for Plastic Yield Stress of Some Foods

Type of food and condition	Yield stress (dyn cm^{-2})
Chocolate, melted	12
Cream, whipped	400
Guar gum, 0.5% solids, in water	20
Guar gum, 1.0% solids, in water	135
Orange juice, concentrated 60° Brix	7
Pear puree, 18.3% solids	35
Pear puree, 45.7% solids	339
Protein from yeast, 10% solids	0
Protein from yeast, 25% solids	42
Protein from soy isolate, 20% solids	1271
Protein, whey, 20%	21
Sucrose, 75% in water	0
Tomato puree, 11% solids	20
Xanthan gum, 0.5% solids, in water	20
Xanthan gum, 1.2% solids, in water	45

Source: Rha (1980).

directly proportional to the shear stress after the yield stress has been exceeded. Table 3.9 lists published values for yield stress of some plastic foods.

Apparent viscosity was defined as the viscosity of a non-Newtonian fluid. Since, in a Newtonian fluid, the flow rate is directly proportional to the shear stress and the curve begins at the origin, a single-point measurement suffices to establish viscosity. One simply measures the shear stress at a standard shear rate, or the shear rate at a standard shear stress, and by drawing a line from there to the origin obtains the true Newtonian viscosity. This is known as a 'one-point test' and is quite satisfactory for specifying the viscosity of Newtonian fluids.

When this test is used (as is commonly done) on a plastic fluid, the apparent viscosity will change, depending on the shear rate. Figure 3.15 shows how apparent viscosity is measured. Suppose the viscosity of a Newtonian fluid is measured at shear rate *a* and shear rate *b*. The shear stress measured at shear rate *a* (*Na*) is marked on the graph and a line drawn from that point to the origin. Similarly the shear stress is measured at shear rate *b* (*Nb*) and a line drawn from this point back to the origin. The slope of the line at both shear rates is the same; this is characteristic of a Newtonian fluid.

In contrast, when a one-point measurement is made at shear rate *a* on a Bingham plastic the apparent viscosity is the slope of the line *OPa*; at shear rate *b* the apparent viscosity is *OPb*. The apparent viscosity changes as the shear rate changes. This explains why the term 'apparent viscosity' is used because it implies a Newtonian-type measurement on a non-Newtonian fluid. Figure 3.15 demonstrates the difficulties that can arise from using Newtonian concepts for non-Newtonian fluids. A plot of apparent viscosity versus shear rate for three Bingham fluids is shown in Fig. 3.14b. This should be compared

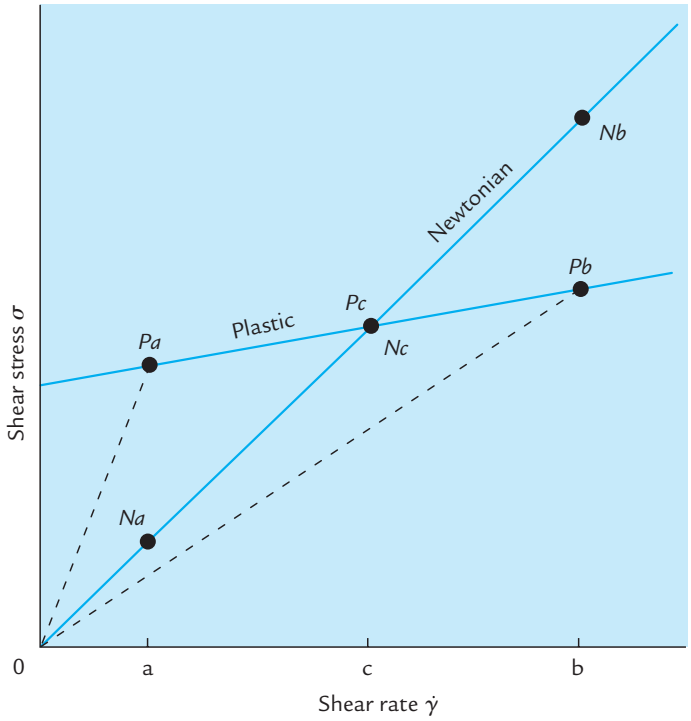


Figure 3.15 Shear stress–shear rate plots for a Newtonian fluid and a plastic fluid. Note that the viscosity of the Newtonian fluid *N* is the same when measured at shear rates a, b and c, whereas the apparent viscosity of the plastic fluid *P* is different at each shear rate.

with Fig. 3.13b. One problem that arises with the use of the concept of apparent viscosity is that fluid A can appear to be more viscous, equally viscous, or less viscous than fluids B and C, depending on the shear rate at which the test was performed (see Fig. 3.14b).

Plastic flow is not always as simple as shown in Fig. 3.14. Houwink (1958) pointed out that the shear stress–shear rate curve for plastic fluids is usually curved at low shear rates and he postulated three yield values, which are shown in Fig. 3.16. The extrapolation of the straight-line position of the experimental curve to zero shear rate gives true plastic or Bingham flow. The downward curvature of the experimental curve at low shear rates is often found in practice. The shear stress at which curvature begins in the shear stress–shear rate plot is defined as the 'upper Houwink yield value;' the intercept on the vertical axis from the extrapolation of the straight-line part of the curve is known as the 'extrapolated yield value' or Bingham value; and the actual intersection of the shear stress–shear rate plot on the vertical axis is known as the 'lower Houwink yield value.' The deviation from linearity of plastic flow at low shear rate is sometimes of importance but for some foods the deviation is so small that it can be safely ignored. For example, Fig. 3.17 shows the experimental shear stress–shear rate plot of a meat extract that shows true Bingham behavior with no curvature at low shear rates.

Another type of plastic flow is the type in which the shear stress–shear rate plot is nonlinear above the yield stress. The curve may be concave downward (dilatant with a yield stress), or convex downward (pseudoplastic with a yield stress). It is sometimes known as the 'mixed type.' This type of flow is

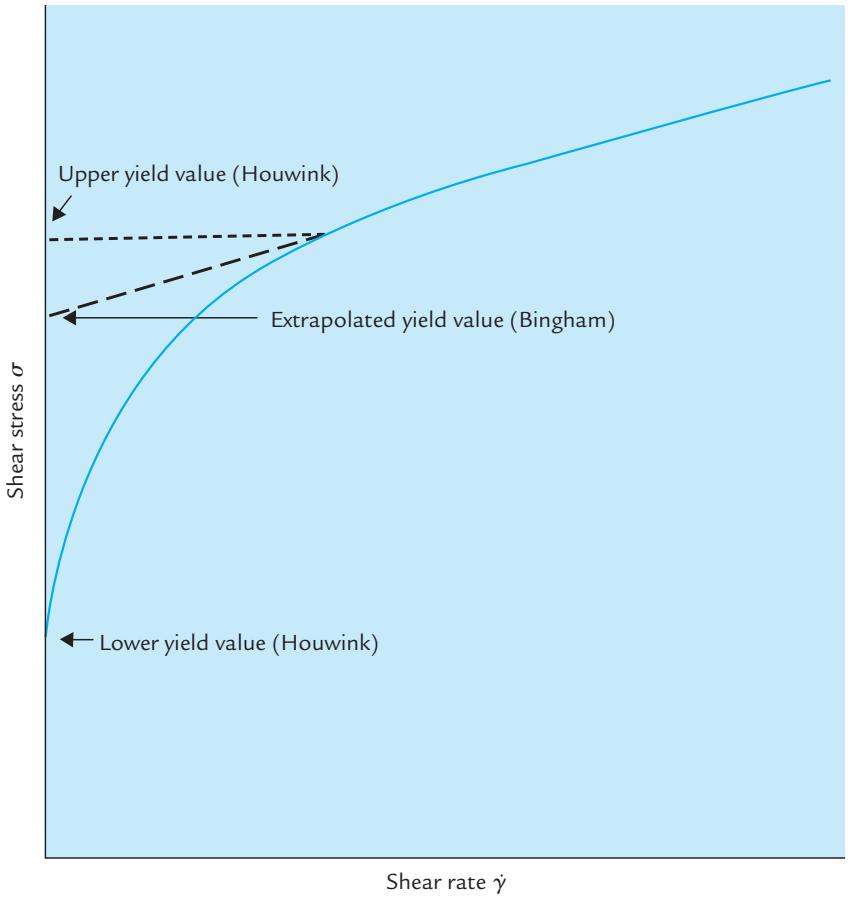


Figure 3.16 The upper yield value, extrapolated yield value and lower yield value that is found in plastic fluids.

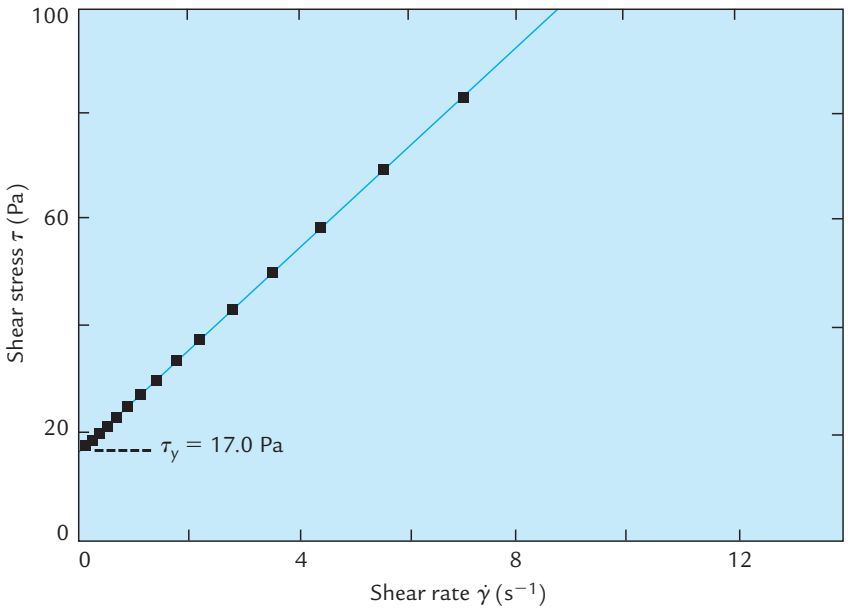


Figure 3.17 Shear stress–shear rate plot for a concentrated meat extract (T = 77°C). This is a true Bingham plastic that shows a linear relationship all the way down to zero shear rate. (Courtesy of Dr A. L. Halmos and Dr C. Tiu. Reprinted from *J. Texture Studies* **12**, page 42, 1981, with permission from Food and Nutrition Press.)

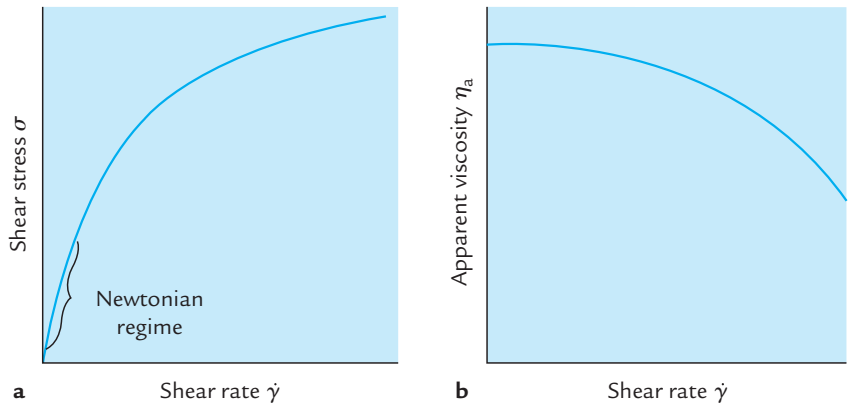


Figure 3.18 Pseudoplastic flow: (a) shear stress versus shear rate (note the convex line that begins at the origin); (b) apparent viscosity versus shear rate (note that the apparent viscosity decreases with increasing shear rate).

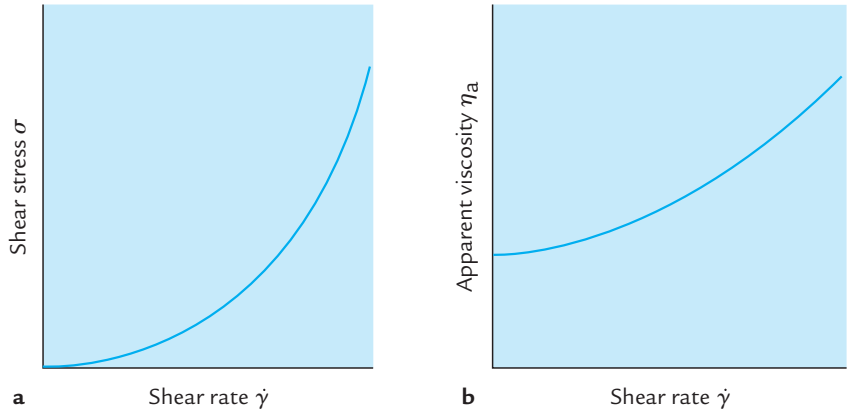


Figure 3.19 Dilatant flow: (a) shear stress versus shear rate (note the concave line that begins at the origin); (b) apparent viscosity versus shear rate (note that the apparent viscosity increases with increasing shear rate).

described by the Herschel–Bulkley equation, which is discussed on page 89 and is illustrated in Fig. 3.20.

Pseudoplastic

In this type of flow an increasing shear force gives a more than proportional increase in shear rate, but the curve begins at the origin. The term 'pseudoplastic' was originated by Williamson (1929); it does not refer to synthetic plastics. Salad dressings are a good example of this type of flow. Figure 3.18b shows that the apparent viscosity of a pseudoplastic fluid is dependent on the shear rate and, as in the discussion of plastic flow, it illustrates the danger of using a single-point measurement and Newtonian concepts for specifying the flow characteristics of a pseudoplastic fluid. Many pseudoplastic fluids exhibit nearly linear shear stress–shear rate behavior at low shear rates. This is called the 'Newtonian regime.'

Dilatant Flow

The shear stress–shear rate plot of this type of a flow begins at the origin but is characterized by equal increments in the shear stress giving less than equal increments in the shear rate (Fig. 3.19). Examples are high solids, raw starch suspensions, and some chocolate syrups. This type of flow is only found in

liquids that contain a high proportion of insoluble rigid particles in suspension. Dilatant flow is fairly rare in the food industry and extremely rare in finished food products.

This type of flow is described as 'dilatant' because it is associated with an increase in volume of the fluid as flow occurs, and it only occurs in high concentration suspensions. Reynolds (1883), who introduced the term 'dilatancy,' gave quicksand as an example, stating:

> When the water-to-sand ratio is such that there is just enough water to fill all the voids, and when the volume of voids is at a minimum, any shear applied to force that material to flow disturbs the position of the particles and causes a dilation of the voids. This leads to the situation in which the total volume of the voids is greater than the volume of water present. This results in an apparent partial dryness which increases the resistance of the material to shearing stress. The dryness is the result of the time necessary for the capillary forces to provide the additional water required for complete saturation. When the pressure is removed, the sand becomes wet because the voids contract, and the water which has become excess escapes at the surface.

An equally good example of this type of behavior can be found with a 60% suspension of cornstarch in water.

True dilatancy can probably exist in any suspension so long as the concentration is high enough for the material to exist in closely packed form. The property of dilatancy disappears when the suspension is diluted. For example, a 40% cornstarch suspension in water shows no dilatant properties. The densest packing of spheres is about 74% and one of the least-dense packing is about 37%. Hence it is usual to find that the property of dilatancy only appears in suspensions between about 40% and 70% solids concentration.

Some fluids that do not dilate when sheared may still exhibit a dilatant type of shear stress–shear rate behavior; that is, equal increments in shear stress give less than equal increments in shear rate. The general term 'shear thickening' applies to these fluids as well as to dilatant fluids.

The General Equation for Viscosity

All the above types of flow can be described by the equation

$$\sigma = b\dot{\gamma}^s + C$$

where σ is the shear stress, b, a proportionality factor (for a Newtonian fluid this factor is the viscosity η), C, the yield stress, s, the pseudoplasticity constant, which is an index of the degree of nonlinearity of the shear stress–shear rate curve, and $\dot{\gamma}$, the shear rate. Figure 3.20a shows all types of flow in a single graph. Newtonian flow is represented by a straight line starting at the origin; dilatant flow starts at the origin and is concave downward, whereas pseudoplastic flow starts at the origin and is concave upward. Plastic flow does not begin at the origin and is linear and mixed-type flow is curvilinear with a yield stress and may be concave upward or downward.

Some authors publish a shear rate–shear stress curve instead of the conventional shear stress–shear rate curve. Figure 3.20b plots the same types of

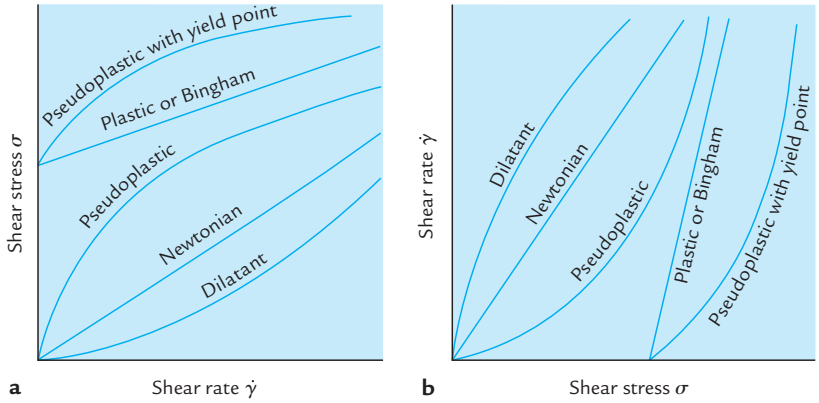


Figure 3.20 (a) Shear stress versus shear rate plots for various types of flow; (b) shear rate versus shear stress plots for the same types of flow.

Table 3.10 Relationship Between Type of Flow and the General Viscosity Equation[a]

Type of flow	s	C	Equation form
Newtonian	1	0	$\sigma = b\dot{\gamma} = \eta\dot{\gamma}^b$
True plastic	1	>0	$\sigma = b\dot{\gamma} + C$
Pseudoplastic	$0 < s < 1$	0	$\sigma = b\dot{\gamma}^s$
Dilatant	$1 < s < \infty$	0	$\sigma = b\dot{\gamma}^s$
Pseudoplastic with a yield value	$0 < s < 1$	>0	$\sigma = b\dot{\gamma}^s + C$
Dilatant with a yield value	$1 < s < \infty$	>0	$\sigma = b\dot{\gamma}^s + C$

[a] The general viscosity equation is $\sigma = b\dot{\gamma}^s + C$.
[b] Term b is the true viscosity η.

flow as Fig. 3.20a but with the position of the axes interchanged. One should learn to recognize the identity of the various types of flow on both types of plot.

The general equation for viscosity can be used for all of the above types of flow. Table 3.10 lists the values for the exponent s and the intercept C for the various types of flow, the form of the general equation that can be used, and a simplified version of the general equation that can be used for that particular type of flow. For example, the constant C (yield stress) can be dropped out of the equation for dilatant, Newtonian, and pseudoplastic flow because there is no yield stress.

Other Flow Equations

A number of other equations, almost all of which are empirical in nature, have been described in the literature. These equations usually have no theoretical foundation, but because they facilitate the handling of empirical data they have some usefulness. Some of the most common ones are listed below.

The Power Equation (also known as the Ostwald–de Wael model)

Although this is often described as the power law it is in fact an empirical relationship. This widely used equation takes the form

$$\sigma = K\dot{\gamma}^n$$

where σ is the shear stress, K is a consistency index, $\dot{\gamma}$ is the shear rate, and n is a dimensionless number that indicates the closeness to Newtonian flow. For a Newtonian liquid $n = 1$; for a dilatant fluid $n > 1$, and for a pseudoplastic fluid $n < 1$. The farther the value of n departs from 1.0 the greater is the deviation from Newtonian flow. For example, a food with a value of $n = 0.9$ is fairly close to Newtonian flow whereas another food with $n = 0.3$ deviates substantially from Newtonian flow. Most non-Newtonian foods are shear thinning, i.e. $n < 1$. However, there are occasional examples of a shear-thickening food.

Taking logarithms reduces this equation to the form

$$\log \sigma = \log K + n \log \dot{\gamma}$$

A plot of the log shear stress versus log shear rate is linear with a slope equal to n for those fluids that obey the power equation. The power equation is frequently used by engineers in designing systems for handling fluid foods. Many systems reduce to a linear relationship over a wide range of shear rates when reduced to a log–lot plot. Table 3.11 lists experimentally determined power equation constants for some fruit purees and Table 3.12 for a variety of processed foods.

Herschel–Bulkley Model

Fluids that obey this model are characterized by the presence of a yield stress and a linear log shear stress–log shear rate plot (Herschel and Bulkley, 1926). The equation for this model is

$$\sigma = \sigma_0 + K\dot{\gamma}^n$$

where σ_0 is the yield stress.

This equation is of the same form as the last two equations in Table 3.10, the only difference being in some of the symbols. It takes the same form as the power equation but with the addition of the yield stress term σ_0.

The numerical value of the exponent n indicates the closeness to a linear shear stress–linear shear rate plot; the plot is rectilinear when n is 1 and the degree of curvature of the plot on linear axes increases as the value of n moves away from unity.

Casson Equation

This equation was developed for printing inks by Casson (1959), but has been found to be effective for some foods, particularly chocolate and some other

Table 3.11 Power Equation Constants for Some Fruit Purees

Product	Solids (%)	Temperature (°C)	Rheological constants	
			n	*K*
Applesauce	11.0	30	0.34	116
Applesauce	11.0	82	0.34	90
Apricot puree	15.4	4.5	0.37	130
Apricot puree	15.4	60	0.46	38
Apricot puree	19.0	4.5	0.32	220
Apricot puree	19.0	60	0.34	88
Apricot concentrate	26.0	4.5	0.26	860
Apricot concentrate	26.0	60	0.32	400
Banana puree	—	24	0.458	65
Orange juice concentrate	—	0	0.542	18.0
Orange juice concentrate	—	15.0	0.584	11.9
Pear puree	18.3	32	0.486	22.5
Pear puree	18.3	82	0.484	14.5
Pear puree	26.1	32	0.450	62.0
Pear puree	26.1	82	0.455	36.0
Pear puree	31.0	32	0.450	109.0
Pear puree	31.0	82	0.459	56.0
Pear puree	37.2	32	0.456	170.0
Pear puree	37.2	82	0.457	94.0
Pear puree	45.7	32	0.479	355.0
Pear puree	45.7	82	0.481	160.0
Peach puree	11.9	30	0.28	72
Peach puree	11.9	82	0.27	58
Plum puree	14	30	0.34	22
Plum puree	14	82	0.34	20

Source: Data from Holdsworth (1971).

Table 3.12 Power Equation Parameters for Steady Viscosities of Some Foods

Food	Flow Behavior Index *n*	Consistency Index *K* Pa·s^n
Butter, stick, unsalted, Land O' Lakes	0.074	333
Butter, whipped, unsalted, Land O' Lakes	0.042	417
Cool Whip, Birdseye	0.378	15.1
Cream Cheese, Whipped, Temptee	0.061	776
Frosting, canned, Betty Crocker	0.273	550
Ketchup, tomato, Heinz	0.107	79.4
Margarine, stick, Parkay	0.0043	549
Margarine, squeeze, Parkay	0.174	7.6
Marshmallow fluff, Durkee-Mower	0.501	670
Peanut butter, creamy, Skippy	0.168	316

Source: Bistany and Kokini (1983). Reprinted from *J. Rheology* **27**, page 608. Copyright by Society of Rheology.

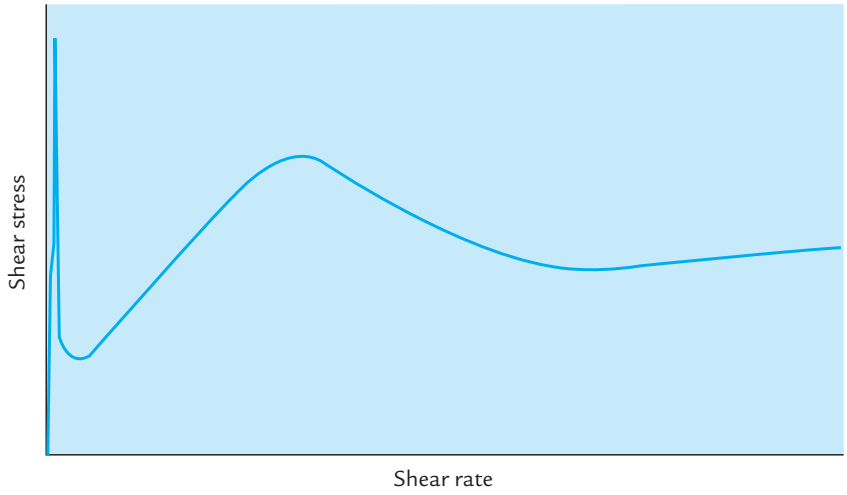


Figure 3.21 Experimentally determined shear stress–shear rate plot for an instant pudding. (Courtesy of Dr A. S. Szczesniak.)

filled fluids. The equation is

$$\sqrt{\sigma} = \sqrt{\sigma_0} + \eta_a \sqrt{\dot{\gamma}}$$

where σ is the shear stress, σ_0, the yield stress, η_a, the apparent viscosity, and $\dot{\gamma}$, the shear rate. This equation gives a linear plot for chocolate. It is used as an international standard for measuring the viscosity of chocolate (Rostagno, 1974). Chevalley (1975) reviewed the validity of the Casson equation for chocolate and factors that affect its flow behavior. However, Chevalley (1991) recommended a modified Casson equation. Instead of using the square root of the shear stress ($\sigma^{0.5}$) he found more consistent results using $\sigma^{0.6}$. Aeschlimann and Beckett (2000) summarized an interlaboratory study of chocolate viscosity and recommended simply reporting shear stress readings at several shear rates.

Structural Viscosity

The shear stress–shear rate plots for some fluid foods do not follow any of the types of viscous behavior explained above nor do they obey any of the above equations, including the general equation for viscosity. Figure 3.21 shows the shear stress–shear rate plot for an instant pudding. It is obvious that this is unlike any of the flow properties discussed above, and it is difficult to reduce this kind of curve to a suitable equation. The first sharp peak in this curve is probably related to some kind of shear stress needed to start the product flowing while the hump in the center probably represents the breakdown of some soft structure. The flow at high shear rates probably approximates pseudoplastic flow. When this test is repeated on the same sample, the second shear stress–shear rate curve frequently gives a smoother line with the bumps absent or much reduced in size.

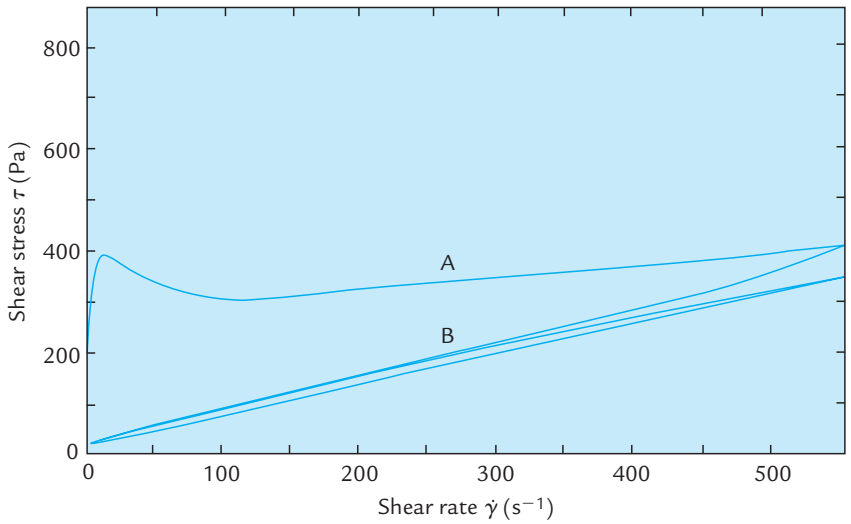


Figure 3.22 Repeated shear stress–shear rate curves on the same sample of concentrated yeast extract ($T = 25°C$). Curve A, first leg 'virgin' sample; curves B, 'destroyed' sample. (Courtesy of Dr A. L. Halmos and Dr C. Tiu. Reprinted from *J. Texture Studies* **12**, 43, 1981, with permission from Food and Nutrition Press Inc.)

At the present time there is no accepted method for analyzing this type of curve and extracting rigorously defined viscosity parameters from it. Halmos and Tiu (1981), who found a similar shape curve when working with concentrated yeast extracts, measured the area between the first and second curves, expressing this as the work required to break down the structural viscosity (Fig. 3.22). Presumably, the curve obtained on the second test and subsequent tests exhibits plastic flow or something close to pseudoplastic flow.

Time Dependency

Thus far we have assumed that the shear stress at a given shear rate remains constant over a period of time. There are a number of fluids in which the shear stress is a function both of the shear rate and the time to which it is subjected to a shearing force. Newtonian fluids are time independent; hence, this discussion does not apply to Newtonian fluids. The four major types of time dependency are as follows.

(1) *Thixotropic*. The apparent viscosity decreases with the time of shearing but the change is reversible; that is, the fluid will revert to its original state ('rebuild itself') on standing. Some starch paste gels are in this class.

(2) *Shear thinning*. The apparent viscosity decreases with time and the change is irreversible; that is, it stays in the thinner state when the shear stress is removed. This condition is frequently found in food systems. Some gum solutions and starch pastes fall into this class.

A fluid may exhibit both thixotropic and shear thinning properties, for example, when the apparent viscosity decreases with time of shearing and partially recovers its original viscosity after resting.

Figure 3.23 shows shear stress–shear rate curves for a thixotropic and a nonthixotropic pseudoplastic fluid. Curve A is nonthixotropic; the curve on

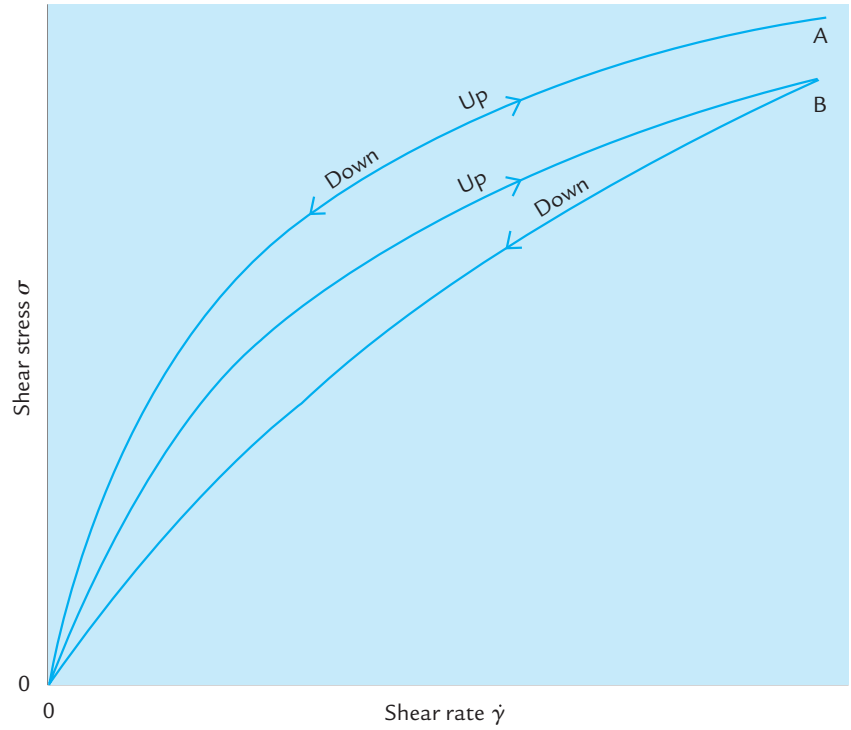


Figure 3.23 Shear stress–shear rate curves for a nonthixotropic pseudoplastic fluid (A) and a thixotropic pseudoplastic fluid (B).

the way down retraces the same path as on the way up. Curve B is thixotropic; the curve on the way down lies below the curve on the way up. The area between the up and down curve is called a hysteresis loop. Pradipasena and Rha (1977) reported that some globular protein solutions showed hysteresis. Davis (1973) showed the presence of hysteresis in lard and shortening. The researcher should be warned that some hysteresis loops are artifacts; two examples are (a) a true Newtonian fluid can give an apparent thixotropic hysteresis loop if viscous heating warms the liquid, and (b) inertial forces can cause a hysteresis loop to appear if the experiment is performed too fast or the rotor has a large mass.

(3) *Rheopectic*. The apparent viscosity increases with time of shearing and the change is reversible; that is, after resting, the product returns to its original apparent viscosity. It is rare to find this type of behavior in a food system.

(4) *Shear thickening*. The apparent viscosity increases with time and the change is irreversible; that is, it stays thick. When egg white or heavy cream are whipped their viscosity increases until they become stiff. This is an example of shear thickening. However, it is not a good example because the change in viscosity is due to physical changes in the egg protein and the fat globules of the cream. Vernon Carter and Sherman (1980) reported that aqueous solutions of mesquite tree gum exhibited shear thickening when the shear rate exceeded $100\,s^{-1}$.

Figure 3.24 portrays in graphical form the various types of time-dependent flow. When a fluid is caused to flow at a constant shear rate over a period of time the apparent viscosity is constant for Newtonian fluids, it increases for

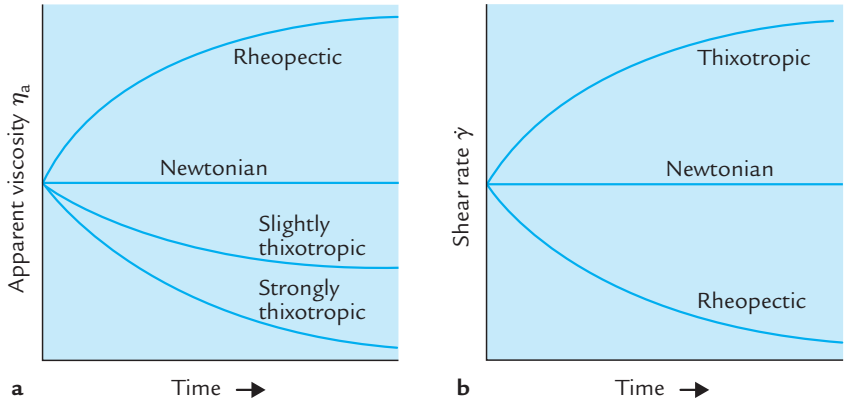


Figure 3.24 Time dependency factors in fluid flow: (a) at constant rate of shear; (b) at constant shear stress.

rheopectic or shear-thickening fluids, and decreases for thixotropic or shear-thinning fluids. On the other hand, when a fluid is caused to flow over a period of time under a constant shear stress, a plot of shear rate versus time is constant for a Newtonian fluid, it increases for a thixotropic fluid (because the product is becoming less viscous), and it decreases for a rheopectic or shear-thickening fluid (because the product is becoming more viscous).

A fluid may exhibit time dependency in addition to other viscous properties. For example, a product may be both plastic and thixotropic, or pseudoplastic and rheopectic. The combination of non-Newtonian flow plus time dependency brings one into very complex systems, many of which cannot be measured and described well by presently available instrumental methods. Nevertheless, the food technologist is faced with handling these systems and needs to obtain reliable and reproducible measurements, even though there are few guidelines.

Green (1949), who was an associate of Bingham, discusses the unsatisfactory state of analysis for some of these complex fluids. He discusses a practical rheologist, 'Bill,' who has viscosity measuring equipment in his laboratory and has to produce results describing the flow properties of the commodities being handled in a manufacturing plant, particularly with regard to the need for quality control purposes. Green writes as follows:

> A dozen theoretical rheologists can give a dozen different explanations as to why Bill's measurements produce the kind of curve they do. Not a single explanation will alter Bill's curves in any visible way. As far as Bill is concerned, the dozen different theoretical explanations might just as well not exist. Bill can, if necessary, get along without them. Bill will find it more desirable, however, to convert his curves into numbers like U, s, and M. Such numbers are easy to enter into reports and are much easier to interpret when making comparisons of different materials. … There are many ways of converting consistency curves into numbers. Which method should he choose?

The last sentence in the above quotation is the end of a chapter. Green never attempted to point out the best way for analyzing these complex consistency curves. The best conclusion that can be drawn about handling substances with complex flow properties is to make as complete a shear stress–shear rate study as possible, using adequate instrumentation and taking into account the possibility of time dependency in order to obtain as complete a picture as possible of the rheological properties of the system. A single-point measurement of

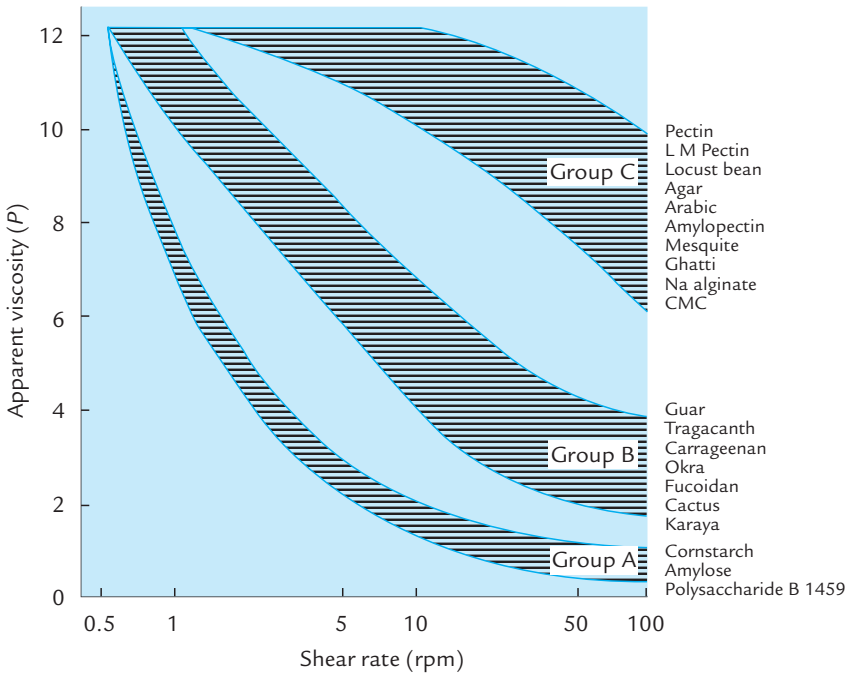


Figure 3.25 Effect of shear rate on apparent viscosity of gum solutions. Group C were classed as very slimy by a sensory panel, group B as somewhat slimy, and group A as nonslimy. (Redrawn from Szczesniak and Farkas, 1962.)

viscosity, which is satisfactory for Newtonian fluids, will be far from satisfactory for these complex fluids.

Time dependency is an important factor in the quality of some foods. For example, Szczesniak and Farkas (1962) found that aqueous solutions of gums that exhibited no time dependency had a slimy mouthfeel, whereas gums that exhibited a high degree of shear thinning or thixotropy had no sliminess (see Fig. 3.25). This finding was confirmed by Stone and Oliver (1966).

Another example is the manner of change of gelatin dessert. When a gelatin gel is put into the mouth it melts into a mobile fluid. This thinning effect (which is temperature controlled rather than mechanically controlled) is an important attribute of the textural quality of gelatin desserts. In contrast, dessert gels made from agar do not melt, because the melting point of agar gels is about 98°C. One has to chew these gels into small lumps for swallowing, and this behavior gives an entirely different type of mouthfeel and flavor release than a gelatin dessert gel.

Weissenberg Effect (Normal Force)

When a rod is rotated in some viscoelastic fluids, the fluid climbs up the rod against the force of gravity because the rotational force acting in a horizontal plane produces another force at right angles to that plane; this is called a normal force. The tendency of a fluid to flow in a direction normal to the direction of shear stress is known as the Weissenberg effect or normal force (Weissenberg, 1949). The effect has been observed with some flour doughs, cake batters, melted cheeses, honeys, and aged condensed milk (see Fig. 3.26).

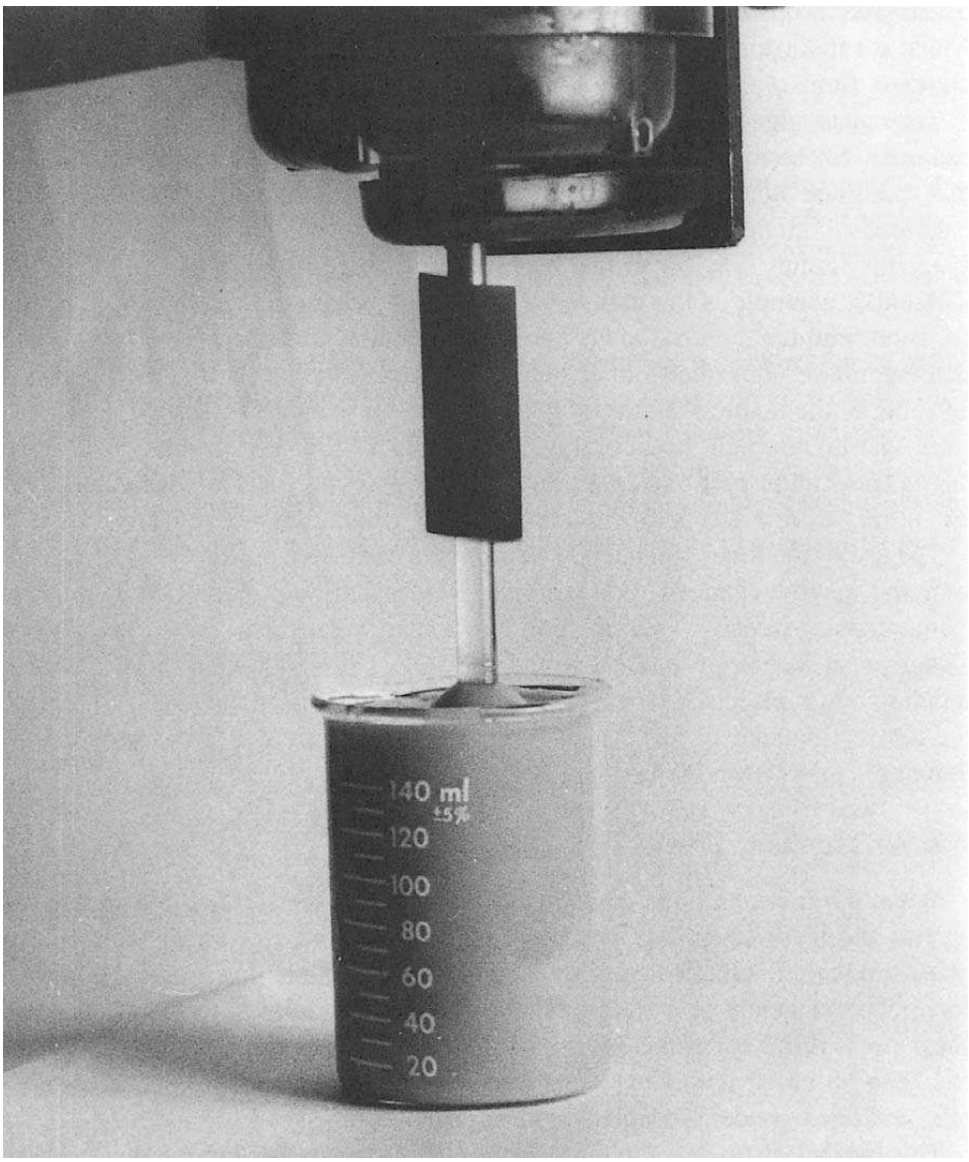


Figure 3.26 The Weissenberg effect: the rotation of the glass rod causes the aged sweetened condensed milk to climb up the rod because of the normal force that is generated by the rotation. Many doughs also exhibit this phenomenon.

Viscoelasticity

The word 'viscoelastic' means that the material simultaneously exhibits some of the elastic properties of an ideal solid and some of the flow properties of an ideal liquid. Some authors reserve the word 'viscoelastic' for materials that are more solid-like than liquid-like and use the term 'elastico-viscous' for materials that are more liquid-like than solid-like. A single word 'viscoelastic' will be used here.

Figure 3.27 shows schematically the differences between an ideal elastic solid, which is called a Hookean solid after Robert Hooke (1660) who first described elastic deformation, an ideal liquid which is called Newtonian liquid after Isaac Newton (1687) who first described the flow of simple liquids, and

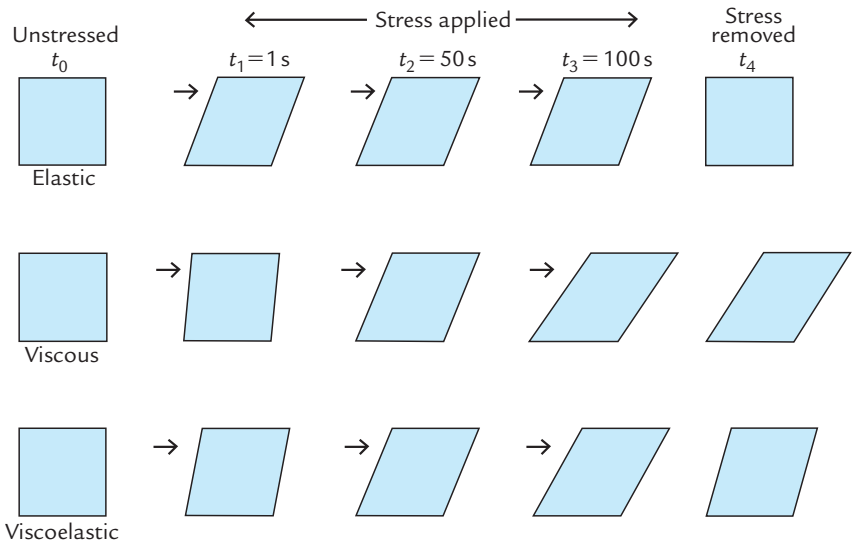


Figure 3.27 Schematic representation of response of elastic, viscous and viscoelastic bodies to the application and removal of a stress.

a viscoelastic material which combines some of the properties of both. Suppose a uniform block of each of these three materials has a constant stress applied for three time periods and then the stress is removed.

(1) Elastic solid (top line). There is an instantaneous deformation when the deforming force is applied and no further deformation with time. There is complete recovery of the original shape when the force is removed.
(2) Newtonian liquid (middle line). The material begins to flow as soon as the deforming force is applied and it continues to flow as long as the force is being applied. There is no recovery of shape when the force is removed.
(3) Viscoelastic solid (bottom line). There is an instantaneous deformation when the deforming force is first applied, and then the material continues to deform so long as the force is pressing against it. When the force is removed there is some recovery of the original shape (elastic component) but not a full recovery (viscous component).

It can be seen from this figure that the time scale over which the force is applied can seem to affect the relative proportions of elastic deformation and viscous flow. Over a short period of time (t_1) a viscoelastic material will appear to be mostly elastic whereas over a long period of time (t_3) it will seem to be mostly viscous. This demonstrates an important principle in testing of viscoelastic materials: the material will appear to be mostly elastic in nature in an experiment that is performed quickly but in an experiment that is performed slowly it will appear to be more viscous. Since the human testing of foods (squeezing in the hand, chewing with the teeth, manipulating with the tongue) is usually of short duration, many foods that are actually quite viscoelastic will appear to be elastic or close to elastic in sensory tests.

Dr Marcus Reiner, a prominent founder of the science of rheology pointed out that, given enough time, everything will flow and cited one example from

the Old Testament (Reiner, 1964). Soon after the Children of Israel arrived in their promised land they won a great battle against the Canaanites under the leadership of the prophetess Deborah. After the victory, Deborah sang praises to God and said: 'The mountains melted before the Lord' (Judges 5:5, King James translation). Dr Reiner pointed out that the Hebrew word translated as 'melted' should really be translated as 'flowed.' During the observation time of a human, the mountains appear to be rock solid, but given God's infinite observation time the mountains can be seen to flow. In other words, everything flows if you observe it for a long enough time. Reiner proposed the following equation to describe this effect:

$$D = \frac{\tau}{T}$$

where D is the Deborah number, τ is the characteristic relaxation time of the material, and T is the time over which the deformation is observed. The relaxation time τ for a perfectly Hookean elastic solid is infinity and for a perfectly Newtonian liquid it is zero (Reiner, 1964). A high Deborah number corresponds to solid-like materials and a low Deborah number to liquid-like materials. As stated above, since T is small for most human–food interactions, the Deborah number will be high, and some foods will appear to the more solid-like in sensory tests than a slow-measuring rheometer would indicate.

Viscoelastic behavior can be divided into two general types.

Type 1: Linear viscoelastic in which the rheological properties are dependent on time alone, and not on the magnitude or rate of application of the stress. Most foods show linear viscoelasticity up to small strains of a few percent. Table 3.2, page 64 lists the range of linear viscoelastic strain for several foods.

Type 2: Nonlinear viscoelastic where the mechanical properties are a function of the time the stress is applied, the magnitude of the stress, and often the rate at which the stress is applied. The study of nonlinear viscoelasticity is experimentally and theoretically much more difficult than linear viscoelasticity and yet this is the range in which most foods are compressed or sheared in the mouth.

Small Amplitude Oscillatory Testing (SAOT)

The viscous and elastic components of viscoelastic fluids can be measured by SAOT. The test material is usually placed between a cone and plate or parallel plates mounted in a controlled stress rheometer and the cone or plate is made to oscillate about a central point with a sinusoidal angular velocity at low amplitude while the shear stress is measured. This is a nondestructive test when the amplitude is small. For an elastic solid the shear stress will be in phase with the strain but for a Newtonian fluid the shear stress is 90° out of

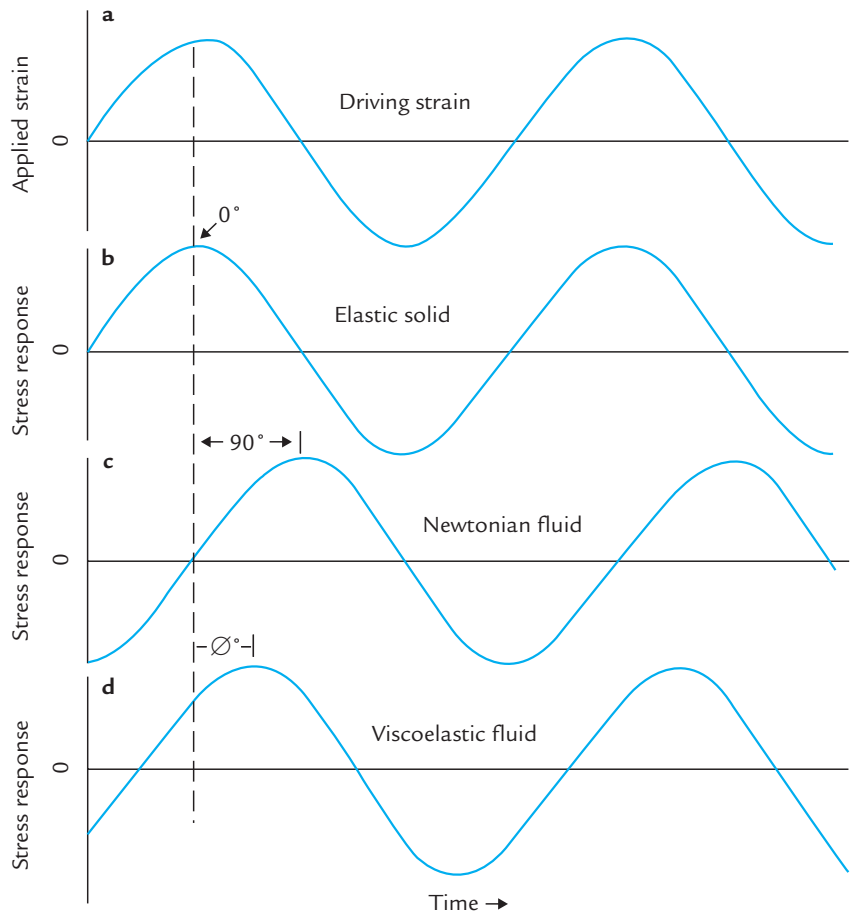


Figure 3.28 The principle of oscillation viscometry. Applied strain versus time (a) and resultant stress versus time that is measured in an elastic solid (b), Newtonian liquid (c) and viscoelastic liquid (d). (Reprinted from Bourne and Rao, 1990. Page 221 in Instrumental Methods for Quality Assurance in Foods, eds Fung and Mathews. By courtesy of Marcel Dekker Inc.)

phase with the strain. For a viscoelastic fluid the shear stress lags behind the strain by an angle of difference Ø that lies between 0° and 90° (see Fig. 3.28). The out of phase angle Ø is measured. The experimental shear stress–time curve can be broken down into two components.

(1) The stress component in phase with the shear strain is defined as the storage (or elastic) modulus G'(G prime). It is the ratio of the stress in phase with the strain to the strain. $G' = \sigma'/\gamma$ where σ' = shear stress in phase and γ = strain.
(2) The stress component 90° out of phase with the shear strain is defined as the loss (or viscous) modulus G'' (G double prime). It is the ratio of the shear stress out of phase with the strain to the strain. $G'' = \sigma''/\gamma$ where σ'' = shear stress 90° out of phase.

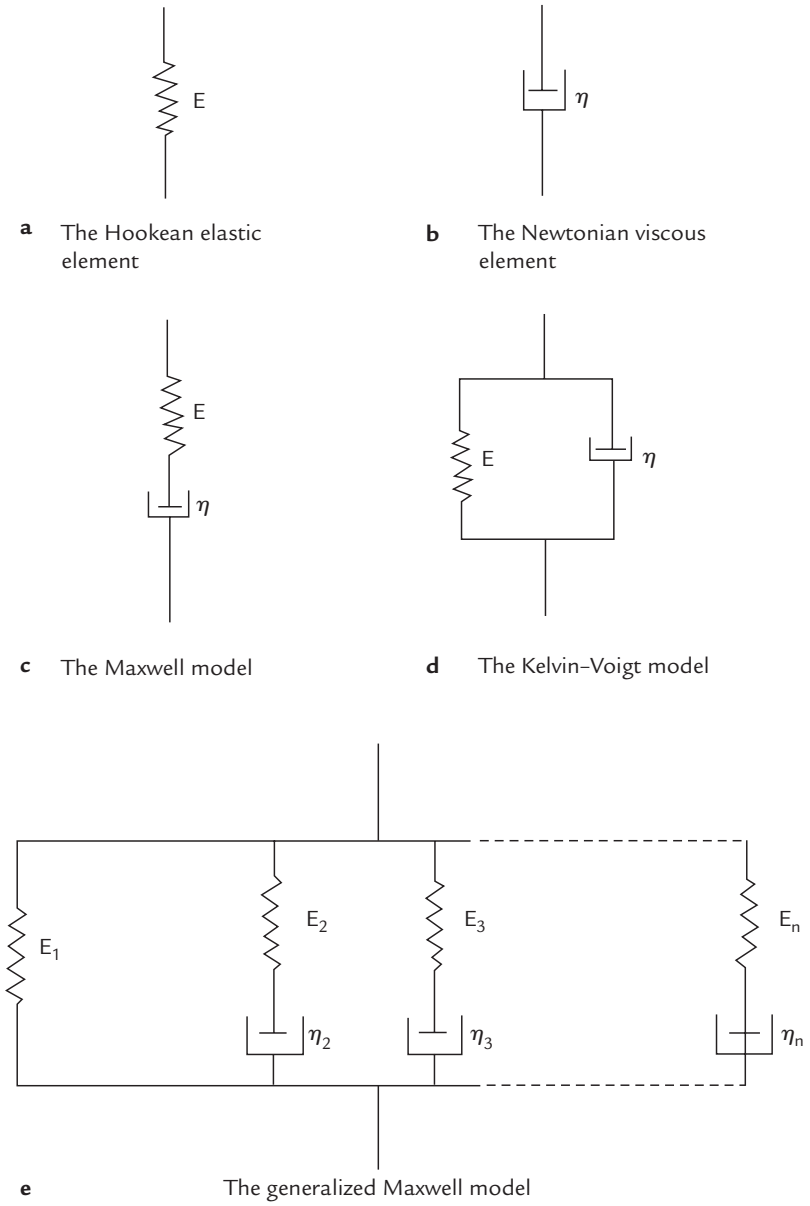
These functions are related by the equation:

$$G''/G' = \text{loss factor} = \tan Ø = \text{loss tangent}$$

It should be emphasized that small amplitude oscillatory testing must use an amplitude that stays within the linear viscoelastic regime.

Mechanical Models

Mechanical models or analogs have been developed to help give a mental picture of the different patterns of viscoelasticity. Figure 3.29a depicts an elastic solid as a spring and Fig. 3.29b a Newtonian fluid as a piston moving in a dashpot of fluid. A spring and a dashpot arranged in series (Fig. 3.29c) is called a Maxwell element and when arranged in parallel a Kelvin–Voigt element (Fig. 3.29d). Many other models using various combinations of springs, dashpots, Maxwell and Kelvin–Voigt models have been proposed for different foods. Figure 3.29e shows one example of a spring linked in parallel with several springs and dashpots in series. Numerical values for different components



a The Hookean elastic element

b The Newtonian viscous element

c The Maxwell model

d The Kelvin–Voigt model

e The generalized Maxwell model

Figure 3.29 Some fundamental elements and models in viscoelasticity. (Reprinted from Finney 1973, pages 49, 50 in Texture Measurements of Food, eds A. Kramer and A. S. Szczesniak with kind permission of Kluwer Academic Publishers.)

for each model can be derived by suitable analysis of stress–strain curves. A third element known as the St Venant slider is included in some of these models to include the concept of a limiting frictional force. There is no deformation when the stress is less than the limiting frictional force, but above this threshold it offers no resistance and slides easily. Drake (1971) proposed another element 'traction failure' represented by two parallel surfaces in close proximity that move apart when the material fractures. The reader is referred to the references at the end of the chapter for more detailed discussion of mechanical models.

Van Wazer *et al*. (1963) point out that electrical circuits can be used just as effectively as mechanical models to represent elastic, viscous, and viscoelastic materials. Electrical models have been used much less frequently than mechanical models in the rheological literature, probably because most people can visualize the action of springs and dashpots more readily than electrical circuits.

Fracture

Engineers design structures ranging from a pencil to a miles-long bridge with the intent that the structure will not fail or fracture under normal conditions of use. The failure of engineering materials of construction is almost always an undesirable event because of the resulting economic losses, interruption of services or availability of products, and, in some cases because human lives are put in jeopardy.

In contrast, food scientists want to design structures that will fail under the limited forces available in the hand and mouth. It can be said that engineers are interested in the strength of materials whereas food scientists are interested in the weakness of materials. Therefore, both engineers and food scientists are interested in fracturing of materials, the former to design a structure that will not fracture and the latter to build a structure that will be certain to fracture.

There are several types of fracture.

Type 1. Simple fracture is the separation of a body into two or more pieces in response to an imposed stress. In most cases the body breaks into two or more pieces but sometimes the fracture may be partial when the fracture plane does completely cross the specimen.

Type 2. Brittle fracture in which there is little or no plastic deformation before fracture and a low energy absorption up to fracture. Nuts and good quality potato chips are a good example of brittle fracture.

Type 3. Ductile fracture in which there is substantial plastic deformation with high energy absorption before fracture. Meat is an example of ductile fracture. It must be noted that there is a continuous gradient from brittle to ductile fracture.

Every fracture process involves three steps: (1) crack initiation; (2) crack propagation; and (3) final failure.

In brittle fracture the cracks spread very rapidly and catastrophically. Once the crack is initiated, propagation continues spontaneously without any increase in the magnitude of applied stress. These are called unstable cracks.

In ductile fracture the process proceeds relatively slowly after initiation. The extensive plastic deformation that accompanies propagation requires additional work so there is no further extension of the crack unless there is an increase in the applied stress. There is usually gross deformation at the fracture surface. These are called stable cracks.

Stress Concentration

Microscopic flaws or cracks usually exist at the surface and within a food. The applied stress may be concentrated at the tip of these cracks which magnifies the stress at that point. These flaws are called 'stress raisers' because of their ability to amplify the stress at the crack. The presence of stress raisers lowers the force required to initiate fracture. Fujii *et al*. (2000) demonstrated the effects of stress concentration by including glass beads in gelatin gels. Increasing the glass bead content and/or increasing the diameter of the glass beads caused a substantial reduction of the rupture force in gelatin gels. Stress raisers have a greater effect in brittle materials than in ductile materials because the plastic deformation leads to a more uniform distribution of stress near the stress raiser.

The three modes of crack growth are shown in Fig. 3.30: (1) the tensile mode, i.e. the manner in which a food is torn apart by two hands; (2) sliding mode, and (3) tearing mode. The sliding and tearing modes are probably the ones that occur in the mouth during mastication.

It should be noted that the failure mode of many foods may be changed from a brittle to a ductile fracture or vice versa. Changing the temperature or moisture content can move the food from a glassy state to a rubbery state by moving it through the glass transition temperature range. Fresh fruits and vegetables that have high turgor undergo brittle fracture, but wilting, dehydration or cooking changes them into ductile materials.

Vincent *et al*. (1991) developed a wedge penetration technique to measure fracture properties of brittle and semibrittle foods such as moderately hard cheeses and fruits and vegetables. They state that the energy or work of fracture

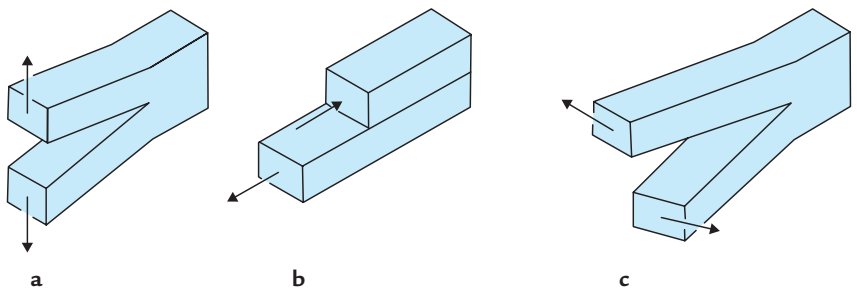


Figure 3.30 Three models of crack surface displacement. (a) Mode 1, opening or tensile mode; (b) mode 2, sliding mode; (c) mode 3, tearing mode. (Reprinted from Callister, Materials Science and Engineering 4th Edition, page 189. Copyright 1997, this material is used by permission of John Wiley and Sons, Inc.)

R can be calculated from the following equation:

$$R = 0.75\ (Eu^2H^3)/a^4(1 + 0.64H/a)^4$$

where E is Young's modulus of the material, u is the distance between the two ears of the sample where the wedge is forcing them apart, H is the half-width of the sample, and a is the length of one of the ears (see Fig. 3.31). Luyten *et al*. (1992) provide a useful review of fracture phenomena in food. They conclude that tension and bending tests give more information than compression experiments even though they are more difficult to perform.

The processes of crushing and grinding rely on fracture to reduce particle size. Rittinger's law states that the work required to grind a product is proportional to the new surface area formed.

Guritno and Hague (1994) reviewed theories of size reduction and concluded that they all are special cases of the general mathematical statement.

$$dE = -K\frac{dx}{X^n}$$

where dE is the energy required to produce a change, dx is the size of a unit mass of material, X is the characteristic dimension, and K and n are constants dependent on the grinding machine and the material. This relationship was developed for grinding minerals which are nonbiological materials. It is not known whether it is applicable to food materials.

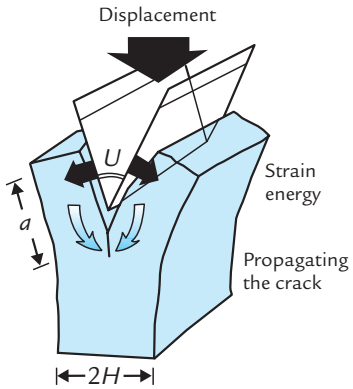


Figure 3.31 The F-wedge test, showing the structure of the wedge and the deformation of, and the transmission of strain energy through, the test piece. (From Vincent *et al*., 1991. Reprinted from *J. Texture Studies* **22**, page 47, 1991. Copyright by Food and Nutrition Press Inc.)

Isotropy and Anisotropy

The words 'isotropy' (noun) or 'isotropic' (adjective) mean that the material displays the same properties with the same values when measured along axes in different directions.

The words 'anisotropy' (noun) or 'anisotropic' (adjective) mean that the material displays different properties and/or different values of properties when measured along axes in different directions.

Some foods are isotropic whereas other foods are anisotropic. For isotropic foods it does not matter in which direction it is tested, but for anisotropic foods it is essential always to test the food from the same direction.

For example, Gonzalez *et al*. (2000) found that the maximum force required to cut cooked lasagna with a standard TA-47 blade mounted in a TA.XT2 Texture Analyzer was higher when the blade was oriented perpendicular to the direction of pasta extrusion during its manufacture than when it was oriented parallel to the direction of extrusion. Therefore, they always set the blade to cut perpendicular to the extrusion direction to ensure consistent results. Abbott and Lu (1996) found that apple flesh was anisotropic and that mechanical properties measured in compression were significantly influenced by specimen orientation, latitude between the stem and calyx, and depth from skin to core. Khan and Vincent (1993) showed that cylinders of apple flesh

compressed in a radial direction fracture by collapse of a single layer of cells at right angles to the force whereas the same size cylinders compressed in a tangential direction fail in shear. The apple compressed in the radial direction shows a higher modulus of deformability and lower strain to fracture than when compressed in a tangential direction. Khan and Vincent also showed that potato flesh is isotropic and the compressive properties are the same no matter in which direction it is tested.

Units of Measurement

Scientists and engineers have established a common worldwide standard system of units to replace the wide range of measuring units that have been used over the years. This system, called the Système International d'Unités (International System of Units) with the abbreviation SI, was adopted at an international conference in 1960. The SI is basically the metric system extended to give a uniform and rational set of units for all types of measurements. Of particular interest to texture technologists is that SI uses the newton as the standard unit of force replacing units of mass (e.g. the pound or kilogram) in expressing force. It is incorrect to use mass to express units of force because force has the dimensions mass $\times$ length $\times$ (time)$^{-2}$. Changing to SI eliminates the disparity of using mass as a measure of force, and it also eliminates using the gravitational constant g to convert mass into force units. One newton force equals the force generated by gravity on 101.9716 g.

The SI system includes three classes of units: (1) base units, (2) supplementary units, and (3) derived units.

Table 3.13 SI Base Units

Quantity	Name	Symbol	Definition
Length	meter	m	The meter is the length of the path travelled by light in a vacuum during a time interval of 1/299,792,458 of a second.
Mass	kilogram	kg	The mass equal to the mass of the international prototype of the kilogram.
Time	second	s	The duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.
Thermodynamic temperature	kelvin	K	The fraction of 1/273.16 of the thermodynamic temperature of the triple point of water.
Amount of substance	mole	mol	The amount of substance of a system that contains as many elementary entities as there are atoms in 0.012 kg of carbon-12.
Electric current	ampere	A	That constant electric current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 m apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} N m^{-1} of length.
Luminous intensity	candela	cd	The candela is the luminous intensity in a given direction of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

The base units and their definition are shown in Table 3.13. Supplementary units are defined angles and are of little interest in texture work. Derived units are expressed algebraically in terms of base units and/or supplementary units (Table 3.14). The prefixes that are used to form decimal multiples and sub-multiples of SI units are given in Table 3.15. The choice of the appropriate multiples of an SI unit is governed by convenience, the multiple chosen for a particular application being the one which will lead to numerical values in a

Table 3.14 SI Derived Units

Quantity	Name of SI unit	Symbol	Dimensions	Commonly used multiple	Conversion factor
Area	square meter	m^2	m^2	—	$1\ m^2 = 10.76391\ ft^2$
Volume	cubic meter	m^3	m^3	—	$1\ m^3 = 1000$ liters 1 liter = $1\ dm^3$ (cubic decimeter)
Frequency	hertz	Hz	s^{-1}	—	—
Force	newton	N	$m\ kg\ s^{-2}$	—	1 N = 101.9716 grams force
Pressure, stress	pascal (or newton per m^2)	Pa	$N\ m^{-2}$ or $m^{-1}kg\ s^{-2}$	—	$1\ bar = 10^5$ Pa
Dynamic viscosity	pascal second	Pa·s	$N\ S\ m^{-2}$ or $m^{-1}kg\ s^{-1}$	m Pa·s	1 centipoise = 1 mPa·s
Kinematic viscosity	square meter per second	$m^2\ s^{-1}$	$m^2\ s^{-1}$	$mm^2\ s^{-1}$	1 centistoke = $1\ mm^2\ s^{-1}$
Work, energy, heat	joule	J	N m or $m^2kg\ s^{-2}$	—	—
Power	watt	W	$m^2kg\ s^{-3}$	—	1 W = 1 J/s

Table 3.15 SI Multiplying Factors

Factor	Prefix	
	Name	Symbol
10^{12}	tera	T
10^9	giga	G
10^6	mega	M
10^3	kilo	k
10^2	hecto	h
10^1	deca	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

Table 3.16 Units Rendered Obsolete by SI

Name	Symbol	Conversion to SI units
erg	erg	1 erg = 10^{-7} J
dyne	dyn	1 dyn = 10^{-5} N
poise	P	1 P = 0.1 Pa·s 1 centipoise = 1 mPa·s
stoke	St	1 St = 10^{-4} $m^2 s^{-1}$ 1 centipoise = 1 $mm^2 s^{-1}$
kilogram force	kgf	1 kgf = 9.80665 N
pounds force	lbf	1 lbf = 4.4482 N
calorie	cal	1 cal = 4.1868 J

practical range. The multiple is usually chosen so that the numerical value will be between 0.1 and 1000.

Working in SI units renders obsolete many of the old units of measurement. Some of these are listed in Table 3.16. Since these units have been in use for many years the researcher will often find them when reading the literature. These obsolete units should no longer be used in present work. However, two obsolete units are still being used by some researchers with some justification: (1) 1.000 centipoise viscosity equals 1.000 millipascal second; (2) 1.000 centistoke kinematic viscosity equals 1.000 square millimeter reciprocal second.

Suggestions for Further Reading

Barnes, H. A., J. F. Hutton, and K. Walters. 1989. "Introduction to Rheology." Elsevier Science Publishers, Amsterdam.

Ferry, J. D. 1980. "Viscoelastic Properties of Polymers." John Wiley, Chichester.

Lewis, M. J. 1996. "Physical Properties of Foods and Food Processing Systems." Woodhead Publishing, Cambridge.

Mohsenin, N. N. 1986. "Physical Properties of Plant and Animal Materials", 2nd edition. Gordon and Breach, New York.

Peleg, M. and E. B. Bagley, (eds.) 1983. "Physical Properties of Foods." Avi, Westport.

Prentice, J. H. 1984. "Measurements in the Rheology of Foodstuffs." Elsevier Applied Science, London.

Rao, M. A. and S. S. H. Rizvi. 1986. "Engineering Properties of Foods." Marcel Dekker, New York.

Rao, M. A. and J. F. Steffe, (eds.) 1992. "Viscoelastic Properties of Foods." Elsevier Applied Science, London.

Sherman, P. 1970. "Industrial Rheology." Academic Press, London.

Steffe, J. F. 1992. "Rheological Methods in Food Process Engineering." Freeman Press, East Lansing, Michigan.

Van Wazer, J. R., J. W. Lyons, K. Y. Kim, and R. E. Colwell. 1963. "Viscosity and Flow Measurement. A Laboratory Handbook of Rheology." Wiley (Interscience), New York.

CHAPTER 4

Principles of Objective Texture Measurement

Introduction

There is such a wide range in types of foods and the types of textural and rheological properties that they exhibit, and such a wide variety of methods used to measure these properties, that it becomes necessary to attempt to classify them into groups in order to understand the system. Several classification systems have been propounded.

It is possible to classify texture measurements according to the commodity that is being tested; for example, tests that are used for cereals, meat, fish, poultry, vegetables, fruit, dairy products, fats, confectionery, beverages, legumes, emulsions, suspensions and oilseeds, and miscellaneous foods.

Matz (1962) classified foods on the basis of their textural properties into liquids, gels, fibrous foods, agglomerates of turgid cells, unctuous foods, friable structures, glassy foods, agglomerates of gas-filled vesicles, and combinations of these. Sone (1972) classified foods on the basis of their textural properties as liquid foods, gel-like foods, fibriform foods, cellular-form foods, edible oils and fats, and powdered foods.

The classification of texture measurements on the basis of commodity or the type of textural properties is useful but what is probably a better type of classification is based on the type of test that is used, because many tests are applicable to more than one type of food. When food is placed in the mouth, the structure is destroyed by the act of mastication until it is ready to be swallowed. The basic process of mastication occurs regardless of what kind of food is in the mouth. Therefore, it seems logical to concentrate on the type of test rather than the nature of the food.

Drake (1961) developed a classification system based on the geometry of the apparatus as follows: (1) rectilinear motion (parallel, divergent, convergent); (2) circular motion (rotation, torsion); (3) axially symmetric motion

Table 4.1 Types of Tests for Measuring Food Texture

Objective		Sensory	
Direct	**Indirect**	**Oral**	**Nonoral**
Fundamental	Optical	Mechanical	Fingers
Empirical	Chemical	Geometrical	Hand
Imitative	Acoustical	Chemical	Eyes
	Other		Other

(unlimited, limited); (4) defined other motions (bending, transversal); and (5) undefined motions (mechanical treatment, muscular treatment).

Table 4.1 lists the type of tests that are used for measuring food texture. These may be divided into objective tests that are performed by instruments and sensory tests that are performed by people. Objective tests can be divided into direct tests that measure real textural properties of materials, and indirect tests that measure physical properties that correlate well with one or more textural properties. Sensory tests can be classified into oral (those tests that are performed in the mouth) and nonoral (in which some part of the body other than the mouth is used to measure the textural properties). Sensory tests will be discussed in Chapter 7.

Fundamental Tests

These tests measure well-defined rheological properties. Before attempting to use this class of test on foods, it should be borne in mind that they were developed by scientists and engineers interested in the theory and practice of materials of construction, and they may not be very useful in measuring what is sensed in the mouth when food is masticated. The outlook of the materials scientist and the food technologist are opposite. One wants to measure the strength of materials in order to design a structure that will withstand the forces applied to it under normal use without breaking. The other wants to measure the strength of food, and frequently weakens its structure deliberately so that it will break down into a fine state suitable for swallowing when subjected to the limited crushing forces of the teeth, imparting pleasurable sensations during the process of comminution.

For example, intact cereal grains are so hard that most people find it unpleasant to chew them. Much of the cereal processing is designed to convert a very hard cereal grain into another form that is easier to chew, e.g. wheat into bread and maize into tortillas (see Table 1.5, page 10).

When a test piece is broken into two pieces materials scientists normally stop the test because they have all the information they need about the material. In contrast, food technologists consider that a test has barely begun when a food is broken into two pieces, and they continue the test in order to break it

down into progressively smaller pieces. Hence, food texture measurement might be considered more as a study of the *weakness* of materials rather than strength of materials.

Fundamental tests generally assume (1) small strains (1–3% maximum); (2) the material is continuous, isotropic (exhibiting the same physical properties in every direction), and homogeneous; and (3) the test piece is of uniform and regular shape. Most textural tests made on foods fail to comply with one or more of the three assumptions listed above.

Fundamental tests are generally slow to perform, do not correlate as well with sensory evaulation as do empirical tests, and use expensive equipment. They are not used to any great extent in the food industry but they do have a place in some research laboratories. Szczesniak (1963b) aptly described the usefulness of fundamental tests as follows:

> Since most foodstuffs do not have simple rheological properties that are independent of stress and strain conditions, and since rheological properties once measured and defined are not meaningful in a practical sense unless related to functional properties, fundamental tests serve the greatest value to the food technologist by providing bases for the development of more meaningful empirical tests.

Table 4.2 shows the results obtained with apples and peaches by a fundamental test and an empirical test as compared with sensory evaluation of firmness. The stiffness coefficient, which is essentially an index of Young's modulus of elasticity and is a fundamental test (see page 68), gives consistently lower correlations with sensory measurements than does the Magness–Taylor test, which is an empirical type of measurement. In view of the fact that the Magness–Taylor pressure tester costs about $100 and one test can be performed in about 30 s whereas the acoustic spectrometer that is used to measure the stiffness coefficient costs over $30,000 and requires about 15 min to make a test, it can be seen why the food industry generally uses empirical tests.

Table 4.2 Correlation Coefficient between Sensory and Instrumental Firmness Measurements

	Fundamental stiffness coefficient[a] (f^2m)	Empirical Magness–Taylor[b]
Red delicious apples		
October 1968	0.84	0.92
March 1969	Not significant	0.71
October 1969	0.68	0.89
March 1970	0.44	0.86
Elberta peaches	0.87[c]	0.957

Source: Data from Finney (1971a) and Finney and Abbott (1972).
[a]Sonic resonance test, a fundamental test.
[b]Puncture test, an empirical test.
[c]Highest value from 22 experiments.

Muller (1969b) surveyed the types of food texture measurements that are used in the United Kingdom and concluded that of the rheological tests used, 'it is striking that with a few exceptions the methods employed are empirical. This might support the jest that theoretically sound instruments do not work in practice and those that are theoretically unsound do.'

Empirical Tests

These tests measure parameters that are poorly defined, but from practical experience are found to be related to textural quality. This is the most widely used class of instruments in the food industry. The tests are usually easy to perform, rapid, and frequently use inexpensive equipment. Problems with this type of test are the poor definition of what is being measured, the arbitrariness of the test, frequently no absolute standard is available, and the tests are usually only effective with a limited number of commodities. Since empirical tests are frequently successful in measuring textural properties of foods and are the most widely used in the food industry, this book will deal with them extensively. It is the author's opinion that these tests should be studied in order to understand the reasons for their successes and the principles on which they operate in order to find how to make them more effective and to make them scientifically more rigorous.

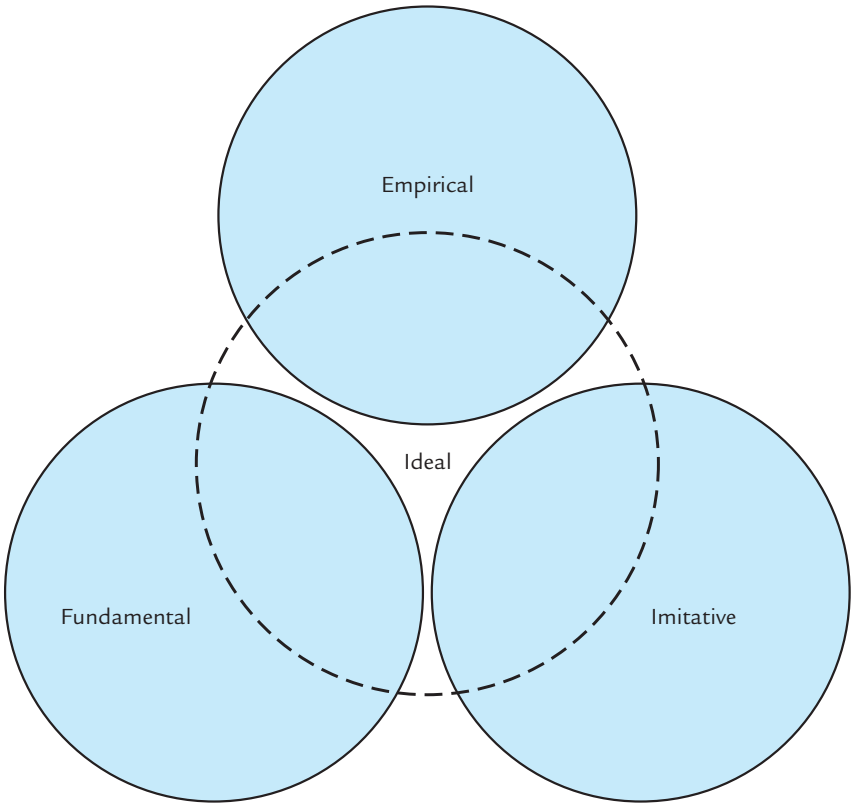


Figure 4.1 Schematic representation of the ideal texture measuring apparatus and its derivation from empirical, fundamental, and imitative instruments. (From Bourne, 1975b; reprinted with permission from D. Reidel Publ. Co.)

Imitative Tests

These tests imitate the conditions to which the food material is subjected in practice. This class may be considered as a subtype of empirical test because the tests are not fundamental tests. Examples of this kind of test are the Farinograph and other dough-testing apparatus that imitate the handling and working of bread dough, the Bostwick Consistometer and Adams Consistometer that measure the flow of semifluid foods across the plate, and butter spreaders.

Figure 4.1 shows schematically the relationships among empirical, fundamental, and imitative tests, and Table 4.3 lists the advantages and disadvantages of each type. The ideal texture measuring apparatus should combine the best features of the fundamental, empirical, and imitative methods and eliminate the undesirable features of each of these. At the present time there is no ideal texture measuring equipment or system. Empirical methods are used almost entirely. The future direction of the research should be to move from the empirical

Table 4.3 Comparison of Different Systems of Objective Texture Measurement of Food

System	Advantages	Disadvantages
Empirical	Simple to perform	No fundamental understanding of the test
	Rapid	Incomplete specification of texture
	Suitable for routine quality control	Arbitrary procedure
	Good correlation with sensory methods	Cannot convert data to another system
	Large samples give averaging effect	Usually 'one point' measurement
		Calibration difficult
Imitative	Closely duplicates mastication or other sensory methods	Unknown physical equivalent measurement
	Good correlation with sensory methods	Arbitrary procedure
	Complete texture measurement	Restricted to 'bite-size' units
Fundamental	Know exactly what is measured	Poor correlation with sensory methods
	Good calibration	Incomplete specification of texture
		Slow
Ideal	Simple to perform	None
	Rapid	
	Suitable for routine work	
	Good correlation with sensory	
	Closely duplicates mastication	
	Complete texture measurement	
	Good calibration	
	Know exactly what is measured	
	Can use large or small size samples	

Source: Adapted from Bourne, 1975c; reprinted with permission of D. Reidel Publ. Co.

into the ideal by including more of the fundamental and imitative aspects in empirical tests. The ideal texture measuring technique will probably be some combination of the present empirical, fundamental, and imitative methods.

Another method of classification of food texture instruments is on the basis of the variable or variables that are measured in the test. Table 4.4 gives such a classification and is the system that will be used throughout this book to discuss and classify the principles of objective measurements of food texture. The system classifies according to the principle of the test, not according to the kind of food. It rests on the assumption that since all foods are ground into a fine state during mastication, there must be many common elements in their textural properties that are not restricted to any one commodity group. The principles of the tests will be discussed in this chapter. Chapter 5 discusses commercially available instruments and their operation and Appendix I lists the names and addresses of the suppliers of the most frequently used instruments for food texture and viscosity.

Table 4.4 Objective Methods for Measuring Food Texture

Method	Measured variable	Dimensional units	Examples
1. Force	Force (F)	mlt^{-2}	
a. Puncture	F	mlt^{-2}	Magness–Taylor, Effi-Gi
b. Extrusion	F	mlt^{-2}	Shear press, Tenderometer
c. Cutting–Shear	F	mlt^{-2}	Warner–Bratzler Shear
d. Crushing	F	mlt^{-2}	—
e. Tensile	F	mlt^{-2}	—
f. Torque	F	mlt^{-2}	Rotary Viscometers
g. Snapping	F	mlt^{-2}	Brabender Struct-o-Graph
h. Deformation	F	mlt^{-2}	
2. Distance			
	a. Length	l	Penetrometers, Deformation
	b. Area	l^2	Grawemeyer Consistometer
	c. Volume	l^3	Bread volume, Juice volume
3. Time	Time (T)	t	Ostwald Viscometer
4. Energy	Work ($F \times D$)	ml^2t^{-2}	—
5. Ratio	F or D or T measured twice	Dimensionless	Specific gravity
6. Multiple	F and D and T	mlt^{-2}, l, t	Instron, TA.XT2
7. Multiple variable	Anything	Unclear	Durometer
8. Chemical analysis	Concentration	Dimensionless (%)	Alcohol insoluble solids
9. Miscellaneous	Anything	Anything	Optical density, crushing sounds

Source: Adapted from Bourne (1966a); reprinted from *J. Food Sci.* **31**, 1114, 1966. Copyright by Institute of Food Technologists.

Force Measuring Instruments

Force measuring instruments are the most common of the texture measuring instruments. Force has the dimensions mass × length × time^{-2}. The standard unit of force is the newton (N). Because of their multiplicity, this heading is broken into the subclassifications (a) puncture, (b) compression–extrusion, (c) cutting–shear, (d) compression, (e) tensile, (f) torsion, (g) bending and snapping, and (h) deformation.

Puncture Test

The puncture test measures the force required to push a punch or probe into a food. The test is characterized by (a) a force measuring instrument, (b) penetration of the probe into the food causing irreversible crushing or flowing of the food, and (c) the depth of penetration is usually held constant.

Puncture testers embody one of the simplest types of texture measuring instruments and one of the most widely used. The first food puncture tester was probably the one developed by Lipowitz (1861), who placed a flat disk 1 or 2 in. (2.5 to 5 cm) in diam on the surface of a gelatin jelly in a beaker (Fig. 4.2). The flat disk was connected to a funnel by means of a vertical iron rod, and lead shot was slowly poured into the funnel until there was just sufficient weight to make the disk penetrate into the jelly. The total weight of the shot, funnel, rod, and disk was used as a measure of jelly consistency. This early test, although primitive, contains the essential elements of the puncture test: namely, a punch that penetrates into the food, application of an increasing force (lead shot), and measurement of the yield point force (by scales not shown in figure). This apparatus evolved into the well-known Bloom Gelometer.

The second food puncture tester was probably the one developed by Carpi (1884), who measured the weight required to force a 2-mm-diam iron rod 1-cm deep into hardened oils. Brulle (1893) used a similar principle for measuring the hardness of butter, and Sohn (1893) spelled out the procedure necessary to obtain reproducible results with the Brulle instrument. This developed into the Van Doorn butter tester. The first puncture tester for horticultural products was developed by Professor Morris in the state of Washington (Morris, 1925). This evolved into the well-known Magness–Taylor, Chatillon, and EFFI-GI fruit pressure testers. Tressler *et al*. (1932) performed a puncture test on meat, which evolved into the Armour Tenderometer (Hansen, 1971, 1972).

Puncture testing instruments are all **maximum-force** instruments. They may be classed into **single-probe** instruments, such as the Magness–Taylor, EFFI-GI, Chatillon, and the Bloom Gelometer, and the **multiple-probe** instruments such as the Armour Tenderometer, the Christel Texture Meter, and the Maturometer.

Puncture testing instruments might also be classified by the manner in which the force is applied. A constant rate of application of force is used for

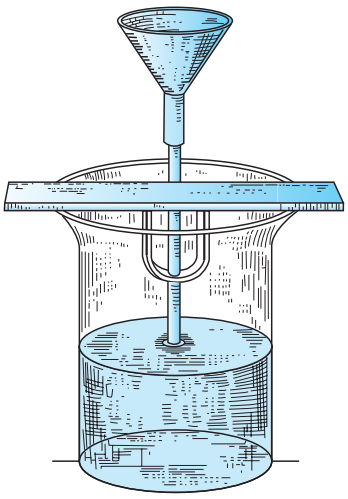


Figure 4.2 The Lipowitz Jelly Tester. (From Lipowitz, 1861.)

some of these instruments (e.g., Magness–Taylor and other fruit pressure testers, the Armour Tenderometer, and the Bloom Gelometer). Motorized testing instruments use a constant rate of travel of the probe, including universal testing machines such as the Instron and TA.XT2 Texture Analyzer.

Theory of the Puncture Test

When a punch is mounted in an instrument that automatically draws out a force–distance or force–time curve (such as the Instron or TA.XT2), five basic types of curves are obtained, as shown schematically in Fig. 4.3. In types A, B, and C there is an initial rapid rise in force over a short distance of movement as the pressure tip moves onto the commodity. During this stage the commodity is deforming under the load; there is no puncturing of the tissues. This stage ends abruptly when the punch begins to penetrate into the food, which event is represented by the sudden change in slope called the *yield point*, or sometimes *'bio-yield point.'* The initial deformation stage is not of great concern in puncture testing.

The yield point marks the instant when the punch begins to penetrate into the food, causing irreversible crushing or flow of the underlying tissues and is the point of greatest interest in puncture testing. Mohsenin *et al*. (1963) showed that this is the point where crushing and bruising begins on fruits such as apples. Considerable work has been done on the implications of the yield point and this will be discussed below.

The third phase of the puncture test, namely, the direction of the force change after the yield point and during penetration of the punch into the food,

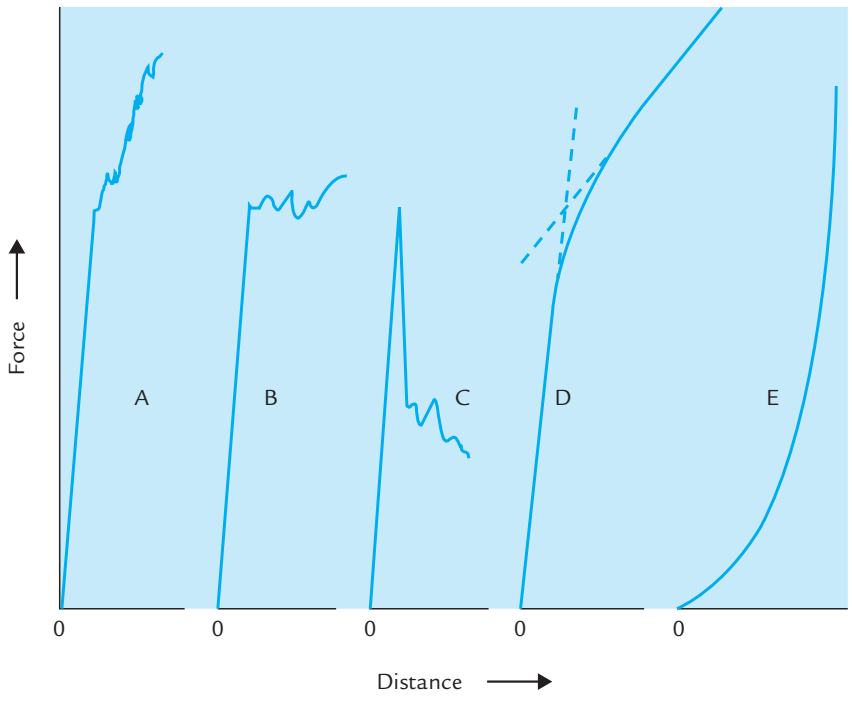


Figure 4.3 Schematic representation of the five different types of force–distance curves that are obtained in puncture tests. (From Bourne, 1979b; copyright Academic Press Inc. (London) Ltd, with permission.)

separates the puncture curves into three basic types: A, the force continues to increase after the yield point; B, the force is approximately constant after the yield point; C, the force decreases after the yield point. There is a continuous change in slope, from positive slope in type A curves to approximately zero slope in type B curves to negative slope in type C curves. Type A curves merge into type B curves, depending on the steepness of the slope of the force–distance curve after the yield point, and, likewise, type B curves merge into type C curves. There are occasions when one needs to use subjective criteria to decide whether a curve is type A or B, or type B or C. The sensory and physical meaning of the difference between type A, B, and C curves is presently not well understood. Friction of the food along the sides of the punch accounts for a slightly increasing positive slope in a limited number of cases (for example, see Thompson *et al.*, 1992), but there are cases (e.g., freshly harvested apples) where friction cannot account for the increase in force after the yield point has been passed.

A fourth type of curve, shown in curve D, is obtained on some starch pastes and whipped toppings and foams. It is essentially a type A curve except that the yield point is not sharply delineated by an abrupt change in slope; rather there is a gradual change in slope. The intersection formed by extrapolating the two straight-line portions of type D curves is usually a precise and reproducible point that can be used as a yield point figure; hence, a type D curve may be considered as a special case of a type A curve.

The type E curve is found with some starch pastes. This type of commodity shows no yield point, behaves essentially as a viscous liquid, and is unsuited to the puncture test because no meaningful results can be extracted from a type E puncture test curve at the present time.

Morrow and Mohsenin (1966) showed that the theoretical stress distribution under a rigid die acting against a semi-infinite elastic body follows the Boussinesq equation:

$$P = F/2\pi a(a^2 - r^2)^{1/2} \tag{4.1}$$

where P is the pressure at any point under the punch, F is the total force applied to punch, a is the radius of punch, and r is the distance from center of punch to stressed area.

According to this equation the stress in the food is highest at the perimeter of the punch and lowest at the center of the punch. This is demonstrated graphically in Fig. 4.4. This is a theoretical stress distribution and there are probably substantial deviations from this equation in practical situations. This equation only applies before the yield point is reached; that is, during the deformation stage. The Boussinesq equation does not apply during or after the yield point. The point of major interest in this equation is that the distribution of the stress under the punch is uneven with the highest stresses at the perimeter.

Using the theory of contact stresses between two bodies pressing against each other Yang and Mohsenin (1974) developed an equation for the initial

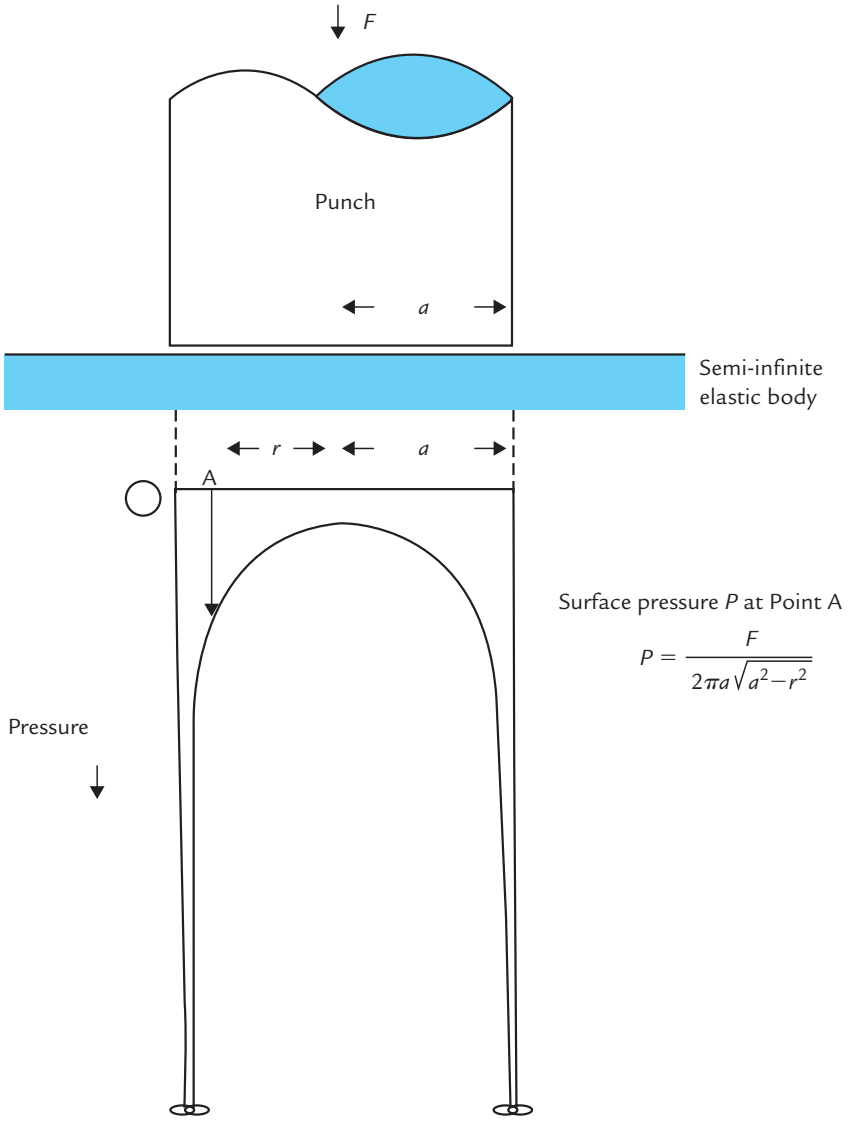


Figure 4.4 Theoretical stress distribution in a semi-infinite elastic body compressed under a rigid plunger. *P*, surface pressure at A; *F*, total force; *a*, radius of punch; *r*, distance to A. (Redrawn from Morrow and Mohsenin, 1966; copyright Academic Press Inc. (London) Ltd, with permission.)

slope in the puncture of Rome variety apples as follows:

$$\begin{aligned} F = &-(2\pi/3)DRh_1(a\xi)[(a^2/R^2)(1-a^2/R^2)^{1/2} \\ &-\frac{5(1-a^2/R^2)^2-14(1-a^2/R^2)^3+9(1-a^2/R^2)^4}{(1-a^2/R^2)^{1/2}(2-3(a^2/R^2)^2} \\ &+\tfrac{1}{2}\ln(1-a^2/R^2)-2(1-a^2/R^2) \\ &+\tfrac{3}{4}(1-a^2/R^2)^2+\tfrac{1}{2}a^4/R^4+\tfrac{5}{4}] \end{aligned} \tag{4.2}$$

where F is the force; D, the deformation at axis of symmetry; R, the radius of curvature of punch; h_1, a complex function; a, the radius of surface of contact; and ξ, a value between 0 and 1 (put at 0.7 by authors).

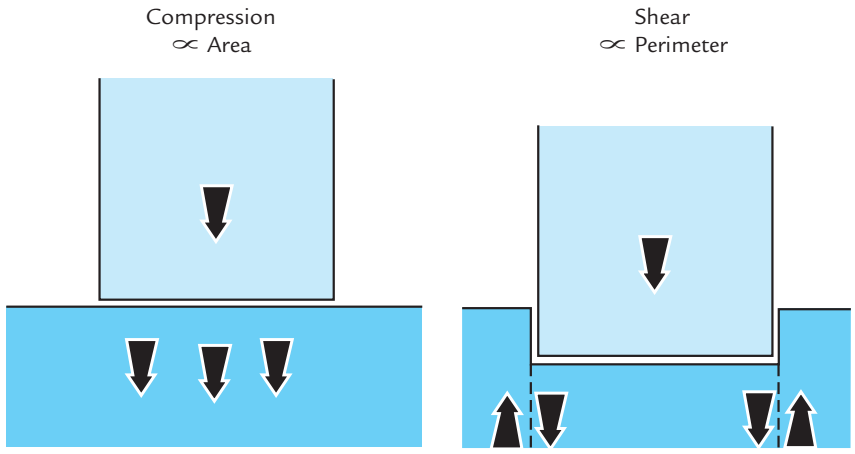


Figure 4.5 Schematic representation of a puncture test. (Reprinted from *J. Food Sci.* **31**, 284, 1966; copyright by Institute of Food Technologists.)

Bourne (1966b) has shown that the yield-point force is proportional to both the area and perimeter of the punch, and to two different textural properties of the food being tested. Figure 4.5 shows schematically what happens at the point of penetration of the punch into the food. There is compression of the food under the punch which is proportional to the area of the punch, and shearing around the edge of the punch which is proportional to the perimeter. This relationship can be expressed in the form of the equation

$$F = K_c A + K_s P + C \tag{4.3}$$

where F is the force on the punch (in newtons but sometimes it is measured in kg or lb); K_c, the compression coefficient of commodity (N mm^{-2}); K_s, the shear coefficient of commodity (N mm^{-1}); A, the area of the punch (mm^2); P, the perimeter of the punch (mm); and C, a constant (N).

The validity of the above equation was proved by means of two sets of flat-faced rectangular-shaped punches: one set had constant perimeter with area varying from 0.25 to 1.00 cm^2 and the second set had constant area with perimeter varying from 4.0 to 8.5 cm. Two circular punches were included: one with a cross-sectional area of 1.00 cm^2 and the other with a perimeter of 4.0 cm. These punches are shown in Fig. 4.6.

Each of these punches was pressed into foamed polystyrene board and the yield points were measured by means of an Instron machine. Figure 4.7, which plots the mean puncture force against punch area for the constant perimeter punches, shows a rectilinear relationship between puncture force and punch area. From the equation it follows that the slope of this line gives the numerical value of the compression coefficient K_c and the intercept on the y axis gives the value ($K_sP + C$).

Figure 4.8 shows that a plot of puncture force against punch perimeter is rectilinear provided the area is kept constant. From the equation it follows that the slope of this line gives the numerical value of the shear coefficient (K_s) and the intercept on the y axis gives the value ($K_cA + C$). Since the values of K_s

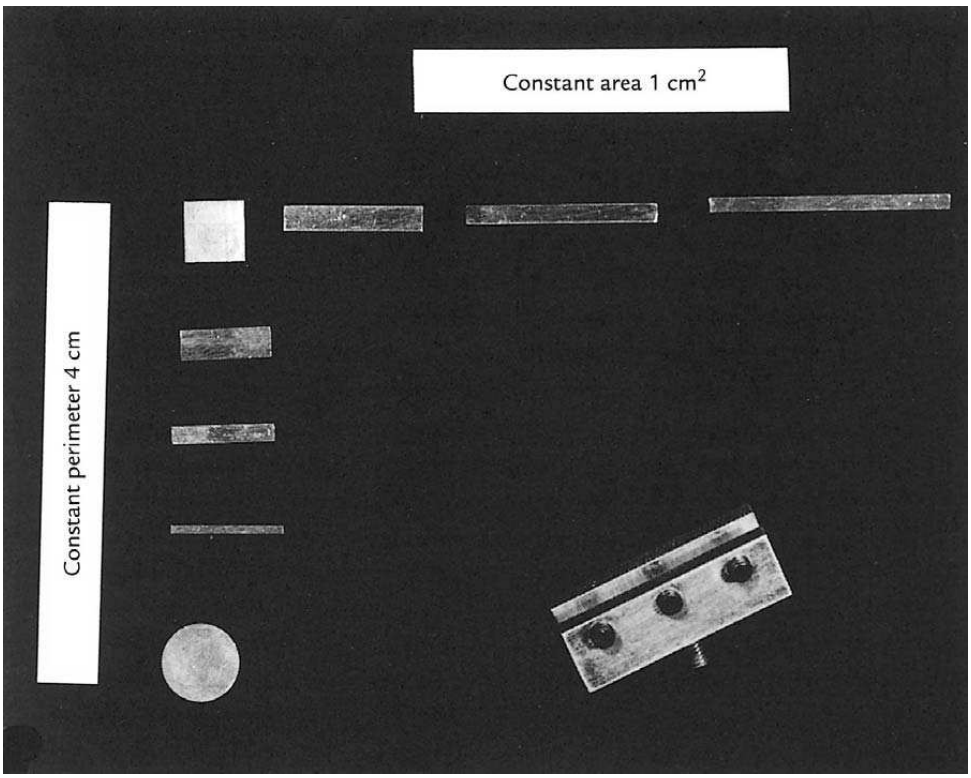


Figure 4.6 Set of rectangular-faced punches used to establish area- and perimeter-dependence of puncture force. The device in the lower right-hand corner holds the various punches. (Reprinted from *J. Food Sci*. **31**, 285, 1966; copyright by Institute of Food Technologists.)

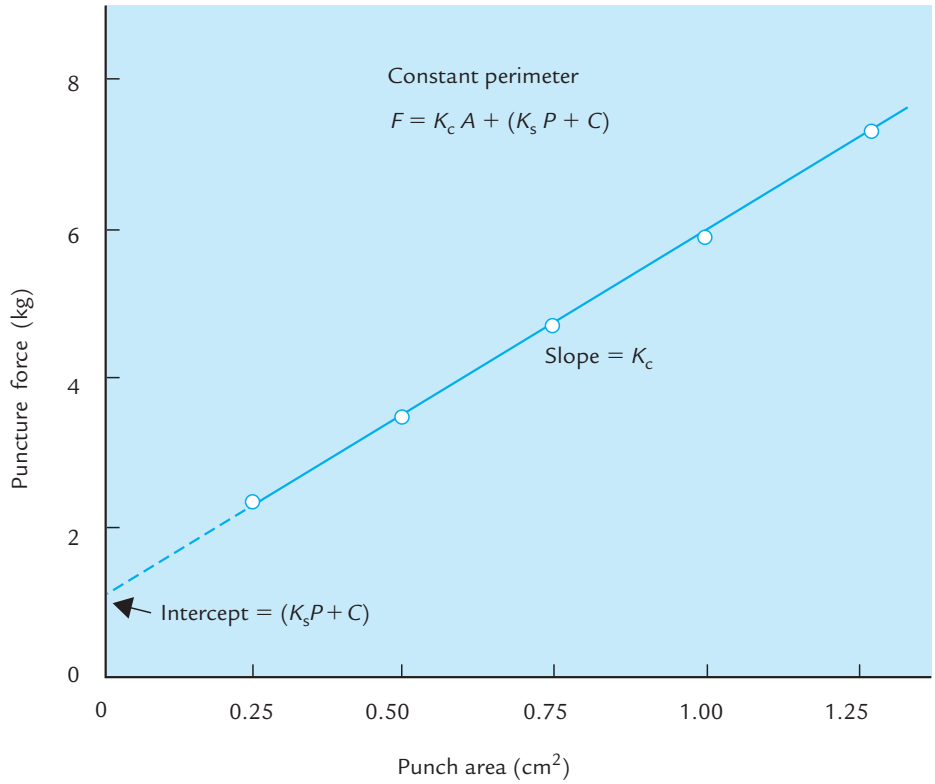


Figure 4.7 Puncture force versus punch area with constant perimeter on polystyrene board using the rectangular-faced punches shown in Fig. 4.6. (Reprinted from *J. Food Sci*. **31**, 286, 1966; copyright by Institute of Food Technologists.)

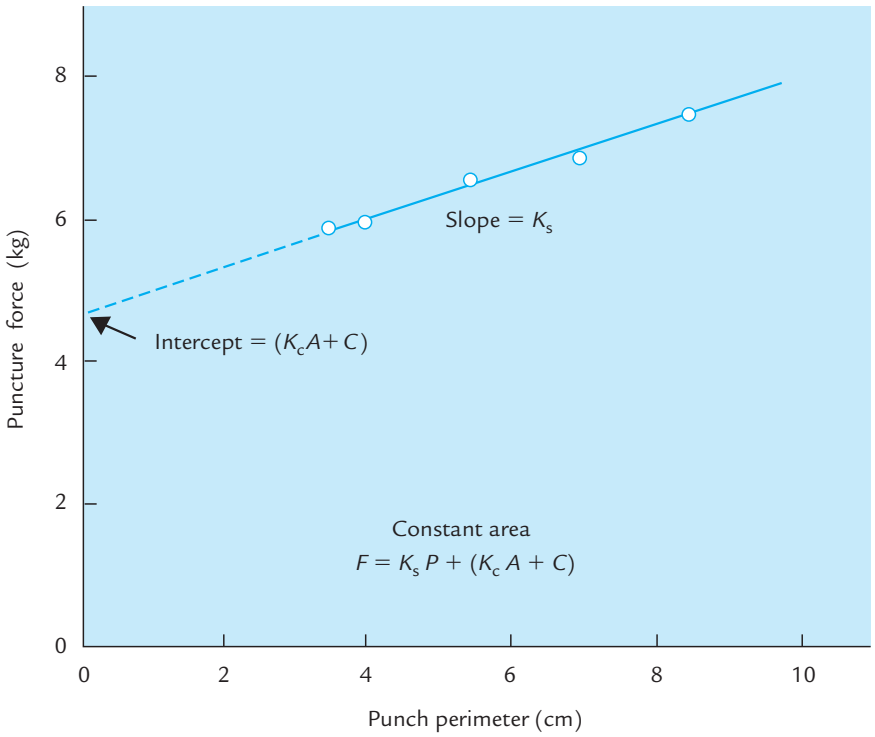


Figure 4.8 Puncture force versus punch perimeter with constant area on polystyrene board using the rectangular-faced punches shown in Fig. 4.6. (Reprinted from *J. Food Sci.* **31**, 286, 1966; copyright by Institute of Food Technologists.)

and K_c can be obtained from the slopes of these plots it follows that the constant C can also be obtained by taking the intercept value and substituting known values for either K_sP or K_cA and calculating the value for C. Thus, it is possible to evaluate all the parameters in this equation from the force measurements made with this series of punches.

This relationship has been found to apply to a wide variety of foods. Figure 4.9 shows the puncture-force/punch-area relationships for a number of foods. In each case a rectilinear relationship was found. A similar rectilinear relationship was found between puncture force and punch perimeter for these same foods (Fig. 4.10).

Table 4.5 lists the numerical values of coefficients for a number of food commodities. The physical meaning of the constant C would be interpreted from the punch force equation as being the force required to puncture a commodity with a punch of zero area and zero perimeter. Constant C has a value close to zero for most of the commodities tested, and in such cases could be neglected without introducing any great inaccuracies. Some commodities have a value for C that is numerically too high to be attributed to experimental error, and these C values are usually negative. In these cases it seems probable that there is a zone of influence around the punch such that the actual compression area on the commodity is larger than the area of the punch. However, the real meaning of the value of C in these instances has not yet been elucidated with certainty.

Jackman and Stanley (1992) noted that the zone of influence in puncture tests on tomato pericarp tissue increased markedly as tomatoes changed from mature-green to red ripe.

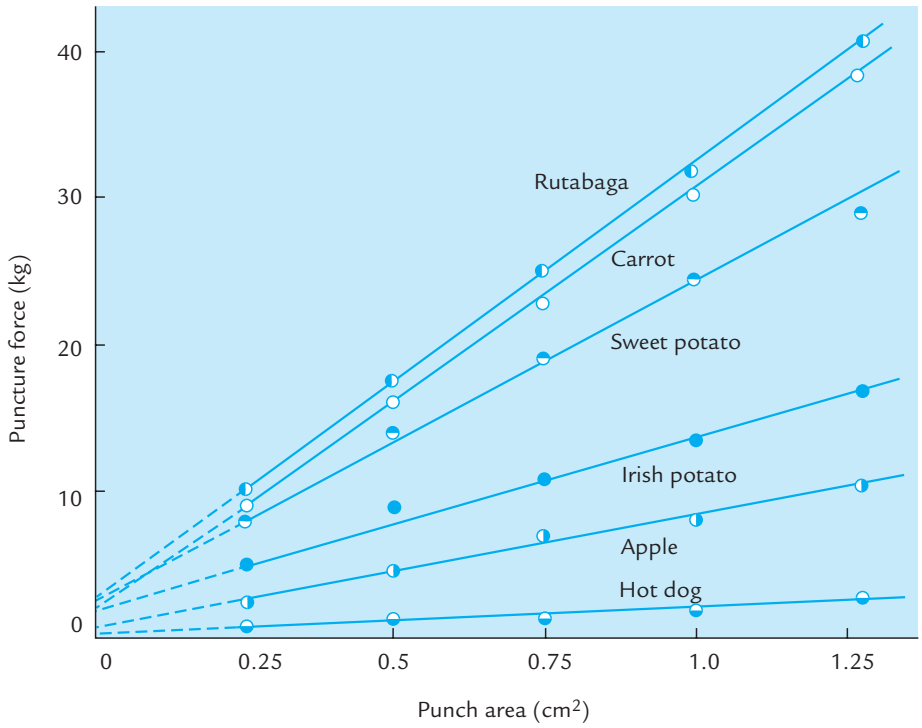


Figure 4.9 Puncture force versus punch area with constant perimeter on various foods using the rectangular-faced punches shown in Fig. 4.6. (Reprinted from *J. Food Sci.* **31**, 286, 1966; copyright by Institute of Food Technologists.)

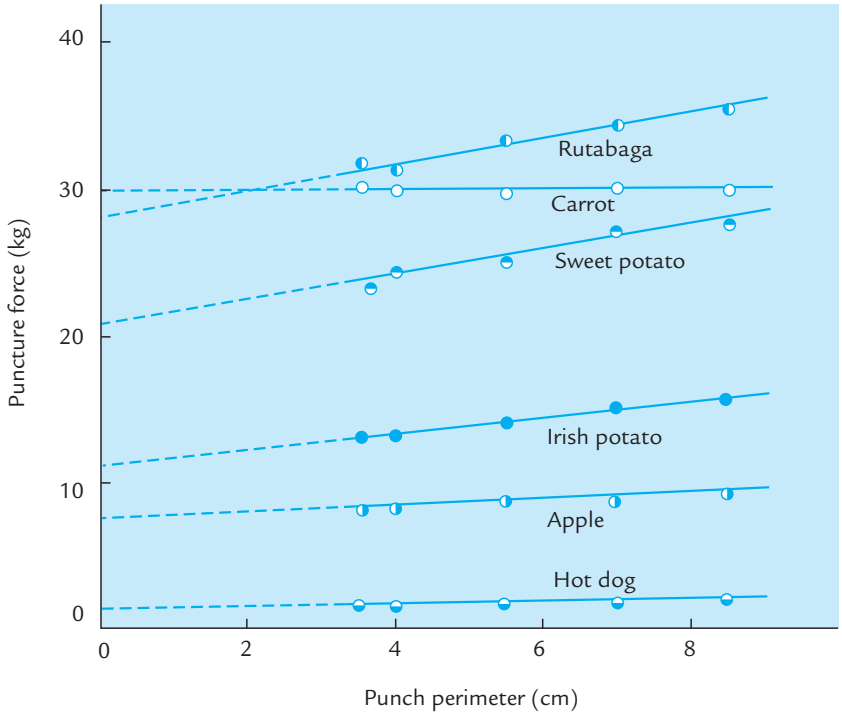


Figure 4.10 Puncture force versus punch perimeter with constant area on various foods using the rectangular punches shown in Fig. 4.6. (Reprinted from *J. Food Sci.* **31**, 287, 1966; copyright by Institute of Food Technologists.)

DeMan (1969) confirmed the fact that the puncture force is dependent on both the area and perimeter of the punch with processed cheese. With butter and margarine, however, he found that the shear coefficient is zero, which causes the term K_sP to fall out of the puncture equation and makes the puncture test on these commodities dependent on area only. DeMan considered

Table 4.5 Numerical Values of Puncture Test Coefficients for Various Commodities

Commodity	Compression coefficient K_c (N mm^{-2})	Shear coefficient K_s (N mm^{-1})	Constant C (N)
Expanded polystyrene	0.477	0.333	−2.26
High-density polystyrene	1.29	2.16	−26.9
Polyurethane	0.350	0.284	−4.61
Apples (raw, Limbertwig variety)	0.737	0.157	0.294
Apples (raw, Fr. vonBerl variety)	0.631	0.0686	3.92
Banana (ripe, yellow)	0.0422	0.0588	−0.588
Creme-filled wafers	0.104	0.137	6.28
Carrot (uncooked core tissue)	2.75	−0.0294	21.4
Wiener (cold)	0.166	0.00392	1.47
Potato (Irish, uncooked)	1.06	0.509	5.88
Rutabaga (uncooked)	2.90	0.843	−1.47
Sweet potato (uncooked)	1.94	0.883	3.43
1% agar gel	0.0147	0.0049	−0.0981
2% agar gel	0.0618	0.0284	−0.196
3% agar gel	0.119	0.157	−3.24

Source: Adapted from Bourne (1966b).

that with fats there is flow rather than compression under the punch, and for these commodities he postulated the equation

$$F = K_f A \tag{4.4}$$

where F is the puncture force; A, the area of the punch; and K_f, the flow coefficient (replacing K_c, the compression coefficient).

For circular punches the area and perimeter can be substituted by functions of diameter that follow from the geometry of circles to give the following equation:

$$F = (\pi/4)K_c D^2 + \pi K_s D + C \tag{4.5}$$

where D is the diameter of the punch.

The puncture equation explains why a simple doubling of the area of a circular punch usually fails to double the puncture force. When the area of a circular punch is increased by a factor of 2.0, the perimeter is increased by a factor $\sqrt{2} = 1.41$. The puncture force will then be doubled only if the shear coefficient K_s is zero or if the shape of the punch changed so that both perimeter and area are doubled.

In designing punches for a test device it is possible to give added or less weight to the shear component by increasing or decreasing the perimeter/area ratio of the punch. Figure 4.11 shows two methods of manipulating the perimeter/area ratio of a punch. The first single punch at the bottom of Fig. 4.10 has an area of 1.00 cm^2 and a perimeter of 3.55 cm. The nest of four punches immediately above it has a combined area of 1.00 cm^2 and a combined perimeter of 7.10 cm. The nest of four punches will normally give a higher puncture force reading than a single punch, even though the areas are equal because the amount of

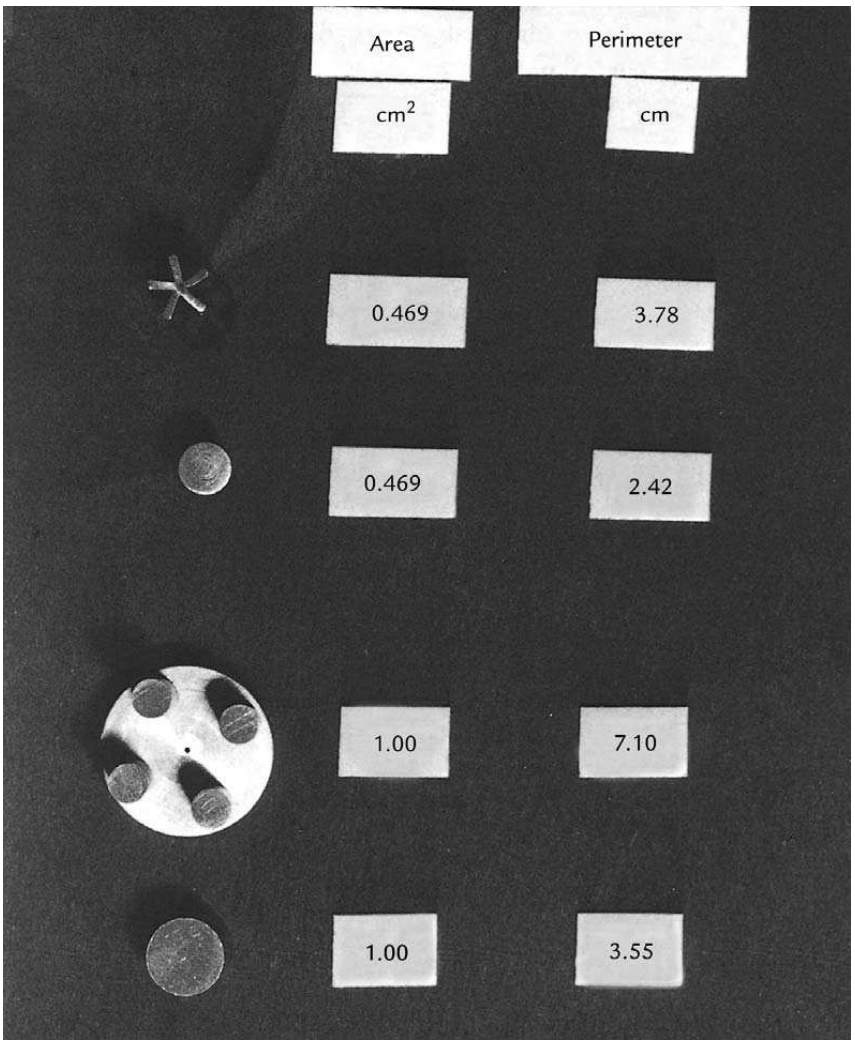


Figure 4.11 Two pairs of punches. Each pair has equal face area but different perimeters. (Reprinted from *J. Food Sci.* **31**, 288, 1966; copyright by Institute of Food Technologists.)

shearing with the nest of four punches is double that of the single punch. The second circular punch above the nest of four punches has an area of 0.469 cm^2 and a perimeter of 2.42 cm, while its star-shaped partner immediately above has the same area but a perimeter of 3.78 cm.

It is possible to obtain numerical values for the shear and compression coefficients of a food by using a set of circular-shaped punches (Su and Humphries, 1972; Bourne, 1975b). Dividing the basic puncture equation (Eq. (4.3)) through by the area and converting the perimeter and area into functions of the diameter gives the following equation:

$$F/A = 4K_p/D + K_a + 4C/\pi D^2 \tag{4.6}$$

According to Eq. (4.6) the plot of F/A against $1/D$ should be rectilinear with a slope equal to $4K_p$ and an intercept on the y axis of $K_a + 4C/\pi D^2$. Dividing Eq. (4.3) by perimeter and converting the area into a function of diameter gives the equation:

$$F/P = K_aD/4 + K_p + C/\pi D \tag{4.7}$$

According to this equation a plot of F/P versus diameter of the punch should be rectilinear with a slope equal to $K_a/4$ and an intercept equal to $K_p + C/\pi D$. The validity of these equations has been shown to hold quite well for foods, provided punches larger than approximately 2-mm-diam are used (Bourne 1975b).

The section of a puncture curve beyond the yield point (see Fig. 4.3, page 114) represents the force required to penetrate into the food. In a type A curve the penetration force beyond the yield point increases with penetration depth; this type of curve is characteristic of freshly picked apples. In a type B curve the force of penetration is approximately constant; this is typical of many apples that have been held in cold storage for periods of several months and soft ripe fruits such as peaches and pears. In type C curves the force to penetrate is lower than the yield-point force. This type of curve is almost always found with raw vegetables. Type D curves are often found with starch pastes, and toppings.

Yang and Mohsenin (1974) used contact stress theory to develop an equation for the penetration of the punch into Rome apples:

$$F = -\pi a^2 k\left[\sqrt{3} + nC_a \ln(D_0/2a)\right] \tag{4.8}$$

where F is the force; a, the radius of the surface of contact; k, the shearing strength; n, a correction factor; C_a, a correction factor; and D_0, the diameter of the assumed cylinder.

Yang and Mohsenin found a good match between the experimental data on Rome apples and the above theoretical equation. It is worth noting however that Yang and Mohsenin's experimental curve is essentially a B type curve where the penetration force is approximately constant. Since this was obtained with Rome apples it seems almost certain that the experiments were performed in the spring on apples that had been held in cold storage for several months. It is unlikely that this equation would apply to freshly harvested Rome apples which give an A type curve. There are no experimental data to show whether or not Eq. (4.8) applies to foods other than the Rome variety of apples that have been held in cold storage for several months.

The significance of type A, type B, and type C curves, as far as measuring sensory textural characteritistics of foods, remains to be determined. With apples, the type A curve is typical of a freshly harvested juicy crisp apple whereas the type B curve is typical of dry, softer, and mealy-textured apples that have been in storage for several months. The type C curve is frequently found in raw vegetables and some apples and seems to be associated with a 'woody' type of texture. Much work, however, remains to be done in this area.

Semi-infinite Geometry

A true puncture test assumes that the sample size is so much larger than the punch that no difference in the puncture force will be found if the sample is made even larger. This is called 'semi-infinite geometry.' There should be no effect from the edges, corners or thickness of the sample on the puncture force. A true puncture test does not occur if there is any cracking, splitting of

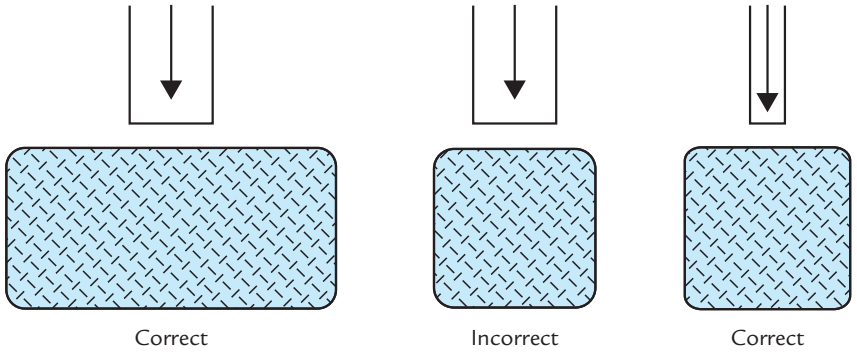


Figure 4.12 The principle of semi-infinite geometry. The puncture test assumes that the sample is semi-infinite in size, i.e. the sample is so much larger than the punch that edge effects and bottom effects are insignificant. (From the Texture Report, Volume 3. Copyright by Texture Technologies Inc.)

the sample, or if a cylinder of food approximately the same diameter as the punch is extruded out in front of the punch. It is generally accepted that the diameter of the sample should be at least three times the diameter of the punch. For fracturable foods the ratio may need to be greater than three.

The principle of semi-infinite geometry is shown schematically in Fig. 4.12. On the left-hand side the sample is more than three times the diameter of the punch and semi-infinite geometry is maintained. When the sample size diminishes to the size shown in the central part of Fig. 4.12, semi-infinite geometry is lost and this will not be a true puncture test. The way to overcome this problem is shown on the right-hand side of Fig. 4.12 where semi-infinite geometry is restored by reducing the diameter of the punch to less than one-third the diameter of the sample.

Base Support for Puncture Test

Attention needs to be given to the base that supports the specimen being subjected to a puncture test because an inappropriate support may introduce errors. When the specimen is large, the punch will only penetrate a small distance into the food relative to the size of the food and a solid support plate is correct (Fig. 4.13a). When the specimen is thin (e.g., a cookie) there is a grave risk of compressing the food against the support plate and the test will become a combination of puncture and compression or pure compression (Fig. 4.13b). A support plate that has a hole in it centered under the punch is needed for thin or small products (Fig. 4.13c). This allows the punch to penetrate all the way through the specimen and into the hole. The diameter of this hole should usually be 1.5–3 times the diameter of the punch to give adequate support to the specimen. When the hole is almost the same diameter as the punch (Fig. 4.13d), the test changes from true puncture to a 'punch and die' test in which a cylinder of material is cut out from the food and pushed into the hole (see below). When the hole in the support plate is much larger than the punch, the sample is likely to be bent and pushed into the hole thus changing the test from pure puncture into a bending test or part bending and part puncture test.

The Punch and Die Test

When the sample is thin and the support plate contains a hole whose diameter is about the same size as the punch diameter, the punch is likely to stamp out

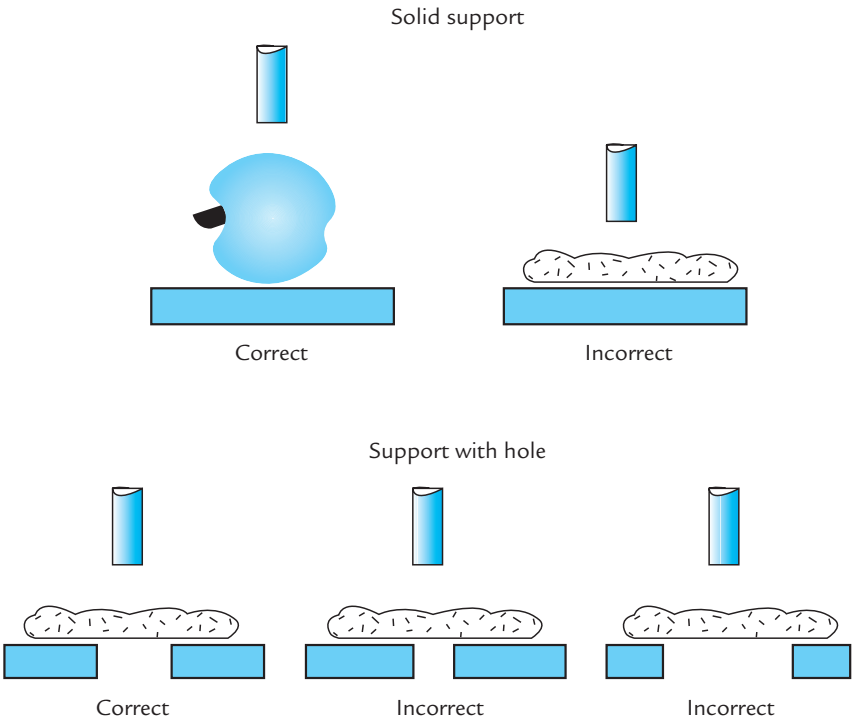


Figure 4.13 Correct and incorrect supports for puncture test. (From The Texture Report Volume 3. Copyright by Texture Technologies Inc.)

a cylinder of food into the hole (Fig. 4.13d). Although this seems to be a punch test it uses a different principle known as the punch and die test.

Ahmed *et al*. (1973) used the punch and die test on citrus skins using the equation

$$S = F/\pi DT \tag{4.9}$$

where S = the shear stress, F = the peak force, D = diameter of the punch and T = thickness of the skin. For this equation to hold, the cylinder of food should be punched out all at once. An incorrect low force will be obtained when the punch breaks through the food at one point only followed by a slow spreading of the zone of shear failure around the punch as it continues to descend.

Segars *et al*. (1975) mounted a punch and die test cell in an Instron to shear through 4 mm-thick slices of cooked beef. The punch had a diameter of 9.9 mm and the hole a diameter of 10.0 mm. They reported correlation coefficients of 0.92–0.98 with sensory evaluation of chewiness and difficulty of cutting the beef.

Factors Affecting the Puncture Test

The force measured in a puncture test depends on the following factors.

(1) Nature of the food. A soft product will give a lower puncture force than a hard product.
(2) Size and shape of the punch (see Eq. (4.3, page 117)).

(3) The number of punches used.
(4) Depth of penetration has an effect on some, but not on all foods (see Fig. 4.3, page 114).
(5) The speed of travel of the punch is a factor when testing viscoelastic foods because they are strain-rate sensitive.

Advantages of the Puncture Test

The puncture principle is probably the most frequently used principle for measuring food texture. Its popularity is the result of a number of advantages.

(1) The tester is mechanically simple and can be performed rapidly.
(2) It is easy to perform, whether by hand or in a motorized testing machine.
(3) It can be used in most locations.
(4) It rapidly distinguishes between samples. For example, Table 4.6 lists the puncture force on nuts. Despite the wide variation in size and shape of the different kinds of nuts, a puncture test clearly distinguishes between them showing puncture forces ranging from 4.5 N for pine nuts up to 20.3 N for almonds.
(5) It is suitable for many different kinds of foods, and to almost any size or shape provided a suitable punch diameter is selected. The author has used punches ranging from 0.05-mm diameter to measure the cell-wall strength of potato, to 50-mm diameter to measure the stiffness of foams. This feature is particularly useful when the size or shape vary. For example, the texture of different pasta shapes cannot be compared by a cutting-shear test, but they can be compared by using the same diameter punch because the size of the sample does not affect the puncture force so long as it exceeds semi-infinite geometry.
(6) It is suitable for heterogeneous foods because each component can be punctured separately. For example, in a chocolate bar containing nuts, raisins and puffed rice, each component can be tested separately

Table 4.6 Puncture Force of Nuts

Nut	Puncture force and standard deviation (N)
Almond	20.3 ± 4.7
Brazil nut	17.0 ± 5.8
Cashew	11.1 ± 3.2
Hazelnut	19.9 ± 4.2
Macadamia	13.6 ± 1.4
Peanut	13.3 ± 2.9
Pecan	6.7 ± 1.3
Pine nut	4.5 ± 0.7
Walnut	5.0 ± 0.9

Tests were performed in a TA.XT2 Texture Analyzer using a 1.17-mm diameter circular punch with a flat face. Crosshead speed 3.0 mm s^{-1}. (Unpublished data from M. C. Bourne.)

whereas most other test principles can only measure some overall property of the composite structure.

(7) Because it is a rapid test, it can be used to measure the distribution of textures within particulate foods. For example, Bourne (1972b) punctured large numbers of various kinds of cooked bean seeds and found an approximately normal distribution of puncture forces, as well as the range of forces encountered in each lot. Peleg (1974) mapped the changes in firmness from skin to center of papaya fruit by a series of puncture tests across the cut surface of fruits split in half.

Compression–Extrusion Test

The compression–extrusion test consists of applying force to a food until it flows through an outlet that may be in the form of one or more slots or holes that are in the test cell. The food is compressed until the structure of the food is disrupted and it extrudes through these outlets. Usually the maximum force required to accomplish extrusion is measured and used as an index of textural quality. This type of test is used on viscous liquids, gels, fats, and fresh and processed fruits and vegetables. Since extrusion requires that the food flow under pressure, it seems reasonable to use it on food that will flow fairly readily under an applied force and not to use it on those foods that do not flow easily, such as bread, cake, cookies, breakfast cereals, and candy.

A simple type of compression–extrusion test is shown in Fig. 4.14, in which the food is placed in a strong metal box with an open top. A loose-fitting plunger is then forced down into the box until the food flows up through the space between the plunger and the walls of the box. This space is called the annulus.

In Fig. 4.14a the food has been placed in a cell and the compressing platen has just contacted the surface. In Fig. 4.14b the food, has been packed down solid so that the air between the particles has been removed. Figure 4.14c shows the actual process of extrusion where the food is forced to flow around

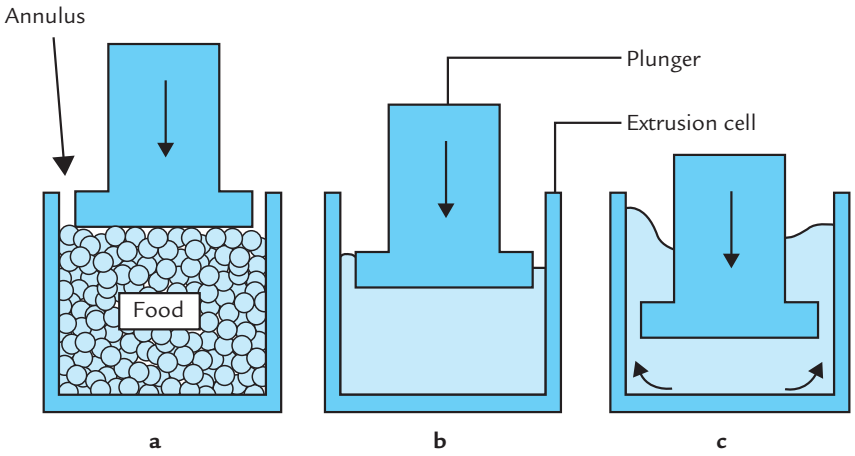


Figure 4.14 Schematic diagram of a simple cell for back-extrusion tests. (a) The plunger goes down and begins to contact the surface of the food; (b) The food is packed down and some liquid may be squeezed out; (c) The food is extruded through the annulus.

the space between the edge of the compressing platen and the inside wall of the cell.

This is called a 'back extrusion test' because the food moves in the opposite direction to the plunger.

The Ottawa Texture Measuring System (OTMS) (Voisey, 1971b) uses a forward extrusion test because the food moves in the same direction as the plunger. Voisey and Nonnecke (1972b) developed test cells for the OTMS that are square in cross-section and 12.8 cm high. Four sizes of cells were made with cross-sectional areas of 20, 30, 40 and 50 cm^2. The 30 cm^2 cell is the most widely used size. A separate frame holding either a series of parallel wires or a plate with a grid of holes in it fits into the bottom of the cell. A plunger that is square in cross-section and clears the inner walls by 0.75 mm is driven down into the cell forcing the food through the wires or holes and the force is measured. Although the OTMS instrument is no longer commercially available, the OTMS test cells can be obtained from the Instron Corporation.

The standard cell of the Food Technology Texture Press (Kramer Shear Press see Fig. 5.5, page 203) is mixed; half the food is extruded forward through the slits in the bottom of the cell and the other half is extruded backwards up between the descending blades.

A typical force–distance curve obtained from such an apparatus is shown in Fig. 4.15. From A to B the food is deformed and compressed to pack more and more tightly into the diminishing space available under the descending plunger; there is almost no rupture or breaking of the food. At approximately the point B the food is packed solid and liquid begins to be pressed from high

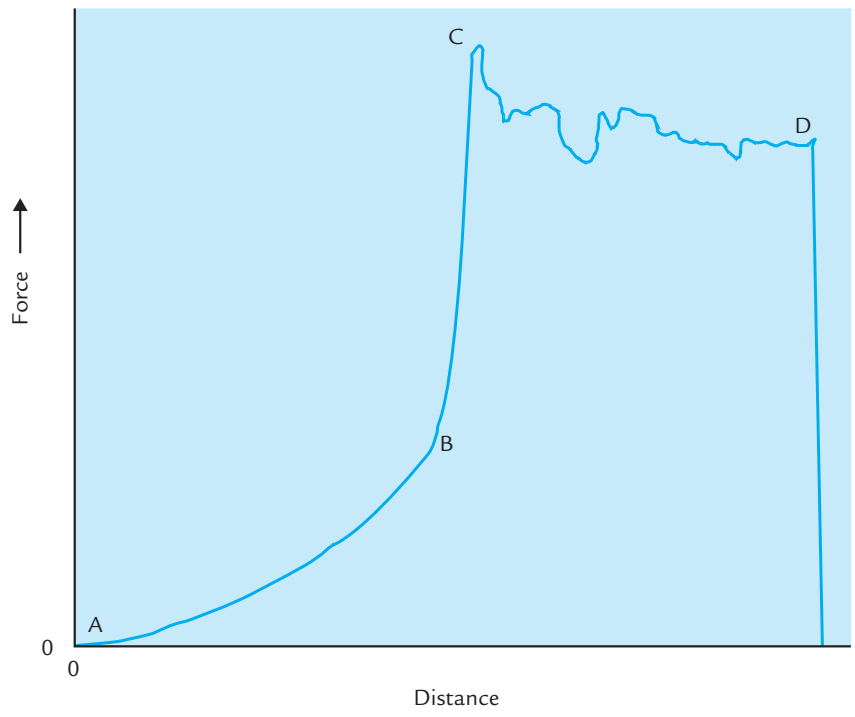


Figure 4.15 Typical force–distance curve obtained with a simple compression–extrusion test. (Reprinted from 'Rheology and Texture in Food Quality' (de Man. Voisey, Rasper, and Stanley, eds.), p. 265; with permission of AVI Publ. Co.)

moisture foods such as fruits and vegetables filling the interstices. At point B or soon afterwards the pack is solid except for small amounts of entrapped air, and the force increases steeply from B to C pressing out more juice in the process. At point C the food begins to rupture and flow up through the annulus, and this process continues to point D when the compressing platen reverses direction and the force falls to zero. Point C gives the force necessary to begin the process of extrusion, and the plateau CD shows the force needed to continue extrusion. From B to C represents the increasing force being applied to an almost incompressible mixture of solids and liquid.

The shape and magnitude of the compression–extrusion curve is influenced by the elasticity, viscoelasticity, viscosity, and rupture behavior of the material; sample size, deformation rate, sample temperature, type of test cell; sample test size; and homogeneity of the sample (Voisey *et al*., 1972). With most processed fruits and vegetables and many other foods the plateau CD is horizontal or nearly so. The unevenness of the plateau is caused by variations in the firmness or toughness of the particles that are passing through the annulus zone at any particular time.

In general, the slope of the curve during the process of extrusion is approximately horizontal, but there are times when it will show a steadily increasing or decreasing slope. According to Voisey *et al*. (1972), the slope of the extrusion part of the curve can indicate four different behavior patterns.

(1) The force reduces rapidly with further compression. This indicates that the sample was compressed until a catastrophic failure occurred, indicating that resistance to shearing is the dominant mechanism of this test.
(2) The force decreases slowly, indicating some shearing resistance combined with some extrusion and possibly adhesion of the sample to test cell.
(3) An approximately horizontal plateau indicates either shearing of successive layers of the sample or a combination of shearing, extrusion, and adhesion occurring simultaneously.
(4) The force steadily increases as extrusion proceeds. This indicates further compression of the sample in addition to various amounts of adhesion, extrusion, and shearing.

Ramkumar *et al*. (1998) extruded grated cheese curd in an extrusion cell with a hole in the front end mounted in an Instron and used the Cogswell equation that was developed for extrusion of polymer melts:

$$F = \frac{9(n+1)^2}{128} \cdot \pi \cdot D_p^2 \cdot \mu g \cdot \eta E \cdot \gamma a^2 \qquad (4.10)$$

where F = maximum extrusion force, n = power law index, D_p = piston diameter, γa = shear rate of sample prior to entering the extrusion zone, ηE = apparent elongational viscosity, and μg = apparent shear viscosity.

Hickson *et al*. (1982) extruded heat-induced protein gels that had been prepared in a test tube of 13.5 mm internal diameter by driving a 9.5 mm plunger

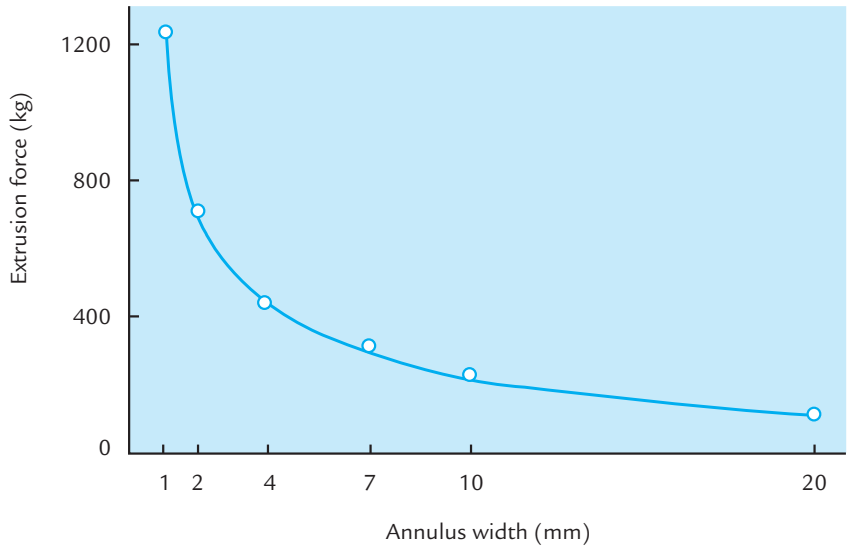


Figure 4.16 Effect of annulus width on maximum extrusion force on fresh green peas. (From Bourne and Moyer, 1968; reprinted from *Food Technol.* **22**, 1015; copyright by Institute of Food Technologists.)

mounted in an Instron into the gel and derived the following equation:

$$n_I = \frac{1}{2\pi V_p}\left[\frac{F_p}{L_p}\right]\left[1-K^2\right]\ln\left[\frac{1}{K}\right]\left[1+\frac{\alpha}{\ln K}\right] \tag{4.11}$$

where n_I = viscosity index, V_p = plunger velocity, F_p = maximum extrusion force, L_p = distance of plunger travel to reach F_p, K = radius of plunger/inner radius of test tube, $\alpha = (1 - K^2)/(1 + K^2)$.

For the type of test cell shown in Fig. 4.14 the extrusion force is inversely proportional to the width of the annulus, as shown in Fig. 4.16 where the maximum extrusion force for a uniform sample of sized, graded fresh green peas is plotted against the annulus width. With a wide annulus, a small change in annulus width has a small effect on the extrusion force, but as the annulus width narrows, the extrusion force increases steeply.

The annulus width also affects the evenness of the force in the plateau region especially for particulate foods. As the annulus width becomes narrower, the force plateau becomes less even, until at very narrow annulus widths the force fluctuates rapidly along the plateau. Figure 4.17 shows force–distance plots for extrusion of fresh green peas in a simple back extrusion cell. A layer of food material moves up between the plunger and the wall of the extrusion cell as extrusion is taking place. When the annulus is wide a large number of peas can be accommodated within the extrusion zone at any instant of time and the extrusion force is the mean force required to crush and extrude a large number of peas. This averaging effect results in a uniform force along the plateau even though the plateau itself is decreasing slowly. As the annulus width is narrowed fewer peas can be accommodated within the extrusion zone at any instant, and the averaging effect is reduced. A single hard pea will therefore make the force rise to a high level while it is passing through the extrusion zone, and likewise a single soft pea will make the force fall a considerable amount when a narrow annulus width is used. This effect is less pronounced in homogeneous foods such as yogurt.

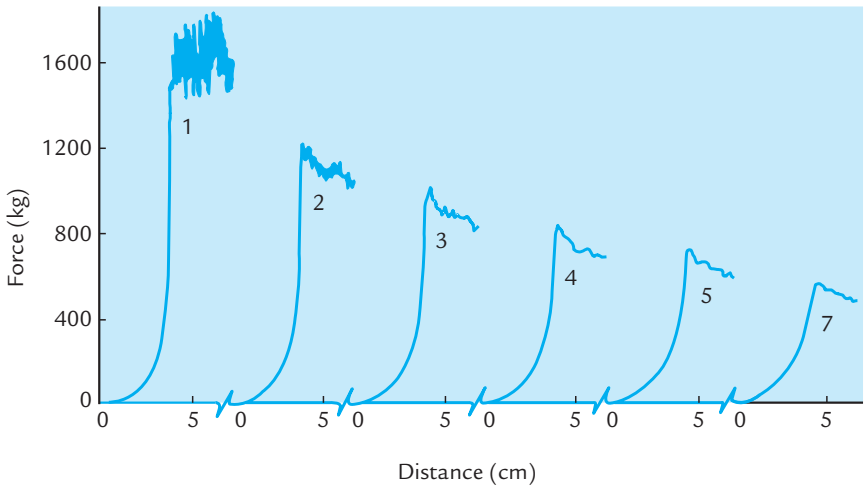


Figure 4.17 Typical force–distance curves obtained from a uniform lot of fresh green peas extruded in a simple extrusion cell with annulus widths of 1, 2, 3, 4, 5, 7 mm. (From Bourne and Moyer, 1968; reprinted from *Food Technol*. **22**, 1016; copyright by Institute of Food Technologists.)

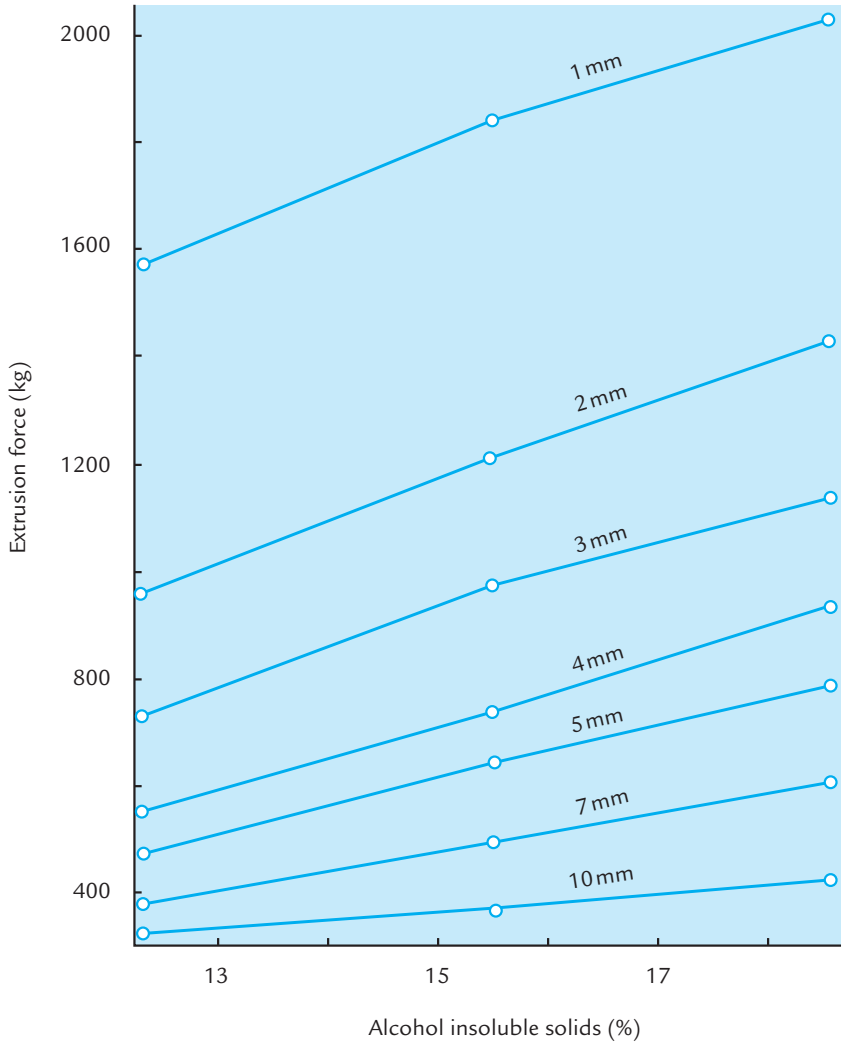


Figure 4.18 Extrusion force as a function of alcohol-insoluble solids in a compression–extrusion test on fresh green peas using annulus widths of 1, 2, 3, 4, 5, 7, 10 mm. (From Bourne and Moyer, 1968; reprinted from *Food Technol.* **22**, 1016; copyright by Institute of Food Technologists.)

An important question concerning the extrusion testing technique arises: What width of annulus gives the greatest resolving power in discriminating between two samples of food that are nearly equal in their textural properties? Figure 4.18 shows a plot of the maximum extrusion force of green peas with

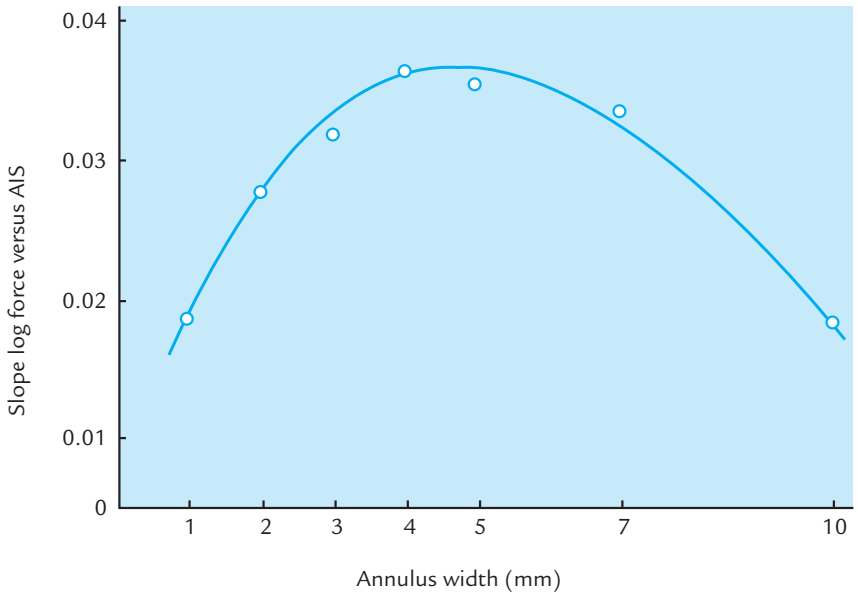


Figure 4.19 Effect of annulus width on the slope of the log force versus alcohol-insoluble solids in compression–extrusion test on fresh green peas. (Plotted from data of Bourne and Moyer, 1968.)

annulus widths ranging from 1 to 10 mm against the alcohol insoluble solids (AIS) of the peas. (Alcohol insoluble solids is a well-established index of maturity of green peas and allows evaluation of the textural properties of the peas independently of the extrusion force.) Figure 4.18 shows that the slopes of the extrusion force versus AIS curves increase as the annulus width decreases. However, we need to take into account the fact that as the annulus width decreases the test is moving into higher force ranges. This problem is overcome by plotting the logarithm of the extrusion force which normalizes the forces. In the normalized log-force–AIS relationship (Fig. 4.19), the slope increases steadily from 1 to 4 mm annulus and then decreases again. There is a fairly broad plateau from about 4 to 7 mm annulus. The greatest resolving power for green peas occurs with a 4 mm-wide annulus. It is noteworthy that the FMC Pea Tenderometer and the Texture Press both use slits 1/8 in. wide (3.2 mm), which comes close to the optimal width for the cylindrical extrusion cell on green peas.

The FMC Pea Tenderometer and the standard multibladed test cell of the Food Technology Texture Test System (Texture Press) (see Fig. 5.5, page 203) were originally considered to be based on the principle of shearing under pressure. Bourne and Moyer (1968) pointed out that this class of instrument was basically an extrusion test on materials such as green peas. Szczesniak *et al*. (1970) concluded from extensive study that different foods undergo different types of disintegration in the Texture Press. They made the following postulates:

(1) In compression, force is proportional to (sample weight)^2.
(2) In shear, force is proportional to sample weight.
(3) In extrusion, force is independent of sample weight.

Table 4.7 Possible Classification of Products' Behavior in the Texture Press

Product	Compression	Shear	Compression and shear	Compression and extrusion	Shear and extrusion	Compression shear and extrusion
Apples, (Rome variety)	a	a	b	c	c	b, poor fit
Apples, (Lyons variety)	a	a	b	c	c	b
Bananas, ripe	a	a	b	c	c	b
Bananas, overripe	a	a	b	c	c	b
String beans, raw	a	a	b	a	c	b
String beans, cooked	a	a	b	a	c	c
Common white beans, cooked	a	a	b	a	a	c
Lima beans, frozen, cooked	a	a	b	a	c	c
Beets, canned	a	a	b	c	c	b
Bologna	a	a	b	a	c	b
White bread, sliced	a	a	c	a	b	b
White bread, cubed	a	a	c	a	b	b
Sponge cake	a	c	c	c	b	b
Carrots, raw	a	a	b	c	c	b
Carrots, canned	a	a	b	c	c	c
American cheese	a	a	b	c	a	b
Cucumbers	a	a	b	c	c	c
Meat	a	a	b	a	c	b
Peas, canned	a	a	b	a	a	c
Peas, frozen, cooked	a	a	b	a	c	c
Peanuts	a	a	c	a	b	b, poor fit
Raisins	a	a	b	c	a	b
Rice, converted	a	a	b	a	a	c
Rice, precooked	a	c	b	a	c	b

Source: Szezesniak *et al.* (1970); reprinted from *J. Texture Studies* 1, page 374, 1970 with permission of Food and Nutrition Press.
a, Almost certainly not an appropriate model.
b, Has one or more negative parameters, certainly not an appropriate model.
c, Possibly an appropriate model.

By measuring the forces generated on 24 different foods at various sample test weights and calculating standard errors for the various models they were able to identify the type of disintegration most likely to occur for that food in the Texture Press.

The results of this analysis are summarized in Table 4.7. More than one model was appropriate for many foods. It is noteworthy that pure compression was not an appropriate model for any of the foods tested whereas pure shear was an appropriate model for only two foods. Extrusion in combination with compression or shear, or compression plus shear was an appropriate model for 21 foods. Only white bread and peanuts did not fit a model that included extrusion, and these two commodities do not flow under pressure. This study concluded that extrusion is an important component in the testing of most foods in the Texture Press.

Nozzle Extrusion

Voisey *et al*. (1979) developed an extrusion test accessory for the Ottawa Texture Measuring System that measures the softness of cake frostings (icing) packed in collapsible tubes. Two rollers are pulled over opposite sides of the tube forcing the frosting through the nozzle, which behaves as an extrusion rheometer because the mass-produced tubes are of uniform dimensions and shape. A high correlation ($r = -0.96$) was found between maximum extrusion force and sensory evaluation.

Benbow (1971) found that the extrusion of ceramic pastes through a short circular hole could be related to the die geometry by the expression

$$P = Y \ln(A_0/A) \tag{4.12}$$

where P is the pressure for flow through a short circular hole; A_0, the area of the barrel; A, the die area; and Y, a material parameter. Benbow (1981) suggested that this equation would probably hold for food pastes such as cake frosting.

Pros and Cons of the Back Extrusion Test

The advantages of the back extrusion test are that it is easy to perform, rapid and rugged. The force for the onset of extrusion is independent of sample weight so it is not necessary to take the time to weigh each sample. It is not affected by free liquid. Cleaning after each use need not be thorough and it is not necessary to dry the cell. A possible disadvantage of this cell is that it requires a high level of force which may be beyond the capacity of some of the universal testing machines in which the back extrusion cell is mounted. Also, it is important to ensure that the descending plunger is concentrically positioned within the back extrusion cup in order to have a uniform annulus width around its circumference.

Cutting–Shear Test

To an engineer ‘shear’ means the sliding of the contiguous parts of a body relative to each other in a direction parallel to the plane of contact under the influence of a force tangential to the section on which it acts. The food technologist sometimes uses shear in this sense but more often uses the word ‘shear’ to describe any cutting action that causes the product to be divided into two pieces. This cutting action is not the same as true shear, but is widely described as ‘shear’ among food technologists. The difference between true shear and cutting is shown schematically in Fig. 4.20.

A new term needs to be coined to describe cutting action: this will preserve the purity of the meaning of the word ‘shear’ and will prevent the confusion that occurs when attempts are made to apply the theory of shear tests to cutting tests.

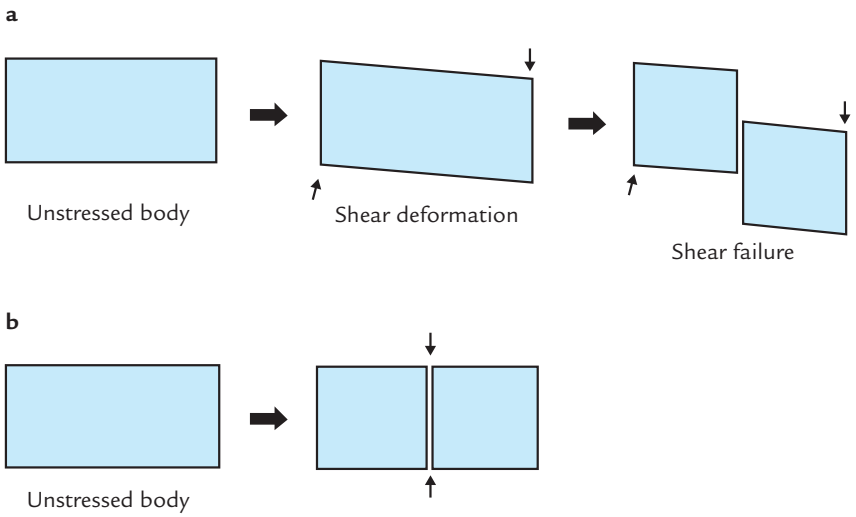


Figure 4.20 Comparison of (a) true shear failure with (b) cutting–shear failure.

Halmos (1997) proposed the term 'planar penetration' to describe this test principle. However, the author will use the term 'cutting-shear' to distinguish this type of test from true shear because it maintains some continuity with the earlier literature while avoiding confusion with the well-established rheological meaning of the word 'shear'.

The best-known shearing apparatus is the Warner–Bratzler Shear (Warner, 1928). The working part of this apparatus consists of a stainless-steel blade 0.040 in. (1 mm) thick in which a hole, consisting of an equilateral triangle circumscribed around a 1-in.-diam circle is cut and the edges rounded off to a radius of 0.02 in. (0.5 mm). (In some publications the Warner–Bratzler shear is misrepresented as having a rectangular-shaped hole in the blade.) A sample of meat, usually a cylinder 0.5 or 1 in. in diam, is placed through the hole and two metal anvils, one on each side of the blade, move down forcing the meat into the V of the triangle until it is cut through (see Fig. 5.7, page 209). A force gauge measures the maximum force encountered during this cutting action. This is a cutting action rather than a true shear.

Voisey and Larmond (1974) mounted the Warner–Bratzler shear blade and various adaptations of the blade in the Instron and studied the effects of changing the dimensions of the blade using wieners as the test material. Figure 4.21 shows how the cylindrical piece of wiener is compressed by the descending anvil and changes cross-sectional shape to conform to the shape of the hole in the blade. Eventually the sample fills all the available area. The type of failure appears to be principally tension as the sample is stretched around the blade. However, a complex stress pattern is established which is a combination of tension, compression, and shear. It seems probable that most of the so-called 'shear' tests used on foods are similar in pattern and result in what is predominately tensile failure of the specimens.

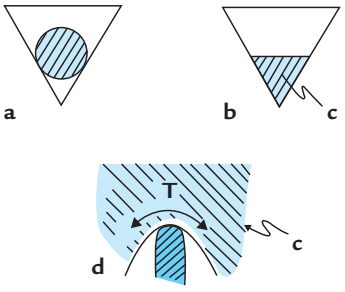


Figure 4.21 Schematic of shearing in the triangular blade of the Warner–Bratzler Shear. a, Unstressed circular test piece; b, sample deforms under compression to fill available space; c, sample; d, tension failure occurs around the edge of the shear blade; T, tensile stress. (Courtesy of P. W. Voisey; reprinted with permission from Canadian Institute of Food Science and Technology.)

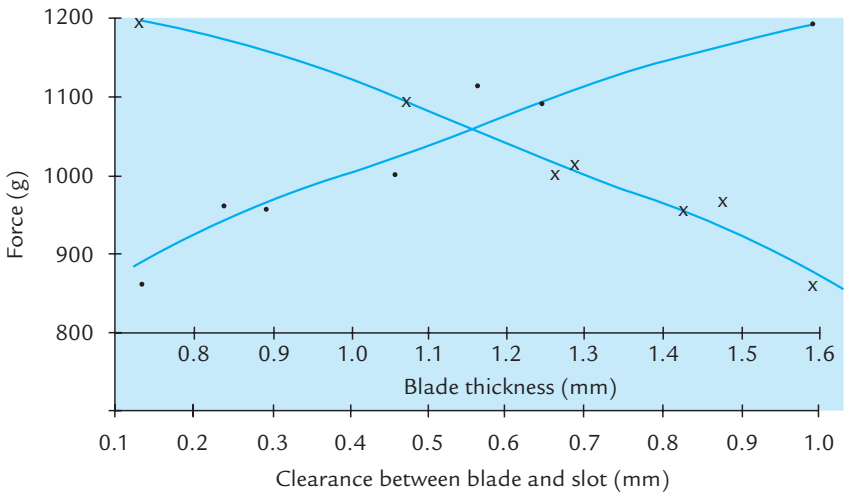


Figure 4.22 Effect of blade thickness (•) and clearance (x) between blade and anvil in shearing wieners. (Courtesy of P. W. Voisey; reprinted with permission from Canadian Institute of Food Science and Technology.)

Voisey and Larmond (1974) studied the effect of changing the angle of the cutting edges of the blade. The shearing force increases as the angle of the blade widens from 30° to about 70° after which further widening of the angle causes no increase in force. These authors also studied the effect of changing the thickness of the blade and the width of the clearance between the blade and the moving anvil. Figure 4.22 shows that the force increases as the thickness of the blade increases and it decreases with increasing clearance. These authors also found that the rate at which the test is performed introduces significant differences in the rupture force and other parameters measured in these tests. In subsequent work Voisey and Larmond (1977) showed that changing the rate of travel of the anvil did not significantly increase the correlation between sensory tenderness rating and the Warner–Bratzler shear rating.

Although no similar work has been reported on muscle meat with its intact fibers, the work of Voisey and Larmond cited above indicates the importance of standardizing test conditions.

The specifications for the original Warner–Bratzler blade are given on page 135. Many of the blades in use today, especially those supplied with some of the universal testing machines, do not comply with these specifications. The thickness of the blade, the angle of the hole in it, and the clearance between the blade and the anvil varies between manufacturers. The studies of Voisey and Larmond (1974, 1977) cited above demonstrate that the lack of standardization of the Warner–Bratzler blade dimensions is a problem that needs to be addressed. It is probably a major cause of the erratic results reported from different laboratories using the so-called 'Warner–Bratzler' blade on meat.

The original Warner–Bratzler blade was made of stainless steel which is resistant to wear. Many of the modern Warner–Bratzler blades are manufactured of aluminum alloy which does not wear as well as stainless steel and probably falls out of dimensional tolerances more quickly than a stainless-steel blade.

For beef and large muscles from other animals it is customary to cut a cylindrical sample with either a 0.5 or 1 in. (1.27 or 2.54 cm) internal diameter boring tool for the Warner–Bratzler test. For smaller muscles, e.g. chicken breast, the whole muscle may be inserted into the triangular hole of the Warner–Bratzler blade. After the sample has been cut into two pieces, the cross-sectional area of the newly cut surface is measured and a correction factor applied to the measured force to compensate for differences in the area of the muscle that was cut. The usual way to measure the cross-sectional area of a noncylindrical specimen such as muscle is to press the freshly cut surface on a piece of filter paper, run a pencil line around the perimeter of the wet spot, and measure its area either by planimeter, or by cutting it out and weighing after drying.

The relationship between diameter or cross-sectional area of noncylindrical specimens of the test piece and Warner–Bratzler shear force is not clear at the present time. Kastner and Henrickson (1969) found with cooked pork chops a nonlinear relationship between diameter and Warner–Bratzler shear force. When their data are recalculated as shear force versus $(\text{diam})^2$ the plot appears to be linear; that is, the shear force is directly proportional to the cross-sectional area. Pool and Klose (1969) found with cooked turkey meat that the shear force was proportional to $(\text{diam})^{1.2}$ and they pointed out that the fibers failed in tension. Davey and Gilbert (1969), using a wedge-type shear on beef, found the shear force to be proportional to the square root of the area; that is, proportional to the diameter. Culioli and Sale (1981) sheared spun fababean protein fibers in a rectangular blade double-shear apparatus and found that the maximum force increased linearly with the initial thickness of the sample over the range 2–13 mm. In view of the uneven results between different researchers the only conclusion that can be made at this time is that the diameter of the test piece should be standardized for any one study.

Wheeler *et al.* (1996) reported on the effects of sampling, cooking, and coring on Warner–Bratzler force values for beef and Wheeler *et al*. (1997) compared Warner–Bratzler shear measurements among five institutions and concluded that proper execution of a highly standardized procedure is imperative for obtaining accurate and repeatable Warner–Bratzler force measurements on cooked beef.

Volodkevich (1938) (sometimes spelled Wolodkevich) described a shear test for meat consisting of two wedges, each with a 2.5-mm radius, that compress and shear the meat. MacFarlane and Marer (1966) developed a similar double-wedge apparatus for measuring the tenderness of lamb, calling their apparatus the MIRINZ Tenderometer. Smith and Carpenter (1973) developed a similar type of apparatus that was hand operated, calling it the NIP Tenderometer.

Rhodes *et al*. (1972) mounted the Volodkevich wedge in the Instron and studied 10 parameters that were extracted from the force–distance curves using computer analysis. They concluded that

> none of the correlations between sensory data and the single instrumental measurement derived from force–deformation curves has improved significantly on those already reported in the literature; nor has the use of multivariate statistical techniques … produced any more than marginal advantages.

Seideman and Theer (1986) confirmed the conclusion of Rhodes *et al*. (1972). They mounted a Warner–Bratzler blade in an Instron and tested broiled longissimus muscle steaks from 96 cattle. They extracted six textural parameters from the resulting force–time curves and found that peak load (maximum force) was the best predictor of tenderness, and the use of additional instrument measurements did not substantially improve predictability of sensory assessment.

Therefore, it seems that simply measuring the maximum force is all the information needed from the Warner–Bratzler test.

The Warner–Bratzler blade is sometimes used on foods other than meat. For example, Venkateswara *et al*. (1986) used the Warner–Bratzler blade to cut through chapaties folded into four layers and found the maximum force gave a correlation coefficient $r = 0.928$ with tearing resistance measured by an Elmender paper tearing test.

A number of other single-blade cutting–shear apparatus are described in the literature; for example, Wiley *et al*. (1956), whose single-blade shear is now an optional accessory to the Food Technology Texture Test System. There are several reports in the literature of cutting–shear testers that are based on the principle of a wire cutting the product; for example, Wilder (1947), Gould (1949), Vanderheiden (1970), Brusewitz *et al*. (1997) and Kachru *et al*. (1995).

The standard cell of the Food Technology Texture Test System (frequently called Kramer Shear Press) has some elements of shear in the test. This feature of this test cell is discussed more fully on page 133.

The American Association of Cereal Chemists have a standard method for a cutting–shear test on spaghetti and noodles using a blade mounted in the TA.XT2 Texture Analyzer (AACC Method 66-50).

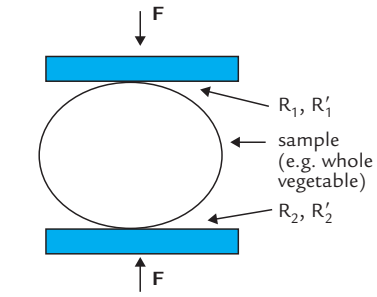
McComber *et al*. (1987) devised a double direct shear test by putting cylindrical samples of potato 30-mm diameter × 30-mm high in a special metal box just large enough to accommodate the specimen. The central section of the box can be moved laterally and shears out a section of the potato about 10-mm thick leaving another 10-mm section below and above which are retained in the box. There are two shear planes in this test.

Compression Tests

There are two main types of compression tests.

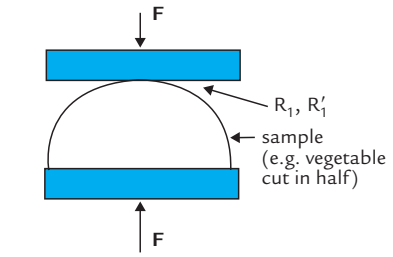
Uniaxial Compression

The sample is compressed in one direction and is unrestrained in the other two dimensions. It causes a change in shape. The volume is unchanged when the Poisson's ratio $\mu = 0.5$. The volume decreases if $\mu < 0.5$, and the smaller the valve of μ, the greater is the decrease in volume. This is a widely used test principle for solid foods. It is usually performed in a universal testing machine. The platen that compresses the food should be larger in diameter than the food specimen for a true compression test. When the platen diameter is less than the diameter of the food it becomes a puncture test.



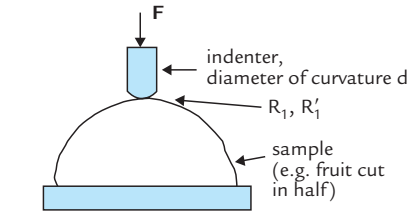
$$E = \frac{0.338\,F(1-\mu^2)}{D^{3/2}}\left[K_U\left(\frac{1}{R_U}+\frac{1}{R'_U}\right)^{1/3}+K_L\left(\frac{1}{R_L}+\frac{1}{R'_L}\right)^{1/3}\right]^{3/2}$$

a Parallel plate contact



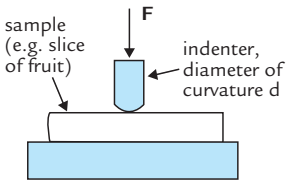
$$E = \frac{0.338\,K^{3/2}F(1-\mu^2)}{D^{3/2}}\left[\frac{1}{R_1}+\frac{1}{R'_1}\right]^{1/2}$$

b Single plate contact



$$E = \frac{0.338\,K^{3/2}F(1-\mu^2)}{D^{3/2}}\left[\frac{1}{R_1}+\frac{1}{R'_1}+\frac{4}{d}\right]^{1/2}$$

c Spherical indenter on a curved surface



$$E = \frac{0.338\,K^{3/2}F(1-\mu^2)}{D^{3/2}}\left[\frac{4}{d}\right]^{1/2}$$

d Spherical indenter on a flat surface

Figure 4.23 Apparent modulus of elasticity calculated from force and deformation data for various loading geometries. E = apparent modulus of elasticity, Pa, (psi); D = deformation, m (in.); μ = Poisson's ratio; F = force in N (lbf); R_U, R'_U = radii of curvature at the point of contact for the upper convex surface for loading case (a), m (in.); R_L, R'_L = radii of curvature at the point of contact for lower convex surface for loading case (a), m (in.); R_1, R'_1 = radii of curvature of convex body at the point of contact for loading cases (b) and (c); (d) = diameter of curvature of the spherical indenter, m (in.). K_U and K_L in case **a** are constants. (From ASAE Standards, 1998, p. 555. Copyright by American Society of Agricultural Engineers.)

For solid foods, uniaxial compression tests can be divided into two classes.

(1) Class A: Nondestructive. The compression force is kept small to ensure there is no fracture, breaking, or any other irreversible damage done to the sample. This is used for the deformation test (described later) which imitates the squeezing of food in the hand. The American Society of Agricultural Engineers published formulas for calculating the apparent modulus of elasticity E of food materials of convex shape that are relatively firm and homogeneous that are compressed by various loading geometries in a universal testing machine (Fig. 4.23).

(2) Class B: Destructive. The compression force is increased to a level that ensures the sample will break causing irreversible damage to the sample. This is used for instrumental profile analysis (described later).

Uniaxial compression can also be used for semisolid foods when the sample does not fracture but flows out between the compressing platen and the supporting plate and the supporting hole. This is biaxial flow; it is called 'imperfect lubricated squeezing flow' and is described under the heading 'Miscellaneous Methods' (see page 175).

Bulk Compression

The sample is compressed in three dimensions, usually by means of hydraulic pressure. It causes a change in volume but usually no change in shape. Bulk compression is seldom used in testing foods, probably because of the slowness and difficulty of performing a test under conditions where the force is applied by means of hydraulic pressure. Many foods contain variable amounts of entrapped gas within their structure and since gases are highly compressible, the amount of entrapped gas profoundly affects the bulk compressibility of the food. White and Mohsenin (1967) describe a low-pressure bulk compression apparatus and Sharma and Mohsenin (1970) give results from bulk compression of apples. Finney and Hall (1967) performed bulk compression tests on potato tubers. Figure 4.24 illustrates the difference between uniaxial compression and bulk compression.

Tensile Tests

Tensile tests are not widely used with foods, which is understandable because the process of mastication involves compression, not tension, of the food between the molars. It has already been pointed out that food fails in tension in many cutting–shear tests. Nevertheless, a few tensile tests are performed. One of earliest tensile tests was that of Howe and Bull (1927), who endeavored to measure the tensile strength of meat but encountered difficulty in making clamps that would hold the meat so that the meat would not tear at the clamps. Platt and Kratz (1933) cut pieces of bread and cake to a standard shape, held them between large spring paper clips, and ran water into a small bucket attached to the lower clip until the piece of bread broke and then measured the volume of water. Personius and Sharp (1938) used a similar simple apparatus for measuring the tensile strength of potato. Halton and Scott Blair (1937) experienced difficulty in performing tensile tests on bread dough because of the sagging of the dough and overcame the problem by supporting

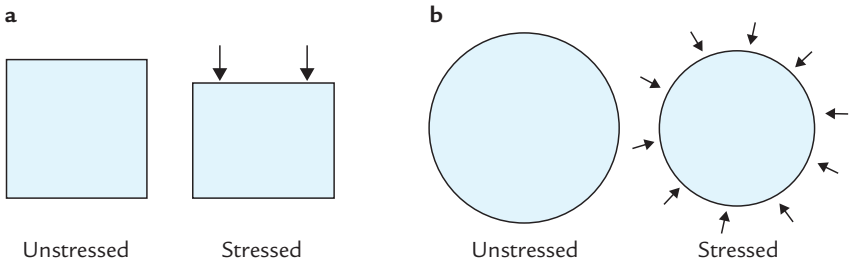


Figure 4.24 Uniaxial compression (a) and bulk compression (b) compared.

the dough on a bath of mercury, performing tensile tests in a horizontal plane instead of the customary vertical plane. It is now known that mercury is slightly volatile at room temperature and that inhalation of the vapor is hazardous to health. Therefore, this technique of Halton and Scott Blair (1937) should not be used even though the principle of performing a tensile test on a frictionless horizontal plane is an interesting way to overcome the problem of handling a food that is too weak to support its own weight.

Guinee and O'Callaghan (1997) performed-tensile tests on Mozzarella cheese by melting the cheese on a horizontal bifurcated platform consisting of a fixed element and a roller-mounted element that is free to move along a rail. After the ends of the cheese are locked in position a motorized winch draws the roller-mounted half of the platform along the rail until the cheese sheet breaks. The distance the cheese stretches up to its breaking point is measured.

Tschoegl *et al*. (1970) overcame the problem of dough sag during tensile testing by suspending doughnut-shaped pieces of dough in a fluid of equal density. This technique was used by Rasper *et al*. (1974) and Rasper (1975).

Nowadays, instruments such as the Instron, Food Technology Texture Test System, TA.XT2 Texture Analyzer or other universal testing machine are generally used to perform tensile tests.

A conventional tensile test assumes that the sample fractures almost instantaneously in a plane that is approximately perpendicular to the plane of the applied tension. The maximum force is the tensile strength of the material. Many foods subjected to tension do not fail suddenly; fracture begins with a small crack that slowly spreads across the sample over a comparatively long period of time and the crack may or may not be perpendicular to the plane of the applied tension. Several cracks may appear and spread simultaneously. This type of break makes it difficult to obtain a meaningful interpretation of the tensile force measurement.

Another problem with many foods is that of holding the sample so that the break occurs within the sample and not at the jaws that hold the sample. This problem is often solved by cutting out dumbbell-shaped test pieces and holding the sample at the wide ends. The sample is then more likely to break in the narrow center portion of the test piece. Pool (1967) devised a unique solution to the problem of holding the sample in tensile tests by using a fast-acting strong adhesive (Eastman 910, methyl 2-cyanoacrylate) to cement the ends of cylinders of chicken meat to metal plates. The cement forms a bond stronger than the tensile strength of the chicken in a minute or two. Pool then mounted the two metal plates containing the piece of chicken in the Instron to perform tensile tests.

Tang *et al*. (1995) solved the problem of holding the sample when performing tensile tests on whey protein concentrate gels by casting the gels in the shape of a doughnut-shaped ring 30-mm external diameter, 12-mm internal diameter and 11-mm thick. The ring-shaped gel specimens were hung over dowel pins mounted in an Instron and subjected to a tensile force to failure. The gels did not fail at the point of support. Failure began on the inside surface of the ring where the stress is predicted to be slightly higher than in other parts of the ring.

Gillett *et al*. (1978) developed an attachment that allows the tensile strength of sliced processed meats to be measured in a horizontal plane. Two horizontal plates, each with four rows of protruding vertical metal spikes, are used to hold and extend the sample. A cable runs around a pulley to the load cell of a recording texturometer and pulls the plates apart when the instrument is operating. This attachment is available as an accessory for the Food Technology Texture Test System.

Tensile tests are used to measure the adhesion of a food to a surface. In this type of test the sample of food has a disk pressed onto it after which the force required to pull it off is measured. Jansen (1961) and Claassens (1958, 1959a,b) used this technique to measure the stickiness or hesion of butter. The Texture Profile Analysis parameter of adhesiveness measures the maximum force required to pull the compression surface from the test piece after the first compression and therefore contains one element of tensile testing (Friedman *et al*., 1963). Henry and Katz (1969; Henry *et al*., 1971) used this technique in an Instron to measure the adhesiveness of puddings and toppings and developed and identified several tensile parameters from the force–distance curve that was so obtained.

Reyes-Vega *et al*. (1998) measured the tearing strength of corn tortillas by cutting 13 mm-wide strips with the center portion angled at 45° from the vertical to make a test specimen shaped according to the American Society for Testing and Materials method D 624 for plastic films and pulling them apart at 2 mm s^{-1} until rupture occurred.

Tensile tests are the preferred method for measuring stickiness or adhesiveness of foods. Hoseney and Smewing (1999) and Kilcast and Roberts (1998) review the literature on this property whose measurement has been difficult to standardize.

Torsion

In a torsion test a force is applied that tends to rotate or twist one part of the object around an axis with respect to the other parts. The tendency of a force to produce rotation about an axis is called the torque T with dimensions mass $\times$ length^2 $\times$ time^{-2}. If a force of F newton is applied to a body at R meter from the axis of rotation (Fig. 4.25)

$$\text{Torque } T = FR \text{ newton meter.}$$

Torque is often expressed in non-SI units. These can be converted into the SI unit of newton-meter (N m) by using the following multiples:

1 N m torque equals	1.000×10^{-7} dyn-cm
	980,600 g force-cm
	9.806 kg force-m
	0.00706 oz force-in.
	0.1129 lb force-in.
	1.355 lb force-ft

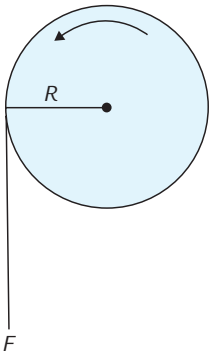


Figure 4.25 The torque principle; force *F* applied at radius *R* from center of body causes a tendency for rotation.

The major application of this test principle is in the rotary viscometers that are widely used to measure the viscous properties of foods. This application will be discussed in Chapter 6 which deals with viscosity and consistency measurements.

The Farinograph and the Mixograph are torque measuring instruments (see pages 211, 212).

Nemitz *et al*. (1960) and Nemitz (1963) developed a laboratory apparatus that twisted a whole fish and used it to measure the progress of rigor mortis. Karacsonyi and Borsos (1961) used a torsion device to measure the strength of dry spaghetti and found it useful for the detection of hidden failures. Scott Blair and Burnett (1963) developed a laboratory torsiometer for measuring the coagulation of renneted milk in a cheese vat called a 'cheese curd torsiometer.' Hashimoto *et al*. (1959) used the principle of torsional strain to measure the firmness of sausage.

Templeton and Sommer (1933), Mueller (1935), and Voisey and deMan (1970) used the torque principle to measure the change in consistency of products that are beaten. Figure 4.26 shows how this apparatus can be used to study the behavior of products that increase in viscosity as they are whipped. Applesauce maintains a constant torque throughout the whipping time, whereas cream reaches a peak viscosity and then lowers in viscosity as it breaks down to form butter. The figure also shows the development of viscosity in egg whites and a topping mix as they are beaten.

Studman and Yuwana (1992) developed a torsion test for measuring the firmness of fruits. A fruit such as an apple is impaled on a spindle that carries a blade 9.8 mm × 7.8 mm. The fruit is rotated by hand causing a vertical rod asymmetrically attached to the spindle to rotate thus raising its center of gravity. The rotation of the fruit is continued until the flesh fails completely. The angle

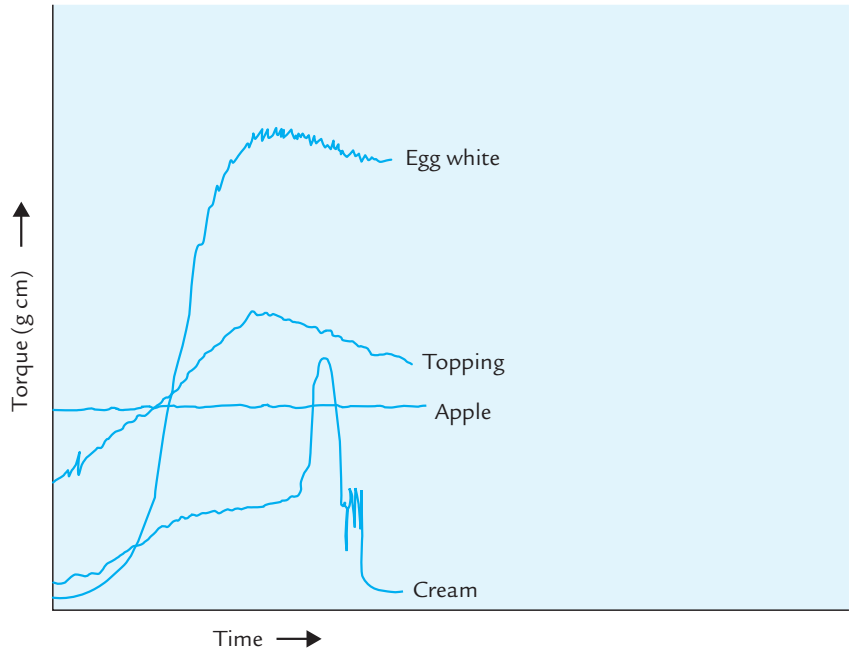


Figure 4.26 Changes in torque as a function of whipping time for egg white, dessert topping, applesauce and cream. (Drawn from data in Voisey and deMan, 1970.)

of the rod measures the crushing strength of the flesh. The measurement takes about 10 s per fruit and can be adapted to a wide range of fruits. This device has been named the Massey Twist Tester.

Diehl *et al*. (1979) designed a torsion test attachment for use in the Instron and used it to measure structural failure in apple, potato, and honeydew melon. They found tension failure in the torsion test but shear failure in simple compression tests. Unlike many previous torsion tests for solid foods, the methods they developed allowed the determination of both engineering and true stress and strain to failure. Torsion tests of this type have long been common for engineering materials such as metals and plastics.

Professor Hamann and coworkers at North Carolina State University improved upon the torsion test for solid foods developed by Diehl *et al*. (1979) by adapting the technique to a Brookfield viscometer. This adaptation has proved to be valuable for testing gels and meat batters (Hamann, 1983, 1988, 1994; Montejano *et al*., 1983a,b; Howe *et al*., 1994). They pointed out that in torsion the true strain (Hencky strain) and engineering strain (Cauchy strain) are nearly equal even for large strains, whereas in uniaxial compression the true strain is often much larger than the engineering strain especially when there is a large degree of compression. This is of particular concern when testing surimi and other gels that require very large strains to reach the point of fracture.

Hamann's group showed that in a torsion test where the twisting moment versus angle of specimen twist is linear up to failure

$$\tau = 2KM/\pi r^3 \tag{4.13}$$

where τ = shear stress at failure, M = twisting moment or torque to failure, r = radius of specimen at its narrowest point and K is a specimen shape factor which is a function of the smallest diameter of the specimen and the radius of curvature of the capstan shape.

They also showed that the shear strain at failure, or maximum strain γ is:

$$\gamma = 2K\psi/\pi r^3 Q \tag{4.14}$$

where ψ is the angle of twist and Q is a specimen shape factor which is a function of the diameter of the cylinder before shaping the capstan, the radius of curvature of the capstan shape, and the length of the shaped section of the food cylinder. For the torsion testing protocol developed by Hamann and coworkers for the Brookfield viscometer, $K = 1.08$ and $Q = 8.65 \times 10^6\ \mathrm{m}^{-3}$ and is specific for the shape and dimensions of specimens used with this device. Q is slightly larger than that for the specimen shape originally developed by Diehl *et al*. (1979), because the disk-shaped ends of the specimen used in the Brookfield procedure contribute to the angle of twist which was not the case in the original.

This group also developed a more precise version of the milling machine developed by Diehl *et al*. (1979) that grinds cylindrical-shape specimens of

gels and other foods such as frankfurters into a capstan or dumbbell-shape with a minimum diameter of 10 mm at the center. A notched styrene disk is then cemented to each end of the shaped specimen with methylcyanoacrylate adhesive and the assembly is placed in a rotary viscometer where it is twisted until failure. The address of Gel Consultants, the company that makes the milling machine, is given in Appendix I.

The advantages of the torsion test are that it produces a pure shear stress and thus maintains sample shape and volume during the test. Also, tension, compression, and shear are created in equal magnitudes, 45° apart, so that a visual examination of the fractured specimen can determine which occurred. More significantly, the stress in which a material is weakest, can be determined. This test principle is particularly suitable for highly deformable foods such as elastic gels. The disadvantages are that the shaping and preparation of the sample are time consuming. Also, it is not suitable for sticky foods such as caramels and very soft foods such as some cheeses (Truong and Daubert, 2000).

Bending and Snapping Test

Bending and snapping tests are usually applied to food that is in the shape of a bar or sheet. The two most common types of apparatus are shown schematically in Fig. 4.27. On the left side is the triple beam apparatus in which the piece of food rests on two supports and a third compressing bar moves down between the two supports bending the food until it snaps.

The Bailey Shortometer is used in the baking industry to measure the shortness and snapping properties of crackers and cookies (Bailey, 1934). The Struc-O-Graph manufactured by the Brabender Company uses the triple-beam principle for measuring snapping and bending in food (see page 212).

The right-hand side of Fig. 4.27 shows a cantilever beam where the product is held at one end and is allowed to bend freely throughout its length. The amount of bending is measured either by the distance that the unsupported end of the food moves or by the angle it subtends to the horizontal plane. Sterling and Simone (1954) used the cantilever beam principle to measure bending and crispness in almonds. Several laboratory-made instruments that use this principle have been described in the literature; for example, the R.P.C. Droopmeter that measures the bending of french fries under gravity (Anonymous, 1966).

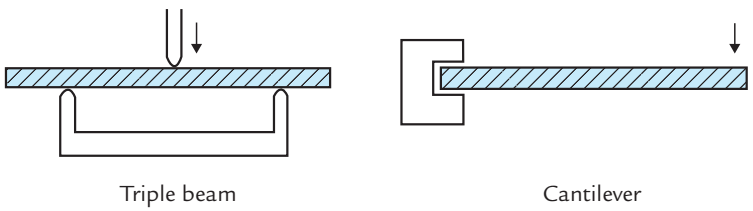


Figure 4.27 Two ways to perform bending and snapping tests.

Somers (1965) gave the following equation for the bending of slices of raw potato 28 mm × 13 mm × 1 mm thick held at one end and considered to be a cantilever:

$$Y = Wl^4/8EIL \tag{4.15}$$

where Y is the downward deflection of the potato strip, W the weight of beam, l the projected length of the beam (distance from clamp), L the total length of beam, E the apparent elastic modulus and I is the moment of inertia of the cross section.

Suhendro *et al*. (1998) mounted 30-mm wide strips of corn tortilla that projected horizontally 6.45 mm from a special clamp mounted in the TA.XT2 Texture Analyzer using cantilever geometry and measured the force required to bend it down 40° from the horizontal position. They reported that the bending force was significantly correlated with subjective scores for rollability and flexibility.

Snappy foods are typified by a rigid unbending texture that breaks suddenly once the fracture force has been reached. Bruns and Bourne (1975) studied snapping in foods and found that the force required to snap a test specimen of uniform cross-section complies with mathematical models derived from engineering theory. For uniform bars with a rectangular cross-section the snapping equation is as follows:

$$F = 2/3\sigma_c bh^2/L \tag{4.16}$$

where F is the snapping force; σ_c, the failure stress; b, the width of beam; h, the height of beam; and L, the length of beam between supports. For uniform bars with a cylindrical cross section the snapping equation is

$$F = \sigma_c \pi R^3/L \tag{4.17}$$

where F is the snapping force; σ_c, the failure stress; R, radius of beam; and L, the length of beam between supports.

The above equations establish the importance of using samples of uniform size and shape in this type of test. Particular attention needs to be paid to the thickness of the sample because the snapping force is proportional to the square of the thickness or cube of the diameter. If it is impossible to obtain test pieces of uniform size and shape, it is advisable to correct the force data according to the equations above.

Leighton *et al*. (1934) used the sagging of ice cream bars resting on two supports as a means of measuring the apparent viscosity. They used the equation

$$\eta = 5gmL^3/1152RI \tag{4.18}$$

where η is the viscosity; g, the gravity constant; m, the mass of sample; L, the length between supports; R, the rate of sag in centimeters per second; and I, the moment of inertia of a cross section ($0.049D^4$ for a beam of circular cross section with diameter D). These workers found that the apparent viscosity of ice cream was in the range of 2×10^7 Pa·s. This seems to be a useful method

for measuring extremely high viscosities. Coulter and Combs (1936) used Leighton's method to determine the sagging properties of butter.

Van Hecke *et al*. (1995) noted that standard bending tests for engineering materials propose that the length of the specimen should be at least 16 times the thickness because shearing and compression factors come into play when the length/thickness ratio is less than about 16. They found this requirement held for crispy-puffed foods where the deformability modulus increased as the length/thickness ratio increased from 8 to 20 and was relatively constant when the ratio exceeded 20. In reviewing published values for bending–snapping tests on foods Van Hecke *et al*. (1995) noted that many of the reports use a length/thickness ratio less than 16 which brings into question whether the data are really reporting a pure bending test.

Baltsavias *et al*. (1997) found that short-dough biscuits subjected to a three-point bending test had a slightly higher fracture stress and strain when the bottom side of the biscuit was upwards than when in the reverse position. They attributed this to air cells on the bottom side acting as sites for stress concentration. Baltsavias *et al*. (1997) used length/thickness ratios of 13.3 and 20 and found no difference in results between these two span lengths.

Although the three-point bending test in which the sample is supported on two parallel beams is the most widely used geometry for the bending–snapping test, other geometries are sometimes used. For example, Bourne *et al*. (1966) supported potato chips over a hollow ring and used a circular die to fracture them whereas Segnini *et al*. (1999) supported potato chips on three pins spaced 15 mm apart in the shape of an equilateral triangle and used a 5.3 mm diameter rounded face punch to fracture them.

Alvarez *et al*. (2000) cut rectangular beams 40-mm long × 4-mm wide × 8-mm high from apple, carrot, celery and cucumber and mounted them on parallel supports spaced 32 mm apart for a triple-beam fracture test. Before snapping these beams, an artificial crack in the form of a notch was made in the center of the underside of the specimen by pushing a sharp razor blade about half-way into the specimen. This is called single-edge notched bend (SENB) geometry which is a well-established test procedure for metals and polymers. Alvarez *et al*. (2000) found SENB geometry was readily applicable to crisp foods that exhibit linear elastic behavior up to fracture.

Distance Measuring Instruments

Distance measurements may be divided into three classes: (1) linear measurement with dimension of length, (2) area measurement with dimension length^2, and (3) volume measurement with dimension length^3.

Linear Measuring Instruments

A number of simple testing apparatus that are based upon distance measurements are known, including the Bostwick Consistometer, which measures the

distance catsup and fruit puree flow along a horizontal trough; the Hilker–Guthrie Plumit, which measures the depth a cylindrical metal rod falls into sour cream and yogurt; the Ridgelimeter, which measures the sag of fruit jellies as a means of obtaining the grade of pectin; and the Haugh egg quality meter, which measures the height the white of an egg stands up after breaking out from the shell. The principle of measurement of these instruments is so simple that it needs no analysis. The instruments themselves will be described in the following chapter.

A ruler, calipers, or other well-known measuring length instruments are suitable for simple applications. For example, Hoseney *et al*. (1979) measured the spread of mechanically rounded balls of dough allowed to rest on a smooth plate with dial calipers and calculated a spread ratio = width/height of the dough ball. A higher value indicates more spread. The factors affecting the spread ratio are gravity, pressure of gas developed by the yeast and cohesive forces within the dough. Dogan and Walker (1999) calculated the spread of cookies after baking and cooling by measuring the width (w) and height (h) and calculating the spread factor as $10\,w/h$. For sugar snap cookies they reported spread factors ranging from 86 to 102.

Arnott *et al*. (1957) measured the meltability of cheeses by placing cylinders of cheese 22-mm diameter × 17-mm high in the center of a glass Petri dish and baking in a convection oven at 100°C for 15 min. After cooling, the height and diameter of the melted cheese mass is measured, and the average value calculated. Other researchers using this procedure call it the 'Arnott Test'. Yang *et al*. (1983) used the Schreiber melting test for cheese by placing a disk of cheese 2.3-cm diameter × 0.5-cm high in the center of a 10-cm diameter Petri dish with a glass cover and baking it for exactly 5 min in an electric oven preheated to 232°C. The diameter after baking was measured by placing the disk on a series of concentric circles with lines drawn 0.65-cm apart. Guinee *et al*. (1999, 2000) measured the flowability of melting cheese by placing cheese disks 6.5-mm thick and 45.5-mm diameter in an oven at 280°C for four minutes then measuring the diameter. They defined flowability as the percentage increase in diameter of the disk after baking.

Robertson and Emani (1974) injected a stream of liquid dye at high velocity (10^3–$10^4\,cm\,s^{-1}$) through a small orifice (0.254-mm diam) for a short time (0.1 s) into bread. The energy of the stream is absorbed by the bread; hence, the distance the stream of dye penetrated is an index of bread texture. Good correlations are reported between sensory tests of bread aging and the liquid jet penetrometry data.

Penetrometer

The Penetrometer consists of a cone and vertical shaft assembly that is allowed to sink into a solid fat under the force of gravity for a standard time after which the depth of penetration is measured. The left-hand side of Fig. 4.28 demonstrates the principle. According to Haighton (1959) the following formula applies to cone penetration on solid fats of a wide range

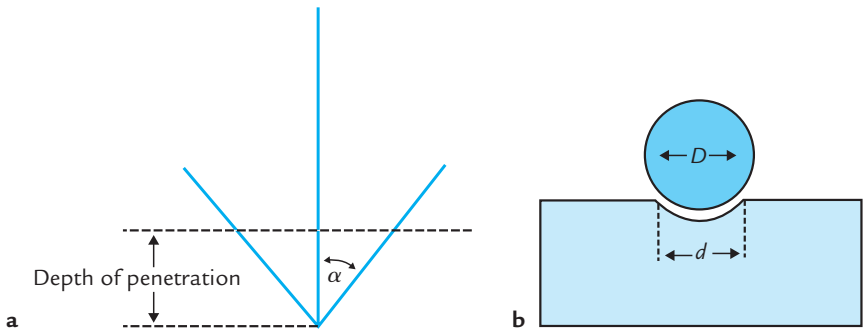


Figure 4.28 Principle of (a) the penetrometer cone and (b) the ball indenter.

of hardness:

$$C = KW/p^{1.6} \tag{4.19}$$

where C is the yield value of the product, K, a constant whose value depends on the cone angle, W, the weight of cone assembly in grams, and P, the penetration depth after 5 s.

Mottram (1961) derived a similar formula from studies of penetrometer tests on printing inks:

$$S_0 = KMg/h^n \tag{4.20}$$

where S_0 is the yield value, M, the mass of cone assembly in grams, g, a gravity constant, h, the depth of cone penetration, $n \simeq 2$ but varies according to the type of material, and K, a constant depending on cone angle.

Although Mottram's terminology is not the same as Haighton's, Eqs. (4.19) and (4.20) are similar in their essential features.

Mottram published an equation for the constant K as follows:

$$K = (\cos^2 \alpha \cot \alpha)/\pi \tag{4.21}$$

where $\alpha = \frac{1}{2}$ cone angle (see Fig. 4.28).

Dixon and Parekh (1979) used a cone penetrometer to measure the firmness of butter and developed the equation

$$\text{butter firmness} = \frac{\text{cone mass} \times (\text{cone angle})^{-1.65}}{(\text{penetration depth})^2}$$

These researchers found that this equation accounted for 96.9% of the variation in observations and 91% of the variation in sensorially perceived spreadability of butter.

Hayakawa and deMan (1982) reviewed the literature on methods of converting penetrometer distances into reproducible units with scientific measuring and proposed a Hardness Index HI, where: HI = mass of cone assembly/penetration depth.

These authors also pointed out that different authors recommend different ranges of penetration readings as suitable for good reproducibility:

- Haighton (1959) 7.5–25 mm

- Mortensen and Danmark (1978) (cited by Hayakawa and deMan) 5.0–30 mm
- Dixon and Parekh (1979) 2.0–15 mm
- Hayakawa and deMan (1982) 1.5–15 mm

The American Oil Chemists Society has a standard for penetrometer used for measuring the consistency of fats (AOCS Method Cc16-60) and this procedure is also an official method for the American Association of Cereal Chemists (method 58-14).

Another type of penetration test that is used on fats and similar products is the ball indenter that is the principle of the SURDD tester (see Fig. 4.28). A steel ball is pressed onto the material with a constant force for a given time, then it is removed and the diameter of the impression measured (Feuge and Guice, 1959). This test is similar in principle to the Brinell and Vickers hardness testers that are used to measure hardness of metals. The following equation applies to this test:

$$H = 100P/(\pi D/2)[D(D^2 - d^2)^{1/2}] \tag{4.22}$$

where H is the hardness index in kilograms per square centimeter; P, the kilogram force on ball; D, the diameter of ball in millimeters (usually in the range 3–12 mm for fats); and d, the diameter of impression in material.

The same principle is used in the Smetar hardness tester, which measures the hardness of wheat grains by the size of the impression made by a diamond indenter (Smeets and Cleve, 1956). It is also used in the adaptation of the Barcol Impressor to measure the hardness of wheat grains (Katz *et al*., 1959, 1961).

Rebound Distance

When dry, mature peas that have been soaked and cooked are bounced off an inclined surface, the horizontal distance they rebound is a function of their elasticity coefficient and is related to textural quality (Crean and Haisman, 1965). Firm peas bounce farther than soft peas. Asymmetry of rheologically identical peas causes some scatter, but the method can fractionate peas into several fractions on the basis of their firmness. The principle of the test is shown in Fig. 4.29. The relationship between rebound range and firmness as measured by the Maturometer is shown in Fig. 4.30. These authors developed the following equation for perfect spheres having known coefficients of elasticity:

$$\text{rebound range} = tv\cos(\phi + \alpha - 90) \tag{4.23}$$

where $t = [-v\sin(\phi + \alpha - 90) \pm (v^2\sin^2(\phi + \alpha - 90) + 2gh)^{1/2}]g^{-1}$; $v = u(\sin^2\alpha + e^2\cos^2\alpha)^{1/2}$; ϕ is the angle at which pea leaves the plate and equals $\cot^{-1}(e\cot\alpha)$; α, the angle of the plate to the horizontal; u, the velocity of pea just before hitting the plate; e, the coefficient of elasticity of the pea; h, the height of the point of impact above the collecting box; and g, a gravitational constant. The principle of rebound distance has been used for more than a century by the cranberry industry of northeastern United States to separate soft and substandard cranberries from sound fruit. Bryan *et al*. (1978) used the principle of

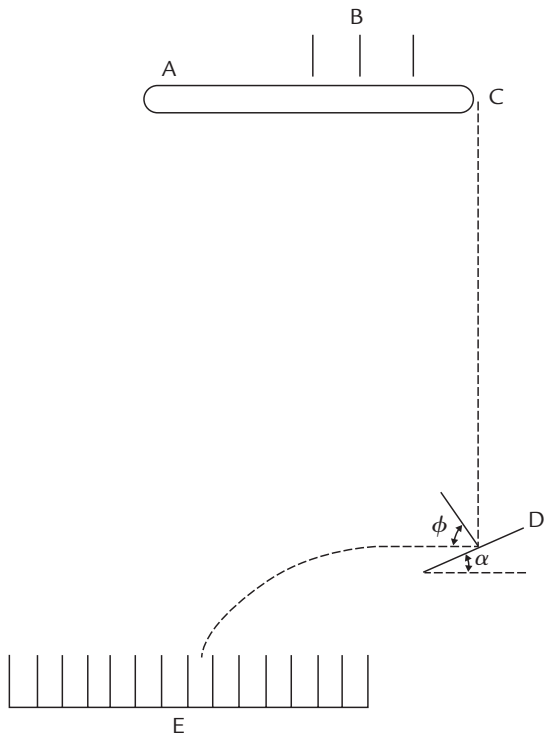


Figure 4.29 Principle of the rebound test: individual peas sorted into single file by gates B fall off conveyor belt AC onto inclined surface D and bounce into compartments at E. (Reprinted with permission from Blackwell Scientific Publications.)

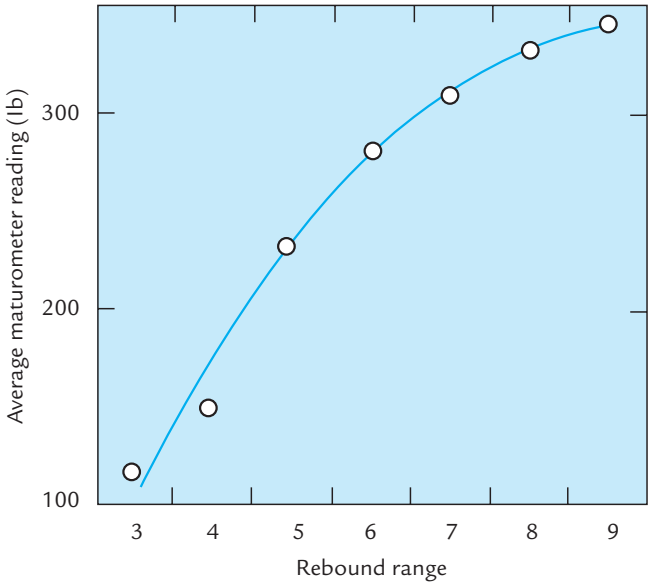


Figure 4.30 Maturity of peas versus rebound range in the bounce test (see Fig. 4.29). (Reprinted with permission from Blackwell Scientific Publications.)

rebound distance to separate cull oranges that have a low coefficient of restitution from sound fruit that have a higher coefficient of restitution.

Hamann and Carroll (1971) used a vibratory technique that depends on elasticity to separate muscadine grapes into maturity grades based on firmness and to separate bruised blueberries from sound blueberries (Hamann *et al.*, 1973).

Lichtensteiger *et al.* (1988) measured the impact force response of tomatoes of about the same mass. The green tomato (firm) had the highest peak force

and the shortest contact time, the red tomato (soft) had the lowest peak force and the longest contact time whereas the pink tomato was intermediate in peak force and contact time.

Botta (1991) measured the rebound distance of raw cod fillets by compressing them to 500 g force under a 2.5 cm diameter platen, then reducing the force to 1 g and measuring the distance the fillet rebounded after 1 s. The ratio rebound distance/initial deformation agreed with the texture grades of three Fish Inspection Officers 75–86% of the time.

Deformation

Deformation is the change in height or diameter of a food under the application of a force. Implicit in this definition is the assumption that this is a non-destructive test; that is, the amount of force applied is less than that required to break, rupture or cause any other irreversible damage to the commodity. This physical property is usually measured sensorially by squeezing the food in the hand. Deformation is generally considered to be one method of measuring the 'firmness' of a commodity. In fact it is preferable to consider it as a measurement of 'softness' because the firm product gives a lower reading than the soft product.

Figure 4.31 shows schematically a straight-line force–compression relationship for a firm, medium, and soft commodity. The deformation test usually measures the deformation under a standard force. The application of force *F* to three ideal commodities gives deformations *f*, *m*, and *s*, respectively, for the firm, medium, and soft product (Fig. 4.31a). Occasionally the force required to achieve a standard deformation is used (Fig. 4.31b) where standard deformation *D* is achieved by forces *s*, *m*, and *f*. In this case the firm product will give a higher numerical value than the soft product, but there is a risk that the firm product will break under the high force required to achieve the standard deformation.

Although deformation is widely used sensorially for measuring firmness of foods, there is little in the way of instrumentation available for this test. The Baker Compressimeter is a commercially available instrument that is used for measuring the firmness of bread crumb, the Ridgelimeter is used to measure

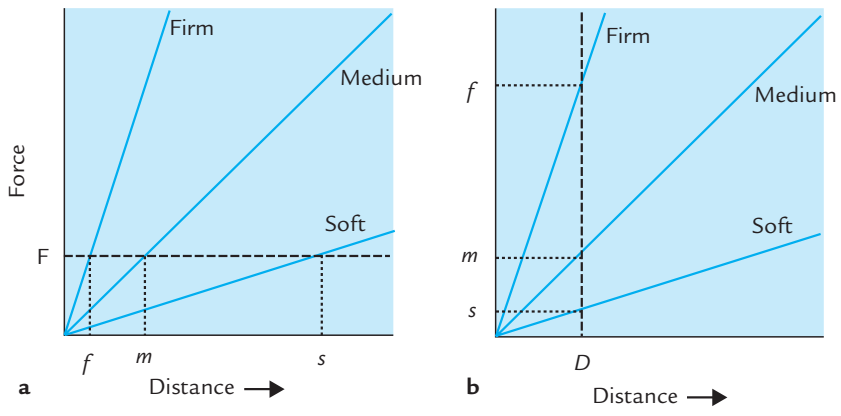


Figure 4.31 Deformation of ideal, firm, medium and soft solids: (a) compression distance is measured at constant force *F*; (b) force required to achieve a standard compression is measured.

the quality of pectin in fruit jellies (Cox and Higby, 1944), and the Marius egg deformation tester is available for measuring the deformability of whole eggs. The Instron has been adapted for performing deformation testing (Bourne, 1967a), and equipment similar to the Instron such as the TA.XT2 Texture Analyzer could also be adapted in a like manner. The Penetrometer can also be adapted for deformation testing of foods that are not too rigid or too small (Bourne, 1973).

Figure 4.32 shows the most common types of force–deformation curves that are found on foods. The majority of products give an A type curve that is concave downward: this shape is typical of products such as marshmallows and the softer fruits and vegetables. The linear B type curve is found with rigid products such as firm green fruits and vegetables, hard candy, and eggs in the shell. This type obeys Hooke's law, which states that the deformation of a body is directly proportional to the force applied to it. Hooke (in 1678) enunciated this law on the basis of tension experiments with metal springs, but any body that obeys this law in tension or compression is called a Hookean solid. The C type curve, which is S shaped, is found with breads, cakes and other highly aerated deformable foods and some cheeses.

It is obvious that the higher the applied force the greater will be the deformation, even when the relationship is nonlinear. From the geometry of Fig. 4.32 it can be seen that the deformation of a B type product is directly proportional to the applied force; hence, the deformation at two forces F_1 and F_2 are directly proportional to those forces; that is,

$$b_1/b_2 = F_1/F_2$$

Type A products are characterized by a rapid rate of increase in deformation at low force with the rate decreasing as the force increases; that is,

$$a_1/a_2 > F_1/F_2$$

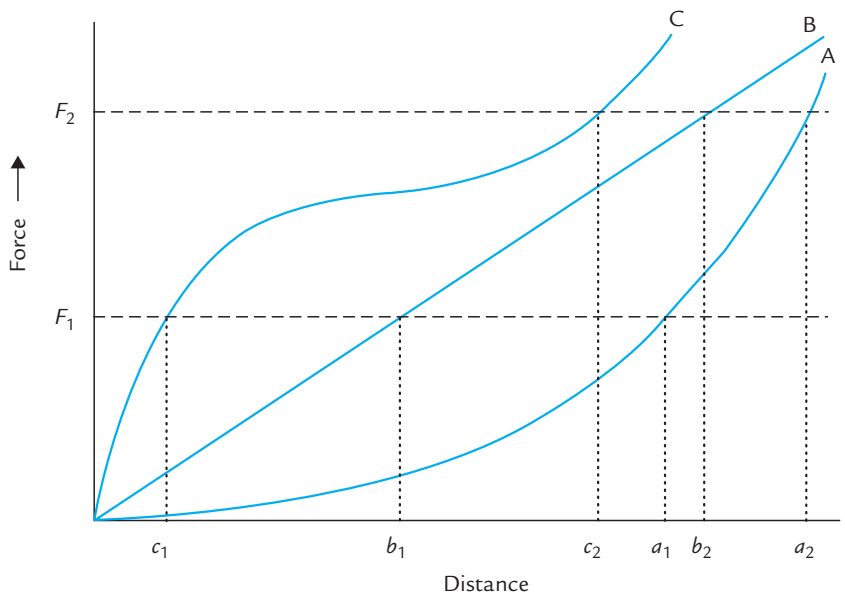


Figure 4.32 Three characteristic types of force–deformation behavior.

Table 4.8 Deformation of Marshmallows

Deforming force (g)	Deformation (mm) A. Soft	B. Firm	Deformation ratio (A/B)
20	0.80	0.022	3.64
100	2.32	0.92	2.52
1000	10.7	6.9	1.55
5000	18.7	14.9	1.25

Source: Data from Bourne (1967a): reprinted from *J. Food Sci.* **32**, 605, 1967. Copyright by Institute of Food Technologists.

For C type products the deformation increases slowly at first and then more rapidly as the force is increased; hence,

$$c_1/c_2 < F_1/F_2$$

Barrett *et al*. (2000) postulated three different behaviors for breads that exhibit the typical C-type curve shown in Fig. 4.32:

Part I. Low force – linear elastic deformation occurs.
Part II. Medium force – plastic buckling of cell walls dominates.
Part III. High force – densification of the aerated structure occurs.

Since the relationship between force and distance is linear in B type products the degree of force that is applied does not change the deformation ratio when comparing two samples. For A type products greater resolution between samples that are of similar quality is obtained with a small deforming force. This is demonstrated in Table 4.8 which shows the deformation of a fresh, soft marshmallow and a stale and firmer marshmallow. The amount of deformation increases as the deforming force increases for both marshmallows, but the ratio of the deformations declines with increasing force. Table 4.9 shows that a similar relationship exists for apples. Under 2-kg force the ratio of the deformations of a flaccid and firm apple was 3.2 whereas above 14 kg the ratios of the deformations became equal.

For foods that exhibit A type characteristics it is desirable to use as small a deforming force as practicable in order to achieve maximum resolution between samples. In order to maintain equivalent resolution, the degree of precision in the measurement of distance must be higher for firm foods than for soft foods because the change in the height of the firm food is less than for soft food.

Geometry of the Test Specimen

Small irregularities in the surface of the test product have the potential to give large errors in deformation. This is demonstrated in Fig. 4.33, which shows the deformation curves on vertical cylinders cut from a single frankfurter and

Table 4.9 Deformation of Rome Apples When Squeezed

Force range (kg)	Deformation of flaccid apple (mm)	Deformation of firm apple (mm)	Ratio $\frac{\text{Flaccid apple deformation}}{\text{Firm apple deformation}}$
0–2	2.7	0.85	3.2
2–4	1.0	0.4	2.5
4–6	0.7	0.3	2.3
6–8	0.55	0.3	1.8
8–10	0.45	0.3	1.5
10–12	0.4	0.3	1.3
12–14	0.4	0.3	1.3
14–16	0.3	0.3	1.0
16–18	0.3	0.3	1.0
18–20	0.3	0.3	1.0

Source: Data from Bourne (1967b); reprinted with permission of New York State Agricultural Experiment Station.

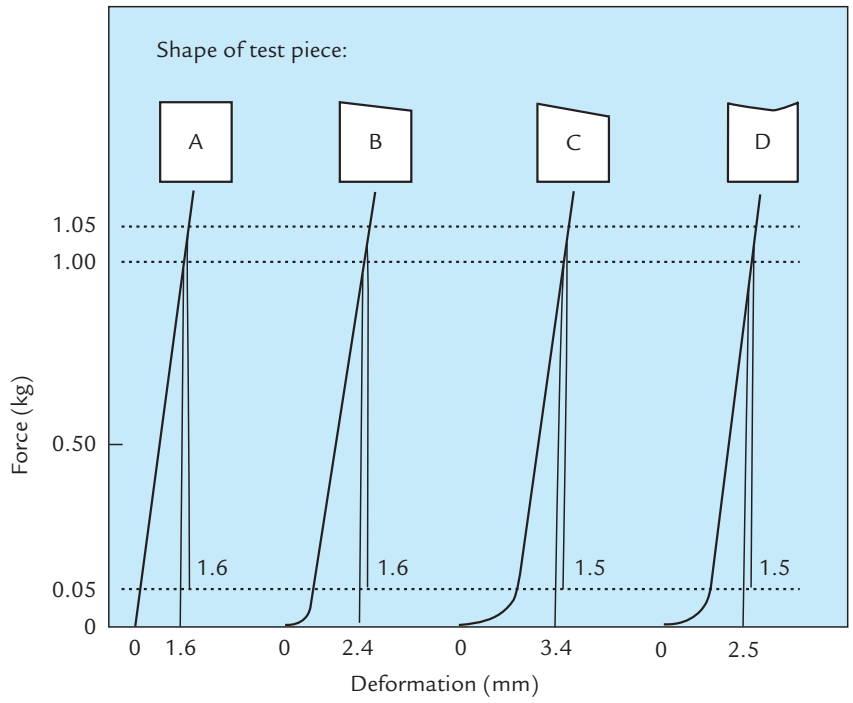


Figure 4.33 Effect of irregularities in surface of test piece on deformation test. Note how the errors are overcome by starting the deformation a little above zero force. (From Bourne, 1967a; reprinted from *J. Food Sci.* 32, 603; copyright by Institute of Food Technologists.)

tested in the Instron. The first curve was obtained on a piece with plane, parallel ends; the next two curves were obtained on test pieces with plane ends that were not parallel; and the last curve was obtained on a test piece with one end curved. The effect of these irregularities in shape is to produce a 'tail' at the low force end of the curve. These tails represent that portion of the deformation when less than the complete cross-sectional area of the test piece is being compressed. They can introduce large errors into the measurement. The test pieces A–D, all cut from the same frankfurter, show deformations of 1.6,

2.4, 3.4, and 2.5 mm under a 1 kg deforming force. This source of error can be overcome by measuring the deformation from some reference force level that is sufficiently above zero to eliminate the effect of the tails. In this case, the deformations of these four test pieces measured between 0.05 and 1.05 kg are 1.6, 1.6, 1.5, and 1.5 mm, which is as uniform as one can expect. Although every care should be taken to minimize the small irregularities at the contact surfaces, corrections for these irregularities can be made by beginning the deformation measurements slightly above zero force (Bourne, 1967a).

When the deformation test is performed in a universal testing machine a 'trigger force' can be installed in the PC program that starts the measurement of compression distance when the trigger force is reached.

For those commodities that give a linear or near-linear force–deformation relationship (i.e. they obey Hooke's law), and also for other commodities that are stressed lightly, it has been shown that the deformation is directly proportional to the height of the samples if the cross-sectional area is uniform (e.g. rectangular or circular in cross section).

The equation for Young's modulus of elasticity (see p. 68) can be rearranged as follows:

$$\Delta L = FL/EA \tag{4.24}$$

Young's modulus of elasticity E is constant for a given sample; hence, if a constant force F is used, the deformation (ΔL) is directly proportional to the unstressed height L and inversely proportional to the area A. This equation has been confirmed on rectangular solids and upright cylinders cut from agar gels (Brinton and Bourne, 1972).

The deformation of horizontal cylinders of a commodity is inversely and linearly proportional to the length of the cylinder.

The effect of the changing diameter is more complex. According to Roark (1965), the change in diameter of a horizontal cylinder under compression is given by the equation

$$\Delta D = \frac{4}{3} P \frac{(1-v^2)}{\pi E} + 4P \frac{(1-v^2)}{(\pi E)} \log_e \frac{(DE)^{1/2}}{1.075 P^{1/2}} \tag{4.25}$$

where D is the diameter; ΔD, the deformation; P, the force per unit length; v, Poisson's ratio; E, Young's modulus; and b, 2.15 $(PD/E)^{1/2}$. According to this equation, the deformation of a horizontal cylinder is the sum of the two terms. The first term $\frac{4}{3} P(1-v^2)/\pi E$ is independent of the diameter and second term is a complex function of the diameter. Experimental data on cylinders of agar gels is in general agreement with Eq. (4.25) (Brinton and Bourne, 1972).

The effect of changing the diameter on the deformability of spheres is complex because the deformation versus diameter plots are U-shaped. As the diameter increases, the deformation first increases, levels off and then decreases. The peak deformation is found at smaller diameters as the stiffness at the gel (concentration of agar) increases. The peak also occurs at smaller diameters as the deforming force is decreased.

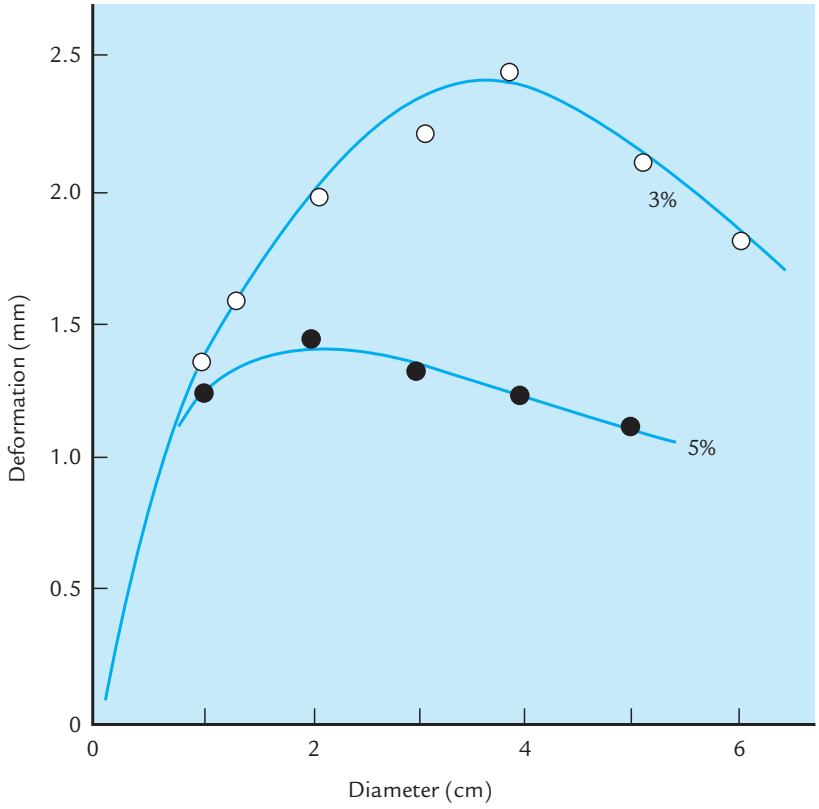


Figure 4.34 Effect of diameter on deformation of 5 and 3% agar gel spheres illustrated by ● and ○, respectively. (From Brinton and Bourne, 1972; reprinted from *J. Texture Studies* **3**, page 293, with permission from Food and Nutrition Press.)

Figure 4.34 shows that changing the diameter of a sphere can cause the deformation to increase under some circumstances, and decrease under other circumstances depending on whether increasing the diameter causes the deformation to approach the peak or move away from it. The peak deformation appears to be a complex function depending on the rigidity of the gel and the force of deformation. If a 5% gel deformed between 50 and 200 g force is considered typical of the type of test that is commonly applied to whole fruits, it can be seen that there is a comparatively small change in deformability over a wide range of diameters. From 1 cm up to 5 cm diameter, the minimum deformation is 1.1 mm and the maximum deformation is 1.4 mm. A 500% change in diameter causes a maximum change of about 30% in deformation. Except with small diameter 3% soft gel spheres, the rate of change in deformation is comparatively small compared with the change in diameter. From this evidence we draw the tentative conclusion that small changes in diameter will have only a slight effect on the deformation of a food that is approximately spherical in shape.

According to Hertz theory, the deformation of a rounded specimen compressed between parallel plates is given by the equation:

$$E = \frac{0.338F(1-\mu^2)}{D^{3/2}}\left[K_1\left(\frac{1}{R_1}+\frac{1}{R_1'}\right)^{1/3} + K_2\left(\frac{1}{R_2}+\frac{1}{R_2'}\right)^{1/2}\right]^{3/2} \qquad (4.26)$$

where E is the modulus of elasticity; F, force; μ, Poisson's ratio; D, deformation; K_1, K_2, constants; R_1, R'_1, R_2, R'_2, radii of curvature at contact points.

Equation (4.26) can be rearranged and simplified for the case of flat plates compressing a sphere to give:

$$D = \left[\frac{0.338F(1-\mu^2)}{E}\right]^{2/3} \frac{k}{R^{1/3}} \tag{4.27}$$

This equation predicts an inverse relationship between deformation and radius (deformation $\propto R^{-1/3}$). The Hertz theory agrees qualitatively with the experimental data for large spheres but it fails to agree for small diameter agar spheres where there is a direct relationship between increasing diameter and increasing deformation.

Roark (1965) gives the following formula for deformation of a sphere under a flat plate:

$$y = 1.55\left(\frac{P^2}{E^2 D}\right)^{1/3} \tag{4.28}$$

where y is the combined deformation of sphere and compressing plate; P, total load; E, Young's modulus and D, diameter of sphere. According to this formula, the deformation should be proportional to $(D)^{-1/3}$ which is similar to the conclusion of the Hertz equation. It should be pointed out that Roark's equation is intended to be applied to ball bearings and similar objects in which the compressing plate and the test sphere presumably have similar mechanical properties. The modulus of an agar gel is different from that of the metal compression plate by several orders of magnitude. However, Roark's equation may apply over a limited range of large diameters for foods.

Real foods of approximate spherical shape such as cherries, apples, onions, tomatoes, and papayas have a far more complex structure than agar gels. As Morrow and Mohsenin (1966) have pointed out: 'an intact product such as fruit violates all fundamental assumptions of homogeneity, isotropy, and continuity that are normally required in solving elementary materials science problems.' When we add to the complex function between deformation and diameter of a uniform material such as an agar gel the additional complexities of the structure of intact foods, the need for additional research, both practical and theoretical, is indicated in order to understand how the diameter affects deformation. It may be that there is a different relationship for each commodity.

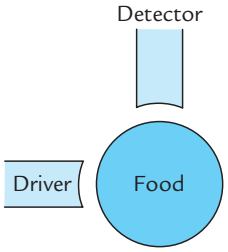


Figure 4.35 Schematic of acoustic spectrometer method for measuring deformability.

Deformation by Acoustics

Another method of measuring what is, in effect, deformation of a food is an acoustical method. The principle is shown in Fig. 4.35. A sound speaker which is the driver is placed in contact with a food and caused to produce sound (sonic waves) of constant amplitude which is transmitted into the food. The frequency of the vibration is gradually increased from a low to a high value.

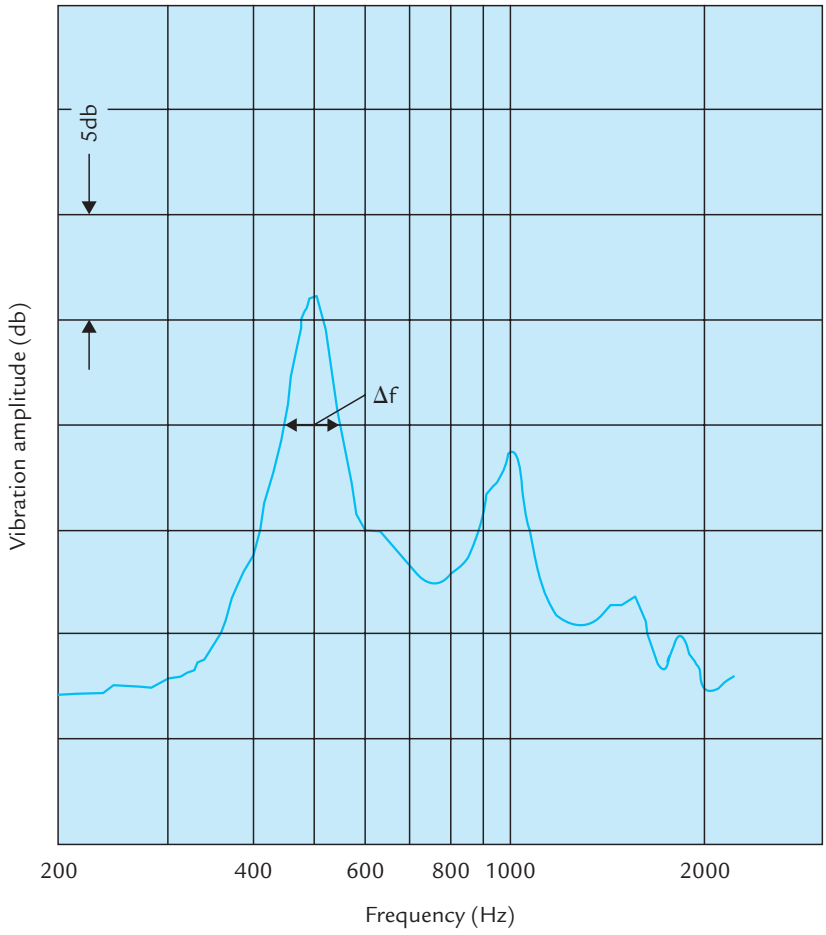


Figure 4.36 A recorder curve showing amplitude of vibration of a fruit versus the frequency of the input vibration. (From Finney *et al*., 1968; reprinted from *J. Food Sci.* **32**, 643; copyright by Institute of Food Technologists.)

A microphone placed in contact with the food at a position 90° to the driver acts as a detector or receiver to pick up the vibrations within the food at each frequency. Electronic equipment plots the amplitude of vibration within the food as a function of the driving frequency. The method has been used for research purposes by Abbott *et al*. (1968a,b), Finney and Norris (1968), Finney *et al*. (1968, 1978), Finney (1970, 1971a,b,c) and is reviewed by Finney (1972).

A typical curve is shown in Fig. 4.36. The amplitude–frequency relationship shows a series of peaks that occur at regular intervals. The first amplitude peak is called the 'resonance frequency' because the natural period of vibration of food is the same as the driver at this frequency. Additional peaks are found at the first, second, and third harmonics, which are simple multiples of the resonance frequency and occur at exactly two times, three times, etc., the frequency of the resonance frequencies.

If the food is in the shape of a uniform cylinder, Young's modulus of elasticity can be calculated from the resonance frequency (assuming the food is elastic, isotropic, homogeneous, and continuous) by means of the following equation:

$$E = 4\rho f^2 L^2 \qquad (4.29)$$

where E is Young's modulus of elasticity (dynes per square centimeter); ρ, the density (grams per cubic centimeter); f, the fundamental longitudinal frequency in hertz (cycles per second); and L, the length of the cylindrical specimen in centimeters.

Since it is frequently inconvenient and sometimes impossible to cut a uniform cylinder of tissue, attempts have been made to measure the firmness of intact units that are approximately spherical in shape. For these cases Finney (1971a) defines a 'stiffness coefficient' as f^2m, where f is the resonance frequency and m the mass of the article. Cooke (1972) and Cooke and Rand (1973) made a theoretical analysis of the deformation of spheres which indicated that $f^2m^{2/3}$ should be the mass independent indicator of the shear modulus rather than f^2m as used by Finney. Clark and Shackelford (1976) used the stiffness modulus $f^2m^{2/3}$ on peaches with limited success. Abbott *et al*. (1997) provide a good update of this technique.

Slump Test

The slump test is claimed to have been initially developed to determine the flow properties of freshly mixed concrete (Pashias *et al*., 1996) but it seems likely that the principle has been used just as long, or even longer, for foods. The American Society for Testing and Materials publishes a standard method for measuring the slump of freshly mixed concrete using the frustum of a cone 31 cm high with lower diameter 20 cm and upper diameter 10 cm (ASTM, 1990, Method C143-90). It provides an inexpensive, quick, easy and effective way to measure the yield stress of high density suspensions. In this test a hollow cylinder is placed on a horizontal surface, filled level to the top with the food, then the cylinder is gently removed and the food is allowed to flow out in a horizontal direction under the force of gravity. This is a time-dependent free-surface flow. The profile of the final mound of material as well as the dynamics by which the final shape is attained are governed by the rheology. Two methods are used to measure the degree of slump.

Method 1 is used for stiff foods. It simply measures the height of the sample after a standard time. This is the basis of an official US Department of Agriculture quality measurement of canned pumpkin pie filling that became effective in July 1957 which requires that cans of grade A (US Fancy) pumpkin or squash shall retain not less than 60% of the original height of the container surface for cans smaller than no. 3 size, and not less than 50% for no. 3 size cans and larger when emptied onto a horizontal surface and allowed to stand for two minutes (Fig. 4.37).

Method 2 is used for foods that have a lower yield stress. The diameter of the slumped food is measured. This is the basis of the Adams Consistometer, the TUC Cream Corn Meter and the USDA Applesauce Consistometer (see Fig. 5.14, page 224).

Pashias *et al*. (1996) summarize the theory behind the slump test and note that it offers a robust and inexpensive method for directly measuring the yield stresses in the range 30–800 Pa. They derive the following equation that gives

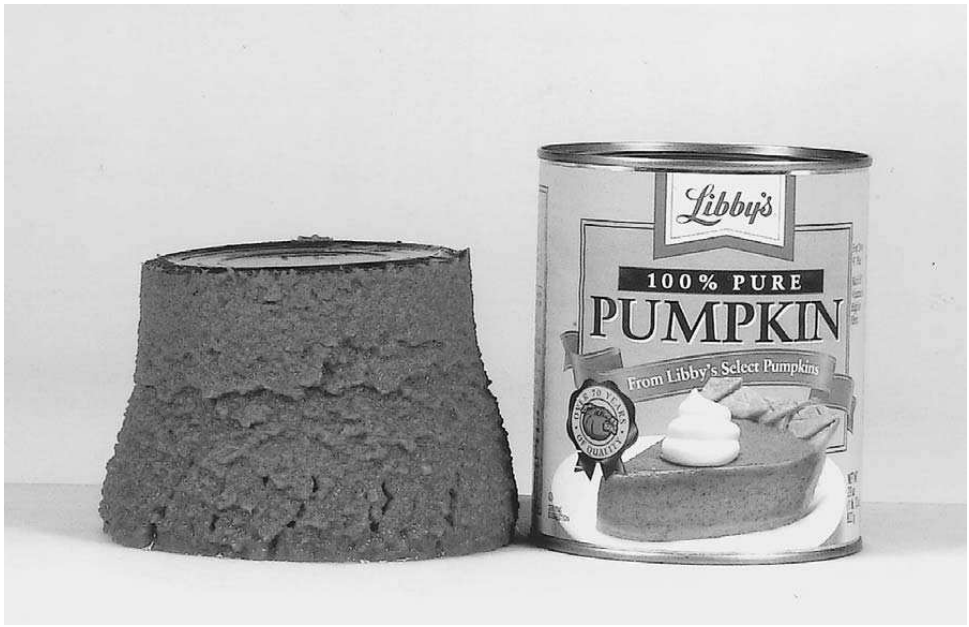


Figure 4.37 The slump test performed on canned pumpkin pie filling. This sample is grade A (US Fancy) because it retained more than 60% of its height after being removed from the can.

a close approximation to the yield stress:

$$\tau_y^1 = \frac{1}{2} - \frac{1}{2}\sqrt{s'} \tag{4.30}$$

where τ_y^1 is yield stress; s' dimensionless slump value, i.e. (original height − slump height)/original height.

Showalter and Christenson (1998) derived the following equation for the slump test of a Bingham solid:

$$s' = 1 - h_0' - 2\tau_y' \ln\left(\frac{7}{(1+h_0')^3 - 1}\right) \tag{4.31}$$

where s' is slump distance (decrease in height); τ_y, Bingham yield stress; h_0', height of unyielded portion after the slump. The prime signs ($'$) indicates that these are dimensionless numbers. These authors showed that this simple analysis mimics the experimental results at least as well as the far more sophisticated finite element solution for yield stress of Bingham materials, such as freshly mixed concrete, mayonnaise and toothpaste.

Omura and Steffe (2001) developed a centrifugal slump test to measure the yield stress of products such as cream cheese, margarine and peanut butter that are too stiff to flow under gravitational force alone. Cylinders of product 1.8-cm diameter × 1.8-cm high were cut with a cork borer and impaled on a pin protruding from a 20-cm diameter ring which was spun at speeds ranging

from 400 to 700 rpm yielding 18–55 *g* force. The height of the specimens was measured after spinning. The yield stresses calculated from this centrifugal slump test agreed well with values obtained by the vane method.

Two questions that seem not to have been addressed thus far are at what level of yield stress is it advisable to switch from method 1 (measure height) to method 2 (measure diameter) and when does the slump principle become the gravity flow principle.

Gravity Current Flow

A fluid that is released and allowed to flow under the influence of gravity primarily in a horizontal direction over a solid surface or another fluid of higher density is called 'gravity current flow.' Well-known examples are the spreading of an oil slick on the ocean, flow of volcanic lava and the Bostwick Consistometer that measures the thickness of tomato purees and similar products (Fig. 4.38). Three flow regimes have been identified in gravity currents (McCarthy and Seymour, 1993).

(1) Inertial regime occurs at very short times where the forces of inertia and gravity predominate.
(2) Viscous regime occurs at intermediate times where flow is determined by the balance of viscous and gravity forces.
(3) Surface tension regime occurs at long times where viscous forces are balanced by surface tension forces. The fluid thickness has decreased so much that gravitational forces play a minor role in the flow.

McCarthy and Seymour (1993) give the following equation for flow in the Bostwick Consistometer:

$$L = \xi_v \left(\frac{gq^3}{3\upsilon} \right)^{1/5} \cdot t^{1/5} \tag{4.32}$$

where L is length of gravity current; ξ_v the similarity value which is theoretically 1.41; g, gravitational constant; q, fluid volume per unit width; υ, kinematic viscosity; and t, time. Figure 4.39 plots the distance four Newtonian fluids flow along the trough of the Bostwick Consistometer versus time$^{0.2}$. The rectilinear relationships shown in this figure demonstrate that the flow of fluids in the Bostwick Consistometer can be modeled as a gravity current.

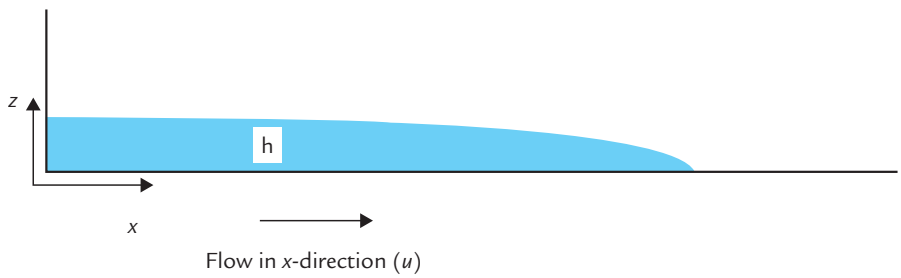


Figure 4.38 Length of gravity current as a function of time and position. (From McCarthy and Seymour, 1993. *J. Texture Studies* **24**, page 7. Copyright by Food and Nutrition Press Inc.)

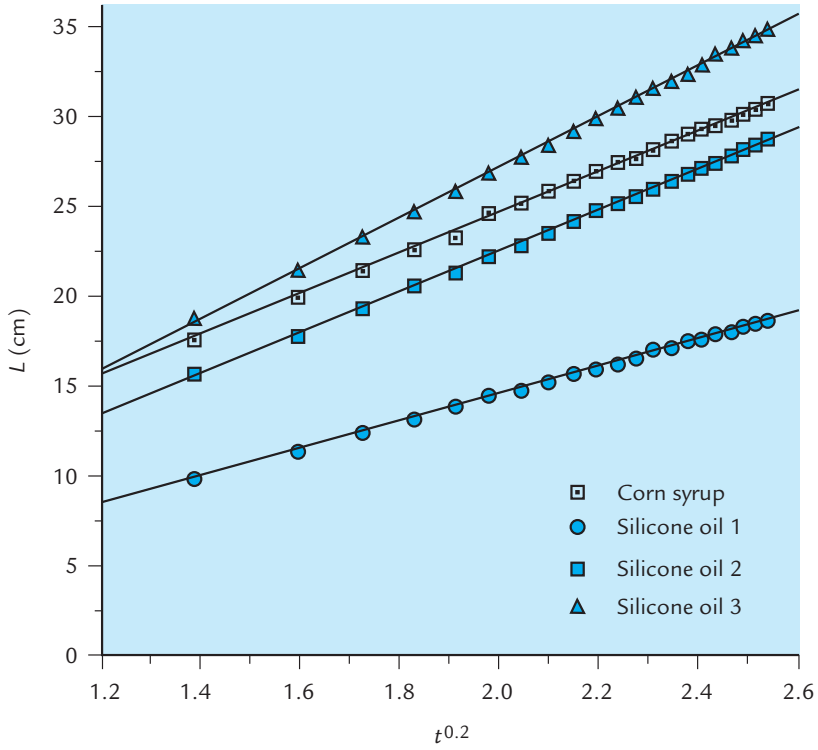


Figure 4.39 Experimental measurements of the distance four Newtonian fluids flow along the trough of the Bostwick Consistometer versus (time of flow)$^{1/5}$. (From McCarthy and Seymour, 1993. *J. Texture Studies* **24**, page 8. Copyright by Food and Nutrition Press Inc.)

Barringer *et al*. (1998) confirmed that the Bostwick reading is directly proportional to (kinematic viscosity)$^{0.2}$ and since kinematic viscosity is directly proportional to time it is equivalent to (time)$^{0.2}$.

McCarthy and Seymour (1993) conclude that the flow of fluids in the Bostwick Consistometer can be modeled as a gravity current, although some modifications are needed to account for the finite channel width of the apparatus and the non-Newtonian behavior of fruit and vegetable purees.

Area Measuring Instruments

There are probably no true area measuring instruments used in food texture measurements. Several consistometers such as the Adams Consistometer, the Cream Corn Meter, and the USDA Standard Consistency Tester (see page 224) measure the flow of a fluid or semifluid food from a circular container out across a horizontal plate and the diameter is measured at two points at right angles. This is a distance measurement rather than area but is close to area measuring instruments.

Particle Size Distribution

Analysis of particle size distribution of particulate foods by sieving is primarily based on area. Standard woven-wire sieves act as 'go–no go' gauges. Particulates with a cross-sectional area less than the screen aperture fall through (go) whereas those too large are retained (no go).

Most sieves are made with woven wires and have rectangular apertures. The American Society for Testing and Materials lists the apertures in the most widely used sets of sieves (ASTM Specification E-11-87). The sieve number is based on the number of wires per linear inch. The number of wires per inch usually increases approximately 1.4-fold for each step which means that the cross-sectional area (aperture) decreases by 2-fold in each step since $1.4^2 = 2$. The normal practice is to nest a series of sieves on top of each other with the coarsest sieve on top and the finest one at the bottom. The sample is placed on the top sieve, and the nest is shaken and tapped causing undersize particles to fall through while the rest of the material is held on that screen. Machines are available that give a standard shaking and tapping to the nest of sieves. The amount retained on each sieve is then weighed and expressed as percentage retained on that sieve. For example, the −20# +28# fraction consists of particles that pass through a 20 mesh sieve but are retained on a 28 mesh sieve. The amount retained can also be expressed on a cumulative basis, that is, the amount retained on one sieve is added to the amount retained on each of the succeeding smaller sieves. A plot of cumulative percentage retained versus the logarithm of the screen aperture is approximately linear for many products.

The American Society for Agricultural Engineers and the American National Standards Institute also have specifications for size analysis, but these standards are directed towards agricultural materials such as grains, hay, and the like, and do not use sieves that are fine enough to discriminate between powdered materials (ANSI/ASAE standard 319.3, July 1997).

A size analysis can be performed on wet foods by washing the product under a stream of running water. For example, Kimball and Kertesz (1952) washed tomato juices, purees and pastes on a series of five sieves to quantify the size distribution of the insoluble tomato solids.

For materials that are water soluble it is possible to wet sieve them by using a fluid other than water. For example, Kean (1958) determined the subsieve particle size distribution of finely pulverized sugars by suspending the samples in anhydrous isopropyl alcohol.

It is difficult to use sieves for sizing very small particles. Other techniques such as sedimentation, sedimentation–photometry, scanning electron microscopy, photon correlation spectroscopy, and transmission electron microscopy must then be used. Indirect methods for determining particle size include centrifugation, conductimetric techniques, ultrafiltration, dynamic light scattering, single-particle optical sensing, zeta potential, laser diffraction, gas sorption and diffusiometric methods (Genovese and Lozano, 2000).

Computer-aided digital image processing techniques now allow one to measure the size, average size and shape of particles (Tan *et al*., 1994, 1997; Psotka, 2001).

Volume Measurement

There are a number of useful tests in which a volume measurement is made that correlates well with some textural property. The volume of a loaf of bread

or a cake made from a standard formula by means of displacement of small free-flowing seeds such as caraway seeds is widely used test in the baking industry. Khan and Elahi (1980) report that the maximum volume before collapsing of a batter prepared from wheat flour, baking powder, and water is highly correlated with volume and protein content of bread made from that flour. The Succulometer (Kramer and Smith, 1946) measures the volume of juice expressed from sweet corn as a measure of its maturity. The volume of juice expressed from various fruits is sometimes used as an index of fruit juiciness.

Many attempts have been made to measure the moistness of meat and fish by measuring the volume of fluid expressed under pressure. Child and Baldwell (1934) made a 'Pressometer' in which a core of cooked beef or chicken 1.27-cm diameter and 1.87-cm high was wrapped in filter cloth and subjected to a pressure of 250 pounds for 10 min. The loss in weight of the meat was reported as percent press fluid. Many others have used pressure to measure the amount of fluid expressed from meat, poultry and fish including Briskey *et al.* (1959), Hamm (1960), Dagbjartsson and Solberg (1972), Karmas and Turk (1976) and Jauregui *et al.* (1981). There seems to be no standard procedure for obtaining the volume to expressed fluid. Zhang *et al.* (1993) reviewed ten papers published between 1981 and 1993 and found that the sample size varied from 0.2 to 1.5 g, the force from 0.0098 to 57.8 kN and the press time from 0.16 to 20 min. They recommended test conditions of 1 g sample size pressed at 20 kN force for 2 min. However, this recommendation has not been implemented (see for example, Ju and Mittal, 1999; Kerr *et al.*, 2000; Zorrilla *et al.*, 2000).

Lee and Patel (1984) found an inverse relationship between compression force on commercial frankfurters and their sensory juiciness. A compression force of 181 kg gave a correlation coefficient of $r = 0.117$ whereas a force of 2–3 kg gave a value of $r = 0.92$ (Table 4.10). Since a force of 2–3 kg is more likely to be used in the mouth than very high forces, it seems that the use of low compression forces would likely give a higher correlation with sensory assessment of juiciness for other meat products.

Lucey *et al.* (1998) measured the volume of whey separating from yogurt by simply pouring off the free liquid and weighing it. They found this gave better results than separating the whey by centrifugation.

Table 4.10 Correlation Coefficient Between Sensory Juiciness and Expressible Fluid of Commercial Frankfurters

Compression force (kg)	Compression time (s)	Sample weight (g)	Correlation coefficient
181	120	2.0	0.117
40	10	0.2	0.27
18	60	1.5	0.61
2–3	17	9–10	0.92

Compiled from data of Lee and Patel (1984).

The US Department of Agriculture standards for canned pumpkin and squash requires the measurement of the volume of free liquor that separates after emptying the can and allowing it to stand for two minutes. For grade A (fancy quality) the volume shall not exceed 10 ml for each 30 oz (0.85 kg) of product and for grade C (standard quality) it cannot exceed 30 ml. The product is classed as substandard if the volume of free liquor exceeds 30 ml.

Olorunda and Tung (1984) measured the volume of free liquid that separated from frozen and thawed plantains and reported that it correlated highly with the degree of cellular damage and texture quality loss.

Time Measuring Instruments

Kinematic viscometers, such as the Ostwald and Zahn measure the time for a standard volume of fluid to flow through a restricted opening. Falling-ball viscometers measure the time for a ball to fall a given distance through a liquid. These will be described more fully in the chapter on viscosity.

A few other time measuring instruments are described in the literature. The Gardner Mobilometer measures the time required for a disk and shaft to fall a standard distance through a fluid (Gardner and VanHeuckeroth, 1927). The British Baking and Research Association Biscuit Hardness Tester measures the time required for a small circular saw rotating at 15 rpm to cut through a stack of biscuits (Wade, 1968) (see page 226). Rogers and Sanders (1942) describe a method for measuring the firmness of cheese curd that is based on the time for a cutting head to move a standard distance through the curd under a constant force. Wilder (1947) describes a Fiberometer that measures the time required to cut across asparagus spears by a 0.041 in.-diam stainless-steel wire under a force of 3 lb.

The Falling Number Method used by the baking industry to determine the α-amylase activity of wheat and rye flours is based on time measurement (Hagberg, 1960, 1961; Perten, 1964, 1967). It measures the time required by α-amylase to liquefy a gelatinized starch paste to a predetermined viscosity level. The viscosity level is that which allows the stirring rod to fall 70 mm in 1 s under the influence of gravity. This technique has been adopted as a standard method by several countries and by the American Association of Cereal Chemists (No. 56–81A), the International Association of Cereal Chemists (No. 107), and the International Standardization Organization (ISO/DIS 3093). The apparatus is made by Falling Number AB, Box 32072, S126 11 Stockholm, Sweden.

Work, Energy, and Power Measuring Instruments

Instruments that use the principle of work and energy are not common. Energy and work both have the dimensions mass $\times$ length^2 $\times$ time^{-2} which is

equivalent to force × distance. Instruments that plot out the force–distance relationship of a test can provide work functions by measuring the area under the force–distance curve or by any other technique that gives the force–distance integral. The area under the curve can be obtained by several methods, including (a) measuring the area with a planimeter (convert the area measurements into work units knowing the force and distance scales); (b) cutting out the paper under the curve, weighing it, and converting this into area knowing the weight of paper per unit area; and (c) counting the number of squares on the paper under the curve. Nowadays, computer retrieval of force–time data is common, and since the computer can be programmed to calculate force–time integrals and force–distance integrals the measurement of work functions is becoming much more common.

It is important to note that there are two work elements in a compression–decompression cycle. (1) The area under the curve during compression represents the work done on the food by the machine. (2) The area under the curve during decompression represents the work returned to the machine by the food as it recovers. Generally, the decompression work is small but in the interest of accuracy it is worth separating these two factors.

The Instron, TA.XT2 Texture Analyzer, the Food Technology Texture Test System, and other universal testing machines provide a force–distance curve and hence the area under the curve can be converted into true measurements of work.

Power is the rate of doing work and has the dimensions mass × length^2 × time^{-3}. A few power measurements have been used. For example, Miyada and Tappel (1956) attached a Wattmeter to the electric motor that powered a meat grinder and, by taking a reading with the meat grinder running empty and then with meat being run through at a constant rate, they were able to obtain an index of the toughness of the meat. Kilborn and Dempster (1965) used a similar principle to measure the power required to knead dough.

Ratio Measuring Techniques

This is not a widely used technique. The numbers obtained are dimensionless since they are derived from the ratio of two measurements of the same variable.

The Texture Profile Analysis parameter of cohesiveness is a ratio because cohesiveness is defined as

$$\frac{\text{area under second bite curve}}{\text{area under first bite curve}}$$

Occasionally relative density correlates with texture. Relative density is the density of a product divided by the density of water and is a dimensionless number. For example, La Belle (1964) found that the texture of sour cherries

and precooked dried beans correlated highly with density. Firm cherries have a low relative density because they do not pack down as much as soft cherries. Precooked dry beans with good texture have a high density because they are solid whereas those beans that have puffed up during the drying process (butterflied texture) have a much lower relative density. Scott Blair and Coppen (1940) measured the bulk density of cut cheese curd and used this as a textural index of the readiness to proceed with the next step in manufacturing. The specific gravity of batters has been associated with good volume and textural quality of baked goods (Funk *et al*., 1969).

Hoseney *et al*. (1979) used a ratio method to measure the spreading properties of wheat doughs. A mixed bread dough is mechanically rounded and placed on a smooth horizontal plate in a fermentation cabinet at 30°C and 90% R.H. The dough is unrestrained and is free to spread out under the force of gravity. The width and height of the dough are measured with calipers every 15 min for 1 h. The spread ratio is calculated as width/height. The researchers obtained spread ratios ranging from 1 to 4.

Multiple Variable Instruments

With this class of instrument one variable is measured while several variables are uncontrolled. The variables may or may not be interrelated and may or may not be linear. It is usually impossible to establish true dimensional units and to convert the results from this type of instrument into a conventional system of measurement. Hence it is advisable to avoid using this type of instrument.

An example of this kind of instrument is the Durometer, which was designed to measure the stiffness of rubber but is occasionally used to measure the softness of foods. It consists of a spring-loaded probe that may be hemispherical or conical in shape that protrudes from an anvil. The probe is pressed onto the food until the anvil contacts the food, at which time a reading is taken from the dial. At this point the probe has penetrated partly into the food, and partly backward into the instrument by compressing the spring.

Figure 4.40 shows the relationships of the various parameters involved. The force exerted on the food by the probe has a direct linear relationship while the penetration of the probe into the food has an inverse linear relationship to the scale reading. The area and the perimeter have an inverse curvilinear relationship to the scale reading. It is impossible to convert a Durometer reading to any other system of measurement because the force, depth of penetration, area, and perimeter in contact with the food all vary in different ways. Table 4.11 shows the irregular manner in which the various parameters change with instrument readings.

At high Durometer readings an increasing force is being applied to a diminishing area until, theoretically, at a scale reading of 100, the maximum force of the spring is being applied to the test material at a point source of zero area; there is zero penetration of the ball into the test material under an infinitely

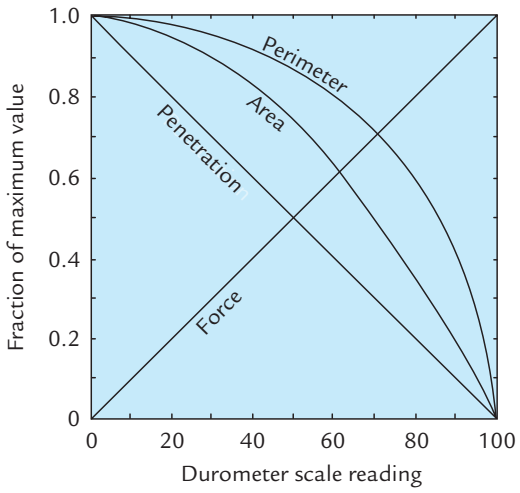


Figure 4.40 Relationships between force, depth of penetration of the ball, area and perimeter of the ball and the Durometer scale reading. (From Bourne and Mondy, 1967; reprinted from *Food Technol*. **21**, 97; copyright by Institute of Food Technologists.)

Table 4.11 Relationship Between Durometer Scale and Instrument Variables

	Percent of maximum			
Durometer scale reading	**Force**	**Area**	**Penetration depth**	**Perimeter**
0	0	100	100	100
30	30	91	70	96
60	60	64	40	80
90	90	18	10	43
100	100	0	0	0

Source: From Bourne and Mondy (1967); reprinted from *Food Technol.* **21**(10), 1388, 1967. Copyright by Institute of Food Technologists.

large force per unit area. This characteristic of the instrument explains why the Durometer is unreliable at readings above 80, even when used on rubber.

Chemical Analysis

This indirect method is occasionally used as an index of textural qualities. Several examples are given below.

Alcohol insoluble solids (AIS) is a good index of the maturity and texture of fresh, raw green peas (Kertesz, 1935: Association of Official Analytical Chemists Method 32.006). This method comprises grinding fresh peas in 80% alcohol in a blender, filtering on a vacuum filter, washing well with 80% alcohol, and drying and weighing the residue. The success of this test depends on the fact that as the peas mature the total solids increase and sugar converts into starch. Since starch is insoluble in alcohol, there is a rapid change in AIS as the peas mature.

The 17th edition of 'Official Methods of Analysis' published by AOAC International now designates this test as 'alcohol precipitate,' method 924.08 (AOAC, 2000).

The pericarp content of sweet corn is a useful index of its maturity (Kramer *et al*., 1949). Corn kernels (100 g) are ground in a blender with water, then washed well on a 30-mesh sieve. The starchy endosperm and germ are ground fine enough to pass through the sieve, but the pericarp is sufficiently tough that it is not chopped fine enough to pass through the screen. After washing thoroughly, the screen is dried and weighed to give the pericarp content, which is normally in the range of 1.3–5.2%.

Brovelli *et al*. (1998) followed the procedure of Kramer *et al*. (1949) to measure the fibrousness of asparagus spears. A 50 g sample of asparagus together with 420 ml distilled water are microwaved for 8 min in a 600 W microwave oven, blended for 1.5 min. in a Waring Blender, then transferred to a 30 mesh wire screen where it is washed under running water until only fibers remain. After drying for 12 h in a 68°C hot air oven the dry fibers are weighed and expressed as a percentage of the initial 50 g.

Moisture content is sometimes an index of maturity. An example of this is sweet corn where a commonly accepted standard is $<$68%, too tough, overmature; 68–70%, cream style for canning; 70–76% is whole kernel for canning; 76–78% is suitable for freezing; $>$78%, too immature.

A chemical index of the amount of collagen in meat performed by determining the hydroxyproline content has been proposed as an index of meat toughness. There is as yet no consensus as to the value of this determination as an index of meat toughness. The subject was reviewed by Szczesniak and Torgeson (1965).

Miscellaneous Methods

The criteria for inclusion under this heading are (a) that it is an objective method, (b) that the measurement correlates well with texture, and (c) that the method does not fit into any of the categories described previously.

Optical Methods

The cell fragility method is an optical method that is used to measure the toughness of fish (Love and Mackay, 1962; Love and Muslemuddin, 1972a,b). In this method a standard weight of fish is homogenized in a blender in a mixture of 2% trichloroacetic acid plus 1.2% formaldehyde for a standard time after which the optical density is measured. Tender fish grind into a fine state and give a high optical density whereas tough fish remain as fewer large particles and give a lower optical density. The cell fragility method is reported to give good results for nonfatty fish but less satisfactory results for fatty fish or

fish in which advanced bacterial spoilage has occurred. Love (1983) reviewed this procedure.

Sound

Drake (1963, 1965) analyzed the amplitude and duration of chewing sounds over a wide range of frequencies. This method shows some promise, particularly with noisy foods, but large variations between sounds generated by different individuals complicate the procedure.

Vickers and Bourne (1976a,b) postulated that the property of crispness is primarily an acoustical sensation that is detected by the ear during the fracturing of crisp foods.

Christensen and Vickers (1981) reported that loudness of chewing sounds correlated highly with sensory crispness and the high correlation was maintained even when a 100 decibel masking noise was used as an auditory block. Lee *et al*. (1988) followed the sounds generated during chewing of potato chips and tortilla chips and found that the intensity of a given frequency range generally decreased with consecutive chews, with the higher frequencies approaching inaudible levels. Edminster and Vickers (1985) distinguished between crispness and crackliness based on sound analysis and Vickers (1985) reported on how crispiness and crunchiness are related to pitch and loudness. Vickers (1991) wrote a succinct review of sound perception and food quality.

Dacremont (1995) analyzed the spectral composition of chewing sounds of eight different foods, and classified items into three classes: (1) crispy foods, such as extruded flat breads, that generate high-pitched sounds with a high level of frequencies above 5 kHz; (2) crunchy foods, such as raw carrot, that generate lower pitch sounds with characteristic peaks in the frequency range 1.25–2 kHz; (3) crackly foods, such as dry biscuits, that generate low-pitch sounds with a high level of bone conduction.

Brochetti *et al*. (1992) pointed out that mastication sounds and speech sounds are both produced within the oral cavity and that speech analysis techniques such as sound spectrography, oscilloscopic analysis and fast Fourier transformation would be useful in analyzing mastication sounds.

It seems within the realm of possibility that audiotapes holding expertly crafted combinations of sound frequencies, loudness and intervals between sound bursts may one day be used as standards for defining the textural qualities of crispness, crunchiness, and crackliness.

Sounds are occasionally used to judge the quality of foods other than crisp or crunchy. For example, to judge the quality of watermelon some people lay one ear on the skin of the whole melon while rapping their knuckles on it. It is under ripe if the sound resembles that of tapping your forehead with your knuckles. If the sound resembles that of rapping your knuckles on the rib cage of your chest it is just right. If it sounds like rapping your knuckles on your abdomen it is over ripe.

Ultrasound Tests

The previous section discussed sound analysis within the range of frequencies heard by the human ear. This section introduces the use of ultrasound with frequencies higher than can be perceived by the ear (>16 kHz).

The velocity of propagation of a compressional ultrasound wave in a solid material is described by the equation:

$$v = \left(\frac{K + 4/3G}{\rho} \right)^{0.5} \tag{4.33}$$

where v is velocity of the wave, K is the bulk modulus, G is the rigidity modulus and ρ is the density of the material. Since a liquid has zero rigidity the equation for a liquid is:

$$v = (K/\rho)^{0.5} \tag{4.34}$$

Ultrasonic measurements are a nondestructive, noninvasive and nonintrusive technique (Povey and McClements, 1988).

Miles *et al*. (1985) found the speed of 2.5 MHz ultrasonic waves in pig adipose tissue explained 88% of the variance in penetrometer measurements of firmness. Nielsen and Martens (1997) reported that ultrasound velocity in carrots cooked for up to 15 min gave a linear correlation coefficient $r = 0.62$ whereas attenuation measurements gave a correlation of $r = 0.52$ with Young's modulus of elasticity. Mulet *et al*. (1999) found the velocity of 1.0 MHz waves in cheddar cheese decreased as the cheese was heated and attributed this to changes in the crystallinity of the fat in the cheese. Mizrach and Flitsanov (1999) reported a second order polynomial coefficient of determination $r^2 = 0.98$ between ultrasonic velocity and firmness measurements on ripening avocado fruits. Mizrach *et al*. (1994) reported a coefficient of determination $r^2 = 0.999$ between firmness and ultrasonic attenuation in melons. Benedito *et al*. (2000a,b) reported coefficient of determinations between ultrasonic velocity and firmness of Mahon cheese of $r^2 = 0.81$, for elasticity $r^2 = 0.84$. Other foods tested by ultrasound include beef (Park *et al*., 1994); biscuits (cookies) (Povey and Harden, 1981); cheese (Lee *et al*., 1992) and tofu (Hack *et al*., 1995). McClements (1997) has reviewed the use of ultrasonics in food testing.

Rollability

Friend *et al*. (1993) devised a simple semiquantitative method for measuring the textural quality of tortillas. It consists of wrapping a tortilla around a 1.0 cm diameter wooden cylinder (dowel) and then subjectively rating the tortilla for cracking and breakage on a five-point scale. The rollability scale is:

1 = no cracking (best quality)
2 = signs of cracking but no breaking
3 = cracking and breaking beginning on one surface

4 = cracking and breaking imminent on both surfaces
5 = unrollable, breaks easily

Using this simple inexpensive device Friend *et al*. (1993) were able to measure the decrease in rollability during storage of tortillas and to identify which hydrocolloids were most effective in retaining rollability during storage. This test is now widely used to measure the textural quality of tortillas, chapaties and similar products.

Electromyography

Small electrical currents are present in muscles when they contract. By attaching electrodes to the skin in the appropriate location it is possible to measure the electrical activity of muscles that are near the surface of the body. A plot of magnitude of the electrical current versus time is called an electromyogram (EMG). It is a relatively simple method for measuring muscle activity because it is not invasive or obtrusive and the attachment of the electrodes to the face does not interfere with normal masticatory behavior. The masseter and temporalis are two of the major muscles that power mastication and since they lie just under the cheeks their electrical activity is easily reached. Tornberg *et al*. (1985) were probably the first food scientists to use electromyography. Sakamoto *et al*. (1989) used EMG to study the chewing pattern of 43 foods and found that the chewing energy varied from 3 to 108 for the masseter muscle (closing mouth) and 13 to 154 for the digastric muscle (opening mouth).

Brown (1994) obtained electromyograms from adults who were given gum to chew and found that the results were reproducible for each person and that the EMG patterns were stable over time, but there were significant variations between subjects. However, the subjects in this study reported that electrodes attached to the face did not interfere with normal chewing behavior. Brown *et al*. (1994a) confirmed that the chewing pattern is stable in each subject for each food they chew and they used EMG to measure chewing rate, duration of the chewing sequence, chewing work, manipulation of the bolus, and swallowing events.

Kohyama *et al*. (1998) used EMG to study the texture of cooked rice and found that rice with a high amylose content required greater masseter muscle activity than low amylose rice. The differences between the cultivars were most strongly evident during the first few chews. Kohyama *et al*. (2000) found that the number of chewing strokes, masticatory time, and total duration of mastication as measured by electromyography showed a higher correlation with adhesiveness and stickiness than with hardness. They also found that the differences in mastication patterns among the seven subjects studied were greater than between rice cultivars.

It seems that electromyography is becoming an increasingly useful tool to study mastication and texture (Sakamoto *et al*., 1989; Brown *et al*., 1994b, 1998; Mathevon *et al*., 1994; Duizer *et al*., 1996; Mioche and Martin, 1998; Mathoniere *et al*., 2000; Kemsley *et al*., 2001).

Electropalatography

Jack and Gibbon (1995) used the technique of electropalatography (EPG) to record tongue movement during eating and swallowing and its applicability to study differences in texture. For EPG, a thin, custom-made artificial palate is precisely molded to fit an individual's hard palate from behind the upper front teeth to the junction between the soft palate and the hard palate. Embedded in this artificial palate are 62 electrodes that cover the entire artificial palate. They are arranged in eight rows with eight electrodes in every row except row no. 1 closest to the teeth which has six electrodes. Leadout wires connect the electrodes to an external processing unit. When the tongue contacts an electrode a signal is sent to the processing unit which records contacts every 10 ms.

A subject consumed three foods with different textures: (1) low-fat pasteurized milk (liquid); (2) yogurt (semisolid); and (3) fruit jelly (gel). Jack and Gibbon (1995) divided the contact patterns into three phases: phase 1, an approach phase when the number of EPG contacts increased; phase 2, a period of full contact between the tongue and 62 electrodes; phase 3, a release phase when the number of contacts decreased. The data showed there is a rolling movement of the tongue beginning near the teeth, spreading back until all the electrodes were in contact with the tongue, and then a falling away of the tongue beginning near the teeth and proceeding to the rear of the palate.

Milk required two of these rolling tongue motions to clear it from the mouth, yogurt required three, and jelly required up to six rolling cycles, some of which did not give full contact between the tongue and the electrodes.

Multiple-point Sheet Sensor (MSS)

Kohyama and Nishi (1997) tested a procedure developed for occlusal analysis on foods. A plastic sheet 5.6 cm × 5.6 cm has printed on it in electrically conductive ink 44 strips in both the x axis and y axis to form a grid of 1936 pressure-sensitive points. The maximum pressure limit is 35 kg cm^{-1}. The grid is connected to a computer that records the data. Panelists insert the multiple-point sheet sensor in the mouth to cover the lower teeth and then chew on foods in as normal a manner as possible. The computer printout gives a three-dimensional display of the force at each of the 1936 pressure points. It also shows changes in pressure and the location of the pressure peaks during mastication. The simultaneous measurement of pressure and its spatial distribution provides valuable insights into the process of mastication and how the food bolus is changing.

Fractal Analysis and Fast Fourier Transform

The force–time plot generated by compression of some foods shows a series of steep peaks and dips in rapid succession indicating multiple catastrophic

failures. Such a plot is called a 'noisy record.' An example of a noisy record is shown in Fig. 4.44a, page 181. Noisy plots are commonly found when crispy–crunchy foods such as prepared dry breakfast cereals are compressed. Deriving useful data from noisy force–time plots was a nearly impossible task until fast computers with appropriate statistical software became available. The algorithm known as Fast Fourier Transform (FFT) seems to be the best way to filter out noise caused by artifacts in the equipment or procedure and to measure the jaggedness of the force–time signature. Professor Peleg at the University of Massachusetts has been leading the development of this technique for foods (Barrett *et al*., 1992; Peleg, 1993; Rohde *et al*., 1993; Peleg and Normand, 1995; Ulbricht *et al*., 1995; Borges and Peleg, 1996) (see also Brusewitz *et al*., 1997 and Norton *et al*., 1998). This method of analysis of noisy data has already been able to characterize the change in texture of dry fracturable foods as their moisture content changes. Fractal analysis of line jaggedness was reviewed by Peleg (1997).

Imperfect Lubricated Squeezing Flow

This test procedure is characterized by an outward and upward flow of a liquid or semiliquid in a shallow container when compressed at a constant rate under a wide plate. It shows promise for measuring the viscous properties of spreadable foods such as peanut butter and cheese spreads that are difficult to handle in rotational viscometers. Figure 4.41 explains the principle of lubricated squeezing flow where the food is held in a shallow container such as a Petri dish and the diameter of the descending platen is much smaller than the diameter of the container. This geometry avoids some of the problems of testing spreadable foods in rotational viscometers including: (1) slip at the wall of the rotating member; (2) disruption of the structure caused by transferring into the viscometer; (3) unknown or variable amount of friction.

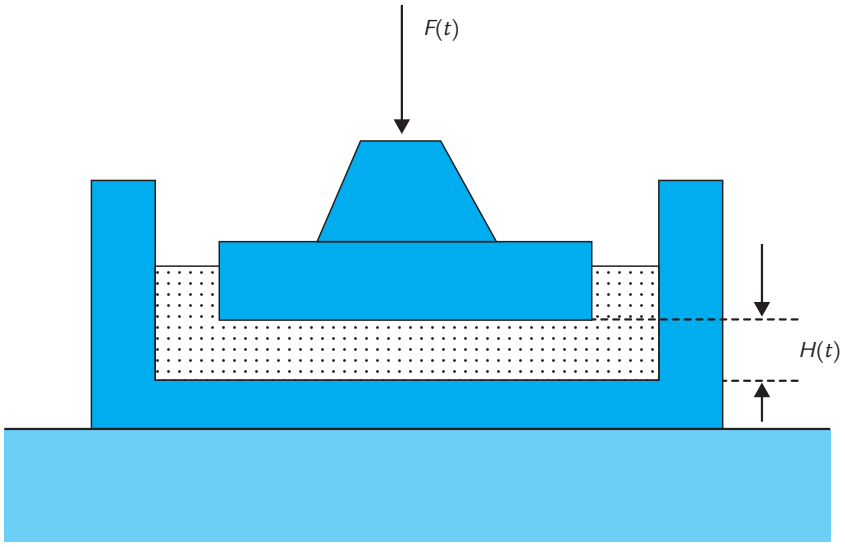


Figure 4.41 The principle of imperfect lubircated squeezing flow. (From Suwonsichon and Peleg, 1999c. Reprinted from *J. Food Engineering* **39**, page 218. Copyright 1999 with permission of Elsevier Science.)

A plot of log (force) versus log (height) becomes linear after several millimeters of travel by the descending platen after entry effects have been passed. From the slope of the linear section of the force–distance plot one can calculate the flow behavior index (n) and consistency index (K) of fluids that fit the power equation.

This procedure requires a thin layer of test material and a wide platen whose diameter is 10-fold to 20-fold greater than the thickness of the sample. The theory behind this test was developed by Chatraei *et al*. (1981), Lee and Peleg (1992) and Damrau and Peleg (1997). The procedure was first used for foods by Casiraghi *et al*. (1985) and Bagley *et al*. (1990). It has been used for tomato products (Lorenzo *et al*. 1997), peanut butter (Campanella and Peleg, 1987a), tomato ketchup, prepared mustard and mayonnaise (Campanella and Peleg, 1987b; Suwonsichon and Peleg 1999c; Corradini *et al.*, 2000), process cheese (Campanella *et al.*, 1987), Ricotta cheese (Suwonsichon and Peleg, 1999a), fresh corn masa (Ramirez-Wong *et al*., 1996), dulce de leche (Corradini and Peleg, 2000), and yogurt (Suwonsichon and Peleg, 1999b).

Campanella and Peleg (2001) provide a good review of the theory and applications of squeezing flow viscometry.

Sliding Pin Consistometer (SPC)

Davey (1983) devised a hand-held instrument for measuring the hardness of fats that simulates the action of cutting with a knife. A cylinder 3.76-mm long and 0.97-mm diameter is pushed into the fat perpendicular to the surface of the fat. The pin is driven across the fat by a pretensioned spring. When the pin is actuated by a trigger mechanism the time for the spring to move laterally a distance of 16.4 mm is measured electronically. The SPC values on the subcutaneous adipose of a side of chilled beef were highly correlated with subjective scores for fat hardness reported by five experienced meat cutters ($P < 0.001$).

Davey and Jones (1985) used the SPC on hard and soft butter, and hard and soft margarine and reported high correlations with sensory assessment of hardness and spreadability ($r^2 = 0.96$).

Pendulum Impact Test

Lu *et al*. (1994) adapted the Izod pendulum test, that is a well-known test for materials of construction to measure the breaking strength of rape seed pods. A pod is clamped in a vertical position directly under the pivot of a pendulum. A pendulum of adjustable mass and length is pulled back a fixed angle, released, and allowed to strike and break the pod.

The angle the pendulum swings up after the impact is measured by an optical encoder and PC. The rupture energy required to snap the pod is measured by the reduction in the angle of the upswing after snapping a pod compared with the upswing angle when no pod is present. The advantage of this test is

that it is dynamic and can achieve rates of loading that are comparable with commercial handling of produce.

Universal Testing Machines (UTM)

The use of these instruments has become widespread during the last 20 years. Probably, the first UTM dedicated to work with foods was the Instron machine purchased by the Department of Food Science and Technology, New York State Agricultural Experiment Station, Cornell University in 1962. The manner in which this strength of materials testing machine was adapted to foods is described by Bourne *et al*. (1966).

UTMs consist of three essential components:

(1) A drive system that imparts motion to a cross-head that holds part of the test cell. The drive system may be double screw, single screw, hydraulic, chain or eccentric and lever system. High-force capacity Instron machines are driven by twin screws and low-force capacity models by a single screw. The standard TA.XT2 Texture Analyzer is driven by a single screw. The Food Technology Corporation Texture Test System is driven hydraulically, the General Foods Texturometer is driven by an eccentric and lever system and the Lloyd model TA5000 is driven by a chain.

(2) Test cells that hold the food and apply force to it. The test cell comprises two parts. The lower part which is usually stationary is attached to the base of the machine and supports or contains the food being tested. The upper part of the test cell is attached to the moving cross-head or arm. Different test cells can be installed that use any test principle requiring rectilinear movement including puncture, gentle compression for deformation, major compression for texture profile analysis, extrusion, cutting–shear, bending–snapping and tensile.

(3) A force measuring and recording system that plots the complete history of the force changes for the duration of the test. The older UTMs use a strip chart recorder whereas the newer UTMs use a computer to accumulate both the force–time and force–deformation history and display the result on a video screen.

An advantage of UTMs is that the same basic machine can be configured for different kinds of tests. Previously, a new machine had to be purchased for every different kind of test. Another advantage is that the complete force history is plotted, giving all the changes that occur, including the rate of change (slopes), maximum force (peaks), fracture events (rapid decreases in force), area under the curve (work), and frequently other parameters of interest. The use of recorders tends to reduce confidence in the old one-point instruments that measure maximum force only. When a pointer moves over a dial and the maximum force reading is taken, there appears to be an element of certainty

about the results that leads to a feeling of confidence in the instrument. When the same test is repeated in a recording instrument, the maximum force often seems to be an arbitrary point to use as an index of textural qualities; there is a loss of confidence in the accuracy of the test and the feeling of infallibility associated with some of these simple instruments is lost.

Speed of Data Acquisition

A finite time is required to record the force data generated when foods are compressed. This was often a serious problem when strip chart recorders were used. Computer acquisition of force–time data is much faster than strip chart recorders so problems associated with speed of acquisition of the data are less frequent. Nevertheless, even computers take time to record the data and errors can occur, especially when the force is changing rapidly.

A computer can record information very quickly, store it, then print a graph and calculate numerical results such as means, standard deviations and any other desired statistical analyses when convenient. Instead of using response time, modern electronics and measurement systems are specified by their bandwidth in Hz. A higher bandwidth equates to a faster response rate. A common method to estimate transducer bandwidth is to measure the time in seconds between 10% and 90% points of a step response, then use the following equation:

$$\text{transducer channel bandwidth} = 0.34/t_{10\text{–}90}$$

From this equation, a strip chart recorder with a 0.5 s response time between 10% and 90% full scale would have an equivalent bandwidth $= 0.34/0.5 = 0.68$ Hz. A high bandwidth system will record force fluctuations more accurately than a low bandwidth system. When testing foods in which the force changes rapidly (e.g. brittle foods) a high bandwidth system will record significantly higher force values as compared to the same test on a low bandwidth system. Buyers should take bandwidth into account when selecting a test instrument.

The following shortened discussion from the first edition referring to strip chart recorders has been kept in this second edition for three reasons:

(1) Many strip chart recorders are still in use. Most new UTMs have a PC but some researchers still prefer to use strip chart recorders.
(2) Until about 1990 almost all data were gathered on strip chart recorders. Therefore, in looking at data published before 1990 one should keep in mind the possibility of pen response errors that cause the chart to record significantly lower forces than the true force thus yielding inaccurate data.
(3) Even though computer acquisition of data is fast, time response errors can still occur. This may become a problem again in the future as higher compression speeds are used.

The recorders that are customarily used in the food industry measure variables that change slowly with time; for example, temperature, gas chromatography,

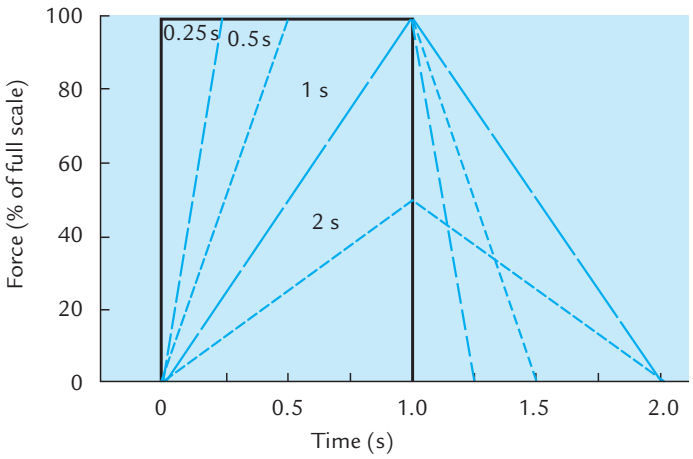


Figure 4.42 Force–time plots given by 0.25, 0.5, 1 and 2s response recorders when a full-scale force is applied instantaneously, held for 1 s, then removed. (Reprinted from deMan, Voisey, Rasper and Stanley (eds), 'Rheology and Texture in Food Quality', p. 248; with permission from AVI Publ. Co.)

and light spectrometry. Consequently, there has been little question or concern about whether the recorder is faithfully plotting the measured variable. This fortunate state of affairs does not apply to texture measuring instruments where rapid changes in force often occur. Many food technologists innocently (and erroneously) place complete confidence in the graphs that are plotted on the charts of their recording texturometers.

Figure 4.42 shows a model that explains the problem. Suppose a force measuring instrument receives a full-scale force applied instanteously, held for 1 s, and then removed instanteously. The solid black line in Fig. 4.42 gives the correct representation of the change of force with time; however, no recorder will reproduce this line exactly because it requires a finite period of time for the pen to travel the width of the chart. This time is known as the pen response time. The dashed lines in Fig. 4.42 show the plots that will be made by recorders with pen response speeds of 0.25, 0.5, 1, and 2 s. The 0.25, 0.5, and 1 s response recorders will correctly give the peak force whereas the 2 s response recorder will show only 50% of the correct peak force. Although the actual full-scale force was applied for exactly 1 s, no recorder will show this correctly; the 0.25 s recorder shows the full-scale force having been in effect for 0.75 s, the 0.5 s response recorder shows full-scale force for 0.5 s, the 1 s response recorder shows full-scale force momentarily, and the 2 s recorder never reaches full-scale force. Table 4.12 summarizes the graphs shown in Fig. 4.42 and illustrates the fact that the errors caused by pen response can be substantial, and that the error increases as the pen response time increases.

Figure 4.43 shows the nature and magnitude of the errors that can be introduced by pen response speed in a real situation. The same curve has been traced in the four examples. In each case the solid line shows the true force–time relationship obtained by compressing a whole apple for 1 s at high speed and then decompressing it, and the dashed lines show where the recorder deviates from the correct position.

The 0.25 s response recorder gives a faithful tracing of changes in force with time during the compression and correctly shows the initial slope, yield point, several shoulders, and maximum force at the end of the compression.

Table 4.12 Effect of Recorder Response Time on Measurements Obtained from Force–Time Curves[a]

	Pen response time (s)				
Parameter	**Instantaneous**	**0.25**	**0.5**	**1**	**2**
Maximum force	100	100	100	100	50
Time to reach maximum force (s)	0	0.25	0.50	1.0	Not reached
Time maximum force is shown (s)	1.0	0.75	0.50	Momentarily	Not shown
Time some force is shown (s)	1.0	1.25	1.5	2.0	2.0
Total area under curve (relative values)	80	80	80	80	40
Area under load portion of curve (relative values)	80	70	60	40	20

[a] Full-scale load applied for 1 s.
Source: Bourne (1976); with permission from AVI Publ. Co.

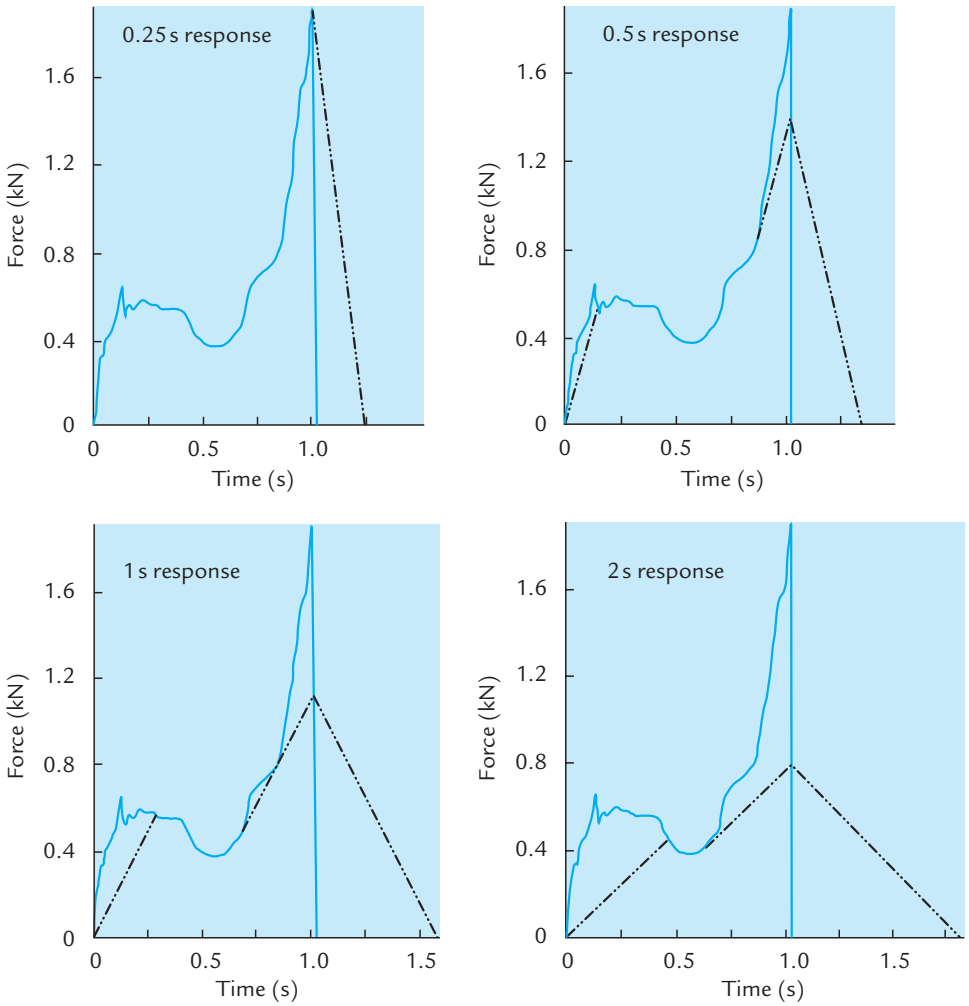


Figure 4.43 Force–time plot for a whole apple that is rapidly compressed in the Instron for 1 s and then decompressed. The solid line shows the true force, the dashed line shows error made by 0.25, 0.5, 1 and 2 s response recorders. (Reprinted from deMan, Voisey, Rasper and Stanley (eds), 'Rheology and Texture in Food Quality', p. 250; with permission from AVI Publ. Co.)

There is an error during decompression because the force drops to zero almost instantaneously while the pen arrived at zero about 0.2 s later. The 0.5 s response recorder gives an incorrect initial slope, misses the abrupt drop in force after the yield point, misses the maximum force at the end of the compression by a

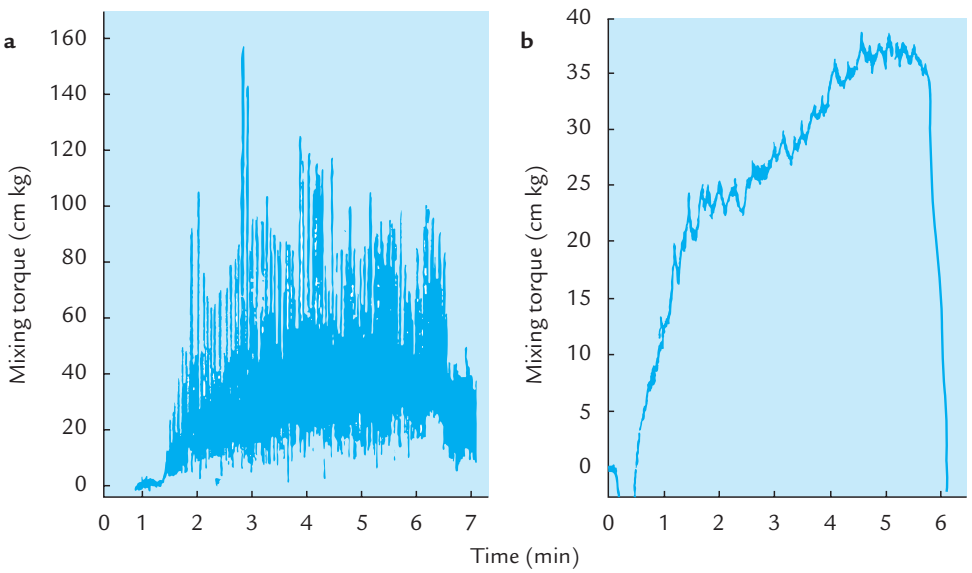


Figure 4.44 Mixing torque versus time for the Mixograph: (a) 0.2 s response recorder; (b) 12 s response recorder. (Courtesy of P. W. Voisey; reprinted from *J. Texture Studies*, with permission from Food and Nutrition Press.)

large margin, and shows a larger decompression area than the 0.25 s response recorder. It does provide an accurate record of the peaks and shoulders in the curve from about 0.2 to 0.8 s.

The 1 s response recorder shows an even greater error in the initial slope, maximum force, and decompression, and also fails to record the large shoulder at 0.8 s. The 2 s response recorder grossly misrepresents the record, aside from showing the trough at 0.5 s for a short period. The evidence in this figure should shatter any feelings of infallibility of recorders and should make every texture technologist aware of the necessity of always being alert to the possibility of errors in the trace the pen makes on the chart.

Occasionally a high-speed recorder is a liability instead of an asset. Voisey (1971a) gave an example of this by attaching a recorder to a Mixograph to measure the changes in torque as a wheat dough was kneaded. Figure 4.44a shows the plot obtained with a 0.2 s response recorder. This recorder shows the rapid fluctuations from moment to moment in such detail that it is difficult to see the trend over a period of some minutes. Figure 4.44b shows the same test repeated with a 12 s response recorder. The momentary fluctuations are lost but the slow development of dough strength is shown more clearly. Also, the torque scale was reduced from 160 cm kg for the 0.2 s recorder to 40 cm kg for the 12 s recorder, spreading the development curve more fully across the chart. The point of this example is that the recorder's behavior in any instrument should not be taken for granted but should be selected to give the type and quality of plots that are best suited to the requirements of each particular experiment.

The important point is whether the rate of change of force occurs more or less rapidly than the ability of the pen to keep up with this rate of change. Figure 4.45 shows the curves that result from compressing a corn curl (a rigid food) and a cube of cream cheese (a nonrigid food) under identical conditions. The 1 s recorder gives an accurate plot for the cheese, which exhibits a slow rate of change in force, but the same recorder gives an inaccurate trace for the

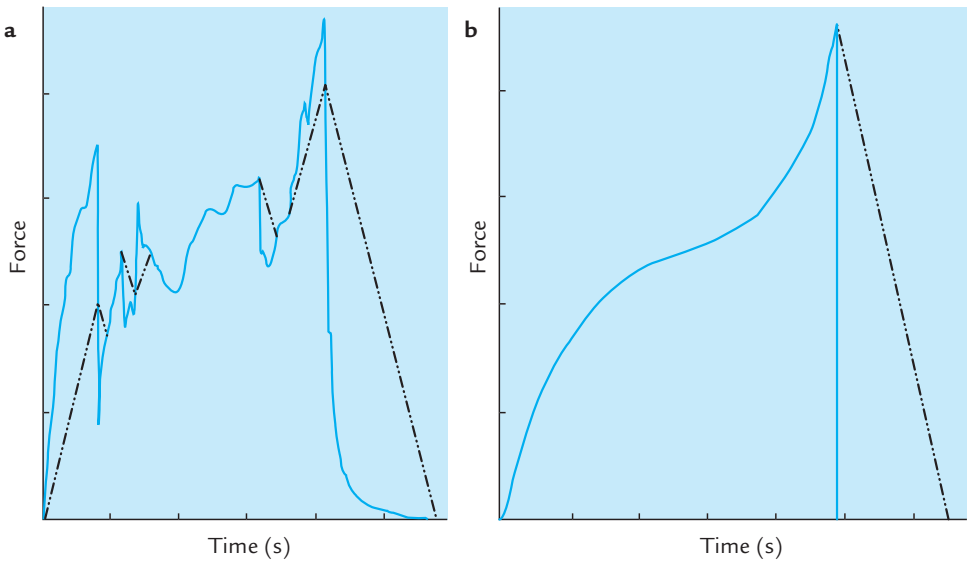


Figure 4.45 Force–time plot for (a) a rigid food (corn curl) and (b) a soft food (cream cheese) compressed at the same rate in the Instron. The solid line shows the true force and the dashed lines show the errors made by a 1 s response recorder. (Reprinted from deMan, Voisey, Rasper and Stanley (eds), 'Rheology and Texture in Food Quality', p. 255; with permission from AVI Publ. Co.)

corn curl, which undergoes rapid force changes. The critical factor is the rate of change of force in the specimen compared to the maximum rate of change that the recorder can accurately reproduce. Foods that give slow changes in force when compressed can tolerate slower response recorders or higher compression speeds than foods that give rapid changes in force.

The force–time plots produced by recording texturometers are generally curved. Straight-line portions are usually of short duration. Whenever one sees long straight lines of uniform slope on the chart or screen one should suspect that perhaps pen response speed is being plotted rather than the true changes in force. After observing the straight-line portions and the true force–time plots in Figs 4.43 and 4.45 one should become suspicious when extensive straight lines of standard slope are seen on their force–time plots. One should also become suspicious when the tops of isosceles triangles with a constant peak angle are seen.

The author has observed laboratories where months or years of data were found to be worthless because the recorder response lagged behind the true forces that were generated, and the discrepancy was never recognized.

Most recorder manufacturers will provide the stated pen response speed of their recorder. The pen response speed can be checked in the laboratory as follows: set the chart running at the maximum speed and then instantaneously apply a full-scale force to the load cell, leave it there for a second or two and then instantaneously remove it. The slope of the force–time line divided by the speed of travel of the chart will give the pen response time of that recorder.

Texture Profile Analysis (TPA)

A group at the General Foods Corporation Technical Center pioneered the test that compresses a bite-size piece of food two times in a reciprocating motion

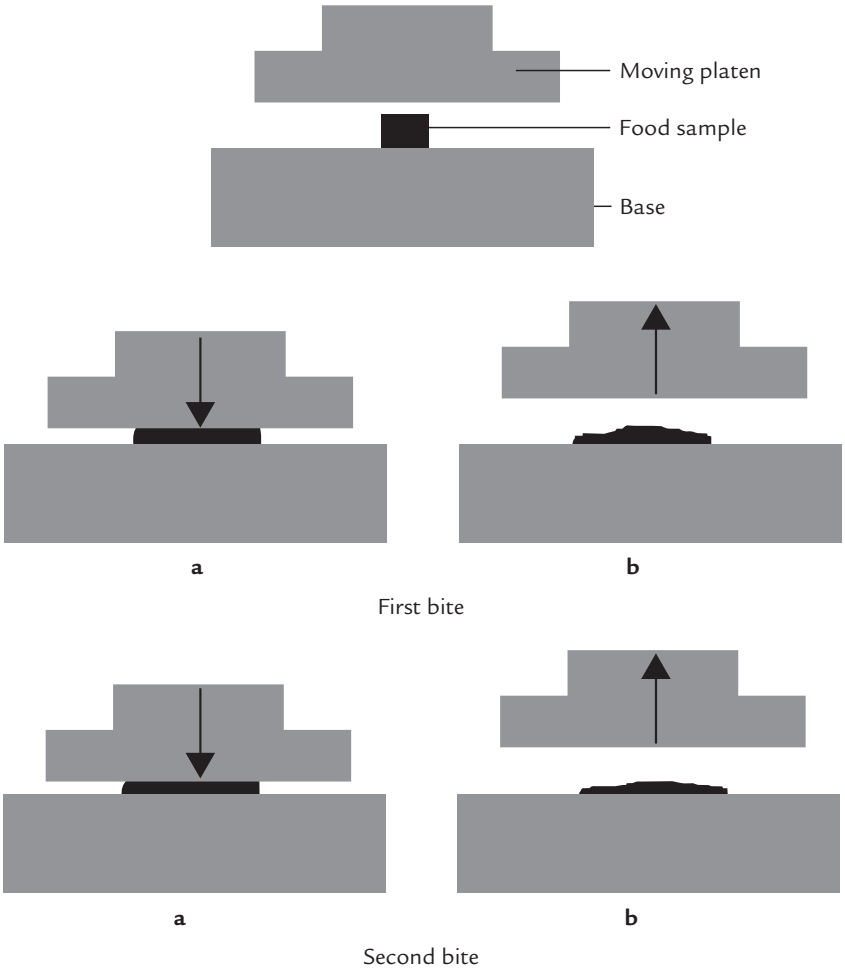


Figure 4.46 Schematic diagram of the two compressions required for the texture profile analysis test. (a) Downstroke actions during the first and second bites; (b) upstroke actions during the first and second bites.

that imitates the action of the jaw, and extracted from the resulting force–time curve a number of textural parameters that correlate well with sensory evaluation of those parameters (Friedman *et al*., 1963; Szczesniak *et al*., 1963). The instrument devised especially for this purpose is the General Foods Texturometer.

The principle of the TPA test is illustrated in Fig. 4.46: A 'bite-size' sample of food of standard size and shape is placed on the baseplate and compressed and decompressed two times by a platen attached to the drive system. To imitate the chewing action of the teeth there should be a high compression. The author usually uses a 90% compression when performing TPA tests in his laboratory. Figure 4.47 shows a typical TPA curve generated by the G. F. Texturometer. The height of the force peak on the first compression cycle (first bite) was defined as hardness; in Fig. 4.47, A is the beginning of the first compression and B is the beginning of the second compression. Fracturability (originally called brittleness) was defined as the force of the significant break in the curve on the first bite (shown as a dashed line in Fig. 4.47). The ratio of the positive force areas under the first and second compressions (A_2/A_1) was defined as cohesiveness. The negative force area of the first bite (A_3)

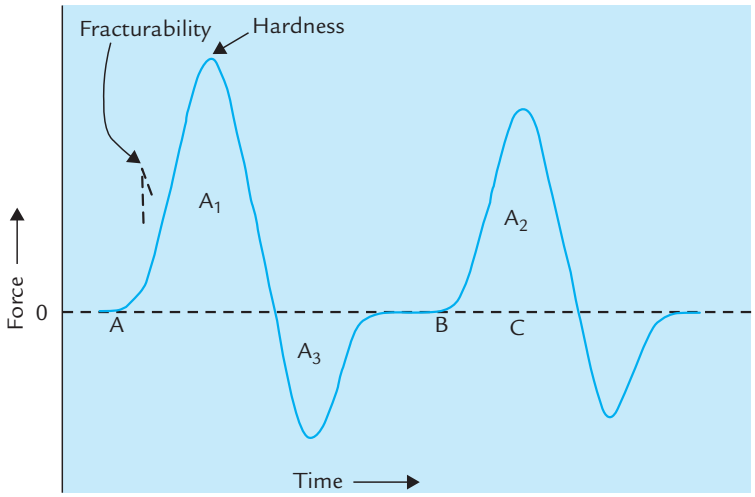


Figure 4.47 A typical GF Texturometer curve (slightly altered). (Courtesy of Dr A. S. Szczesniak with permission.)

represented the work necessary to pull the compressing plunger away from the sample and was defined as adhesiveness. The distance that the food recovered its height during the time that elapsed between the end of the first bite and the start of the second bite (BC) was defined as springiness (originally called elasticity). Two other parameters were derived by calculation from the measured parameters: gumminess was defined as the product of hardness × cohesiveness; chewiness was defined as the product of gumminess × springiness (which is hardness × cohesiveness × springiness). Szczesniak (1975b) gave an updated account of the development and changes in the technique since 1963.

In the original description of TPA chewiness was defined as the energy required to masticate a solid food product and gumminess as the energy required to disintegrate a semisolid food to a state of readiness for swallowing. Szczesniak (1995) pointed out that the distinction has often been overlooked that gumminess and chewiness are mutually exclusive. Therefore, in reporting TPA measurements one should report either chewiness values, or gumminess values but not both for the same food.

The texture parameters identified by the General Foods group gave excellent correlations with sensory ratings (Szczesniak *et al*., 1963). Figure 4.48 shows the correlation for the hardness scale. High correlations between sensory and instrument measurements were obtained for the other texture parameters.

The Instron, TA.XT2 Texture Analyzer and some other universal testing machines have been adapted to perform a modified texture profile analysis (Bourne, 1968, 1974). A typical Instron TPA curve is shown in Fig. 4.49. Bourne closely followed the interpretation of Friedman *et al*. (1963) with one exception: instead of measuring the total areas under the curves to obtain cohesiveness, he measured the areas under the compression portion only and excluded the areas under the decompression portions.

A typical TPA curve obtained in the Instron differs in several major respects from that obtained by the GF Texturometer. This can be seen by comparing Figs 4.47 and 4.49. The Intron curves show sharp peaks at the end of each

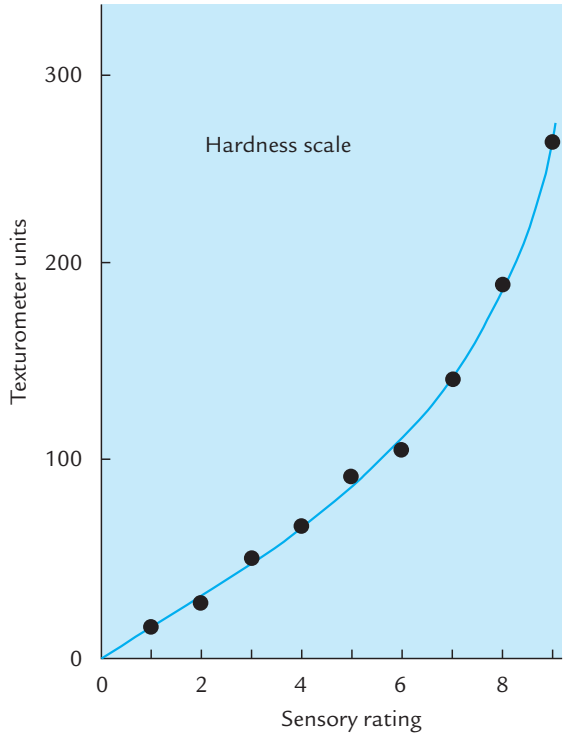


Figure 4.48 Correlation between sensory evaluation and GF Texturometer for hardness of nine selected foods. (Courtesy of Dr A. S. Szczesniak; reprinted from *J. Food Sci.* **28**, 401, 1963; copyright by Institute of Food Technologists.)

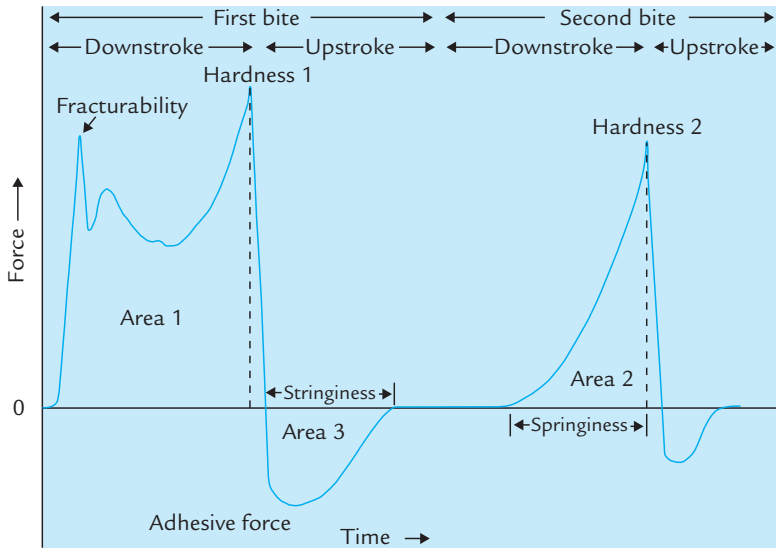


Figure 4.49 A generalized texture profile analysis curve obtained from the Instron Universal Testing Machine. (Reprinted from *Food Technol.* **32**, 63, 1978; copyright by Institute of Food Technologists.)

compression while the GF Texturometer shows rounded peaks. These differences arise from differences in instrument construction and operation. The GF Texturometer is driven by means of an eccentric rotating at constant speed and imparting a sinusoidal speed to the compressing mechanism, while the Instron is driven at constant speed. The GF Texturometer decelerates as it approaches the end of the compression stroke, momentarily stops, and then slowly accelerates again as it makes the upward stroke. In contrast, the Instron approaches the end of the compression stroke at constant speed, abruptly reverses direction,

Table 4.13 Dimensional Analysis of TPA Parameters[a]

Mechanical parameter	Measured variable	Dimensions of measured variable
Hardness	Force	mlt^{-2}
Cohesiveness	Ratio	Dimensionless
Springiness	Distance	l
Adhesiveness	Work	ml^2t^{-2}
Fracturability (brittleness)	Force	mlt^{-2}
Chewiness	Work	ml^2t^{-2}
Gumminess	Force	mlt^{-2}

Source: Bourne (1966a). Note: This table was incorrectly presented in the original publication. The correct table was published in *J. Food Sci.* **32**, 154, 1967. Copyright by Institute of Food Technologists.

and performs the upward stroke at constant speed. The constant speed of the Instron versus the continuously changing speed of the GF Texturometer largely accounts for the sharp peaks in the Instron in contrast to the rounded peaks of the Texturometer.

Another difference is that the supporting platform of the GF Texturometer is flexible; it bends a little as the load is applied. The Instron is so rigid that bending of the instrument can be ignored. Yet another difference is that the compressing plate of the Texturometer moves in the arc of a circle, whereas in the Instron it moves rectilinearly. These three factors taken together account for the differences in the TPA curves obtained by the GF Texturometer and the Instron.

Since the Instron gives both a force–time and force–distance curve, the TPA parameters obtained from it can be given dimensions, which are listed in Table 4.13.

Henry *et al*. (1971) provided a more detailed analysis of the adhesiveness portion of texture profile curve for semisolid foods such as custard, puddings, and whipped toppings. In addition to measuring the area of the adhesiveness curve they measured its maximum force (symbolized by F_a to denote firmness under tension), the recovery in the adhesion portion between the first and second compressions (E_a to denote elastic recovery under tension), and the ratio of the two adhesion areas (C_a to denote cohesiveness under tension). They calculated gumminess under tension ($Ch_a = F_a \times C_a \times E_a$). They also measured the property of stringiness (or, inversely, shortness) as the distance the product was extended during decompression before breaking off (Henry and Katz, 1969). Their experiments showed that eight of these parameters accounted for more than 90% of the variation of four sensory factors.

Reports on the Texture Profile Analysis of a number of commodities have appeared in the literature with some variations on the main themes described above. Breene (1975) gave a complete review of this area.

Accuracy and Precision of Measurement

It is important to distinguish between accuracy of measurement and precision of measurement. **Accuracy** means how closely the measured value comes to the true value. **Precision** means how many significant figures are used to express the measurement. A nonfood example of the difference between accuracy and precision follows.

The posted air distance between New York's Kennedy Airport and London's Heathrow Airport is 3452 miles. This number, 3452, is accurate and carries a justifiable degree of precision of four significant figures. When the distance is stated in sequence as:

3452 miles
3453 miles
3462 miles
3552 miles
4452 miles

the degree of precision is maintained but the degree of accuracy is degraded at each step in the series because the error becomes greater each time the erroneous digit is moved one place to the left.

When the distance is stated in sequence as:

3452 miles
3450 miles
3500 miles
3000 miles

the number is accurate in each step, but the degree of precision is degrading in each step because there are fewer significant numbers.

One must be alert to expressing measurements to a degree of precision that cannot be justified by the measuring technique. Continuing with the above example, the distance from New York to London is 3452 miles. Conversion tables state 1 mile = 1.609344 km. Therefore, the distance from New York to London can be recalculated as:

$$3452 \text{ miles} \times 1.609344 = 5555.455488 \text{ km}$$

This value is accurate but is given with an unwarranted degree of precision because the expressed value of any quantity should not be given to a greater degree of precision than is obtained by the original measurement. In this case, the distance in miles is given to four significant figures (3452 miles). Hence after converting into kilometers the result cannot be given to more than four significant figures (5555 km). Every number after four significant figure is worthless because there is no way to determine whether or not it is correct.

The accuracy of the force measuring system in most universal testing machines is stated to be 0.5% of the full-scale force. Hence, force measurements, and measurements containing a force element (e.g. work) cannot be

listed to more than two significant figures from a single measurement, or more than three significant figures when the mean of several replicate tests is reported. Many UTMs that have a computer readout of force list the force to five or more significant figures. In such cases it must be remembered that any numbers past three figures are fictitious and should not be used when reporting the results of the test.

Practice of Objective Texture Measurement

CHAPTER 5

Introduction

This chapter discusses the major commercially available texture measuring instruments that are available at the present time. The principles on which these instruments operate were discussed in the previous chapter. The order in which the instruments are described will follow the same sequence as used in the previous chapter. Appendix I lists the suppliers of these instruments, to whom inquiries for further information and prices should be sent.

Several instruments that are no longer commercially available are described. This is because a considerable amount of data generated by these instruments has been published and a brief summary will give the reader a better understanding of the significance and meaning of the published data.

Force Measuring Instruments

Hand-Operated Puncture Testers

These testers are derived from the improved type of pressure tester developed by Magness and Taylor (1925). These are frequently called 'pressure testers' but a better description would be to class them as 'puncture testers.' Table 5.1 lists the specifications of these puncture testers and Fig. 5.1 shows some of the instruments. All these instruments use a spring to measure applied force with an indicator to show the maximum test force. This class of instrument is widely used to measure the firmness of fruits and some vegetables.

The Ballauf Company makes two testers, one with a 30-lb spring for firmer products and the other with a 10-lb spring. Two punches are provided: 7/16 in. and 5/16 in. diam. The punches have a rounded face and an inscribed line 5/16 in. back from the front end of the punch, indicating the depth to which it

Table 5.1 Specifications of Hand-operated Puncture Testers

Manufacturer	Force full scale ✖ graduations	Plunger travel to full scale force (cm)	Punch		Instrument	
			Diam (in.)	Face	Length (cm)	Weight (g)
Ballauf Co.	30 × 1 lb	13	7/16, 5/16	Rounded	52	700
Ballauf Co.	10 × 1/2 lb	13	7/16, 5/16	Rounded	44	530
Chatillon 719-40 MRPFR	40 × 1/2 lb 18 kg × 200 g	10	7/16, 5/16	Flat	50	500
Chatillon 719-20 MRPFR	20 × 1/4 lb	10	7/16, 5/16	Flat	50	450
Chatillon 719-10 MRPFR	10 lb × 2 oz 4.5 kg × 50 g	10	7/16, 5/16	Flat	50	420
Chatillon 719-5 MRPFR	5 lb × 1 oz 2.2 kg × 50 g	10	7/16, 5/16	Flat	50	400
Chatillon 516-1000 MRPFR	1000 × 10 g 2 lb × 1/2 oz	10	0.026, 0.032, 0.046, 0.058, 0.063	Flat	46	180
Chatillon 516-500 MRPFR	500 × 5 g 1 lb × 1/4 oz	10	0.026, 0.032, 0.0468, 0.058, 0.063	Flat	44	180
Effi-Gi	12 × 1/4 kg 5 × 0.1 kg	2	7/16, 5/16	Rounded	13	170

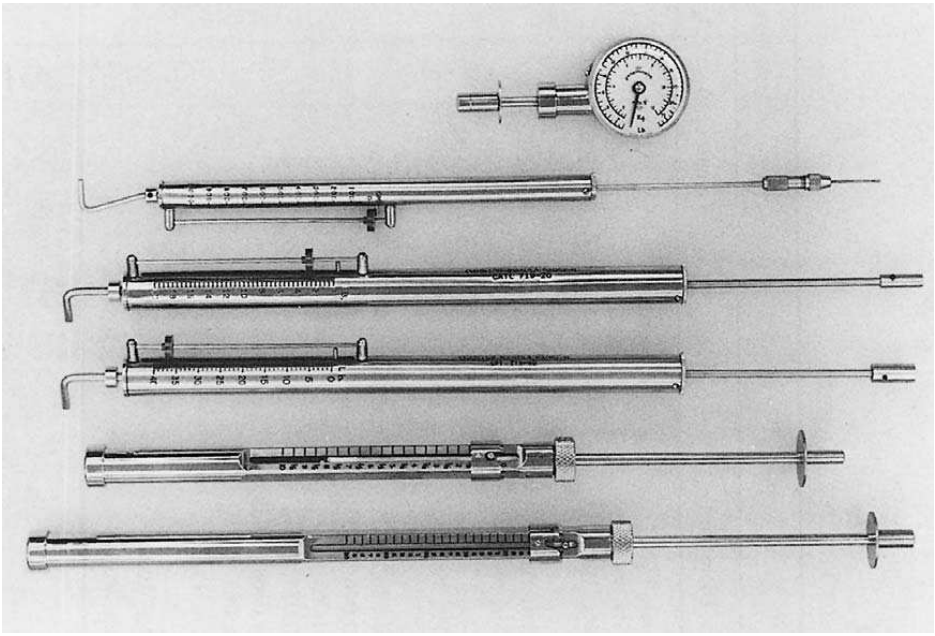


Figure 5.1 Hand-operated puncture testers of the Magness–Taylor type. From the bottom up: 30-lb Ballauf with 7/16-in.-diam punch, 10-lb Ballauf with 5/16-in.-diam punch, 40-lb Chatillon with 7/16-in.-diam punch, 20-lb Chatillon with 5/16-in.-diam punch, 1000 g Chatillon with 0.058-in.-diam punch, and Effi-Gi with 7/16-in.-diam punch.

should be pressed into the test sample. A splash collar prevents juice from running back along the shaft.

Chatillon makes two series of testers. The 719 series covers force ranges of 5, 10, 20, and 40 lb and provides 7/16- and 5/16-in.-diam punches. These have a flat face, there is no inscribed line indicating how far the punch should penetrate into the test sample, and there is no splash collar. The Chatillon 516 series are smaller, lighter instruments with force ranges of 500 and 1000 g.

A small chuck at the end of the shaft is used to hold one of the five punches that range from 0.026 to 0.063 in. diam.

The Effi-Gi is the smallest and lightest instrument and most convenient to handle. It has a dial force gauge and uses the same punches as the Ballauf; 5-kg and 12-kg force scales are available.

The testers are held in one hand, the punch is placed against the sample to be tested (most commonly a fruit), and steadily increasing force is applied until the punch penetrates to the inscribed line. The operator has to decide how far to make the punch penetrate for those punches that have no inscribed lines. The maximum test force is recorded by a pointer on the force gauge. The pointer must be returned to zero after each test.

The manner in which these hand gauges are operated affects the readings that are obtained. Therefore, it is mandatory to use a standard method to operate this class of instrument. Table 5.2 lists the operating rules that have been devised in our laboratory.

The springs of these instruments should be calibrated regularly to ensure that they are giving the correct force readings. The Ballauf instrument is calibrated by placing the tester vertically on weight scales with the punch down,

Table 5.2 Operating Rules for Use of a Hand-operated Puncture Tester on Fruits and Vegetables

Remove skin from test site (unless it has been shown the skin does not affect the result).
Hold food in one hand against a rigid vertical surface such as a wall, tree trunk, or heavy bench. Keep test surface perpendicular to the punch face.
Hold puncture tester in the other hand with the side of the hand resting on the hip and steadily 'lean into' the tester with hip; this gives a more even rate of force application than pushing with the arm. Tester must be in a horizontal plane. Erratic motions due to lack of firm support, and pushing with the hand only can cause jerky movement which may cause spuriously high readings. Since these are maximum force instruments a momentarily high force will be recorded as the test force.
When penetration begins, the operator should pause momentarily in increasing the applied force. Penetration will continue at constant force and approximate constant speed with type B products (see Fig. 5.2, page 193). In type C products the punch will accelerate into the flesh past the inscribed line. The penetration will stop for the type A products even though the force is maintained; the force is now increased in small increments with a pause between each increment in order to allow the punch to penetrate as far as possible at that force; continue until tip penetrates to the inscribed line.
Use a constant diameter punch for any series of tests. If necessary, change to another instrument with a different force spring to cover the force range but do not change the punch diameter during the experiment.
Do not test near the edge of the test sample. If the edge cracks or splits during a test the result should be rejected. This problem can be overcome by testing farther away from the edge or using a smaller diameter punch.
It is customary to use at least 20–30 fruits per test to obtain representative data. Two readings are usually made on each fruit: on opposite sides midway between the stem and the blossom ends, and away from the suture line.

Source: From Bourne (1979b); with permission from Academic Press Inc. (London) Ltd.

applying force steadily until a given force is registered on the scale, then releasing the force and taking the reading on the Ballauf instrument. Continue in this way increasing the force in increments of 10% of the range up to the force range of the instrument. The weight of the shaft assembly to which the punch is attached must be subtracted from the instrument reading for comparison with the spring balance reading. The shaft assembly in the 30-lb instrument weighs approximately 300 g (10 oz) and the shaft assembly in the 10-lb instrument weighs approximately 200 g (7 oz). The Ballauf Co. will recalibrate their instruments at the factory for a nominal fee. These instruments can also be calibrated in a universal testing machine.

The vertical calibration method described in the previous paragraph compares the instrument spring force plus the mass of the shaft assembly against a scale reading. There is, therefore, a positive constant error equal to the mass of the rod in the calibration readings that must be subtracted. When the instrument is used in the normal horizontal operating position, the mass of the shaft assembly no longer affects the reading.

The Effi-Gi is calibrated in the same way as the Ballauf. The zero is adjusted by adding or removing shims to the inside of the instrument.

The Chatillon pressure testers have a knurled knob at the end of barrel nearest the pressure tip. Rotating this knob adjusts the zero point. The zero reading should be checked while holding the instrument horizontal before each use and adjusted to the correct value. Once this adjustment has been made the knurled ring should not be moved. This instrument has a hook at the top end that can be used for measuring tensile forces. To calibrate, the instrument is held in a vertical position with the tip upward, the knurled ring is adjusted to account for the weight of the shaft to bring the indicator to the zero point, and then weights are hung on the hook to increase the force applied in suitable increments.

Voisey (1977a) studied the static and dynamic calibration of the Ballauf and Effi-Gi testers by mounting them in the Instron and found that the primary source of differences between instrument readings was systematic calibration errors. These can be corrected. Voisey (1977a) recommended dynamic calibration because this simulates the actual operation of the instrument. He also suggested that differences between operators could be reduced by training operators to achieve a constant rate of force increase.

These instruments are widely used in the horticultural industry for measuring the firmness of fruits and some vegetables, but they could quite well be used for a number of other foods. Ballauf units are operated by holding one hand over the smooth end of the tester. The Chatillon instrument must be held by the body because of the tension hook protruding from the top. This poses no problem for the lower force ranges but for the 40-lb instrument the body must be grasped very tightly to supply sufficient force to prevent the body from slipping through the hand. A complete set of Chatillon instruments is an economical method for obtaining a wide range of forces and a wide range of tip diameters. The Effi-Gi is the most compact of the instruments and can be carried in a pocket. The rounded dial fits comfortably between the forefinger

and the thumb. The spring on the Ballauf and Chatillon testers needs to be compressed a long distance to reach full-scale force, whereas on the Effi-Gi the distance is much less (Table 5.1). This makes a difference when performing a large number of tests because the amount of work (force × distance) required to operate the Effi-Gi on similar foods is about one fifth that for the other testers that cover the same force range.

A person using these instruments for the first time may be perplexed by the different ways in which these puncture testers handle. Sometimes the punch can be pushed into the commodity smoothly and gently, making it easy to control the depth of penetration. At other times the punch tends to penetrate with less control, and with some foods it suddenly plunges in past the inscribed line. The punches from these instruments have been mounted in an Instron testing machine, which automatically records the complete history of the force changes that occur during tests (Bourne, 1965a; Voisey, 1977a). These studies have thrown considerable light on the performance of the hand puncture testers and on how they should be used. Figure 5.2 shows the three basic types of curves that are obtained with horticultural products. In each case there is an initial rapid rise in force over a short distance as the punch moves onto the sample. During this stage the sample is deforming under the applied force; there is no puncturing of the tissues. This stage ends abruptly when the punch begins to penetrate into the food, which event is represented by the sudden change in slope called the 'yield point' or sometimes 'bioyield point.' The yield point occurs when the punch begins to penetrate into the food, causing irreversible crushing. The third phase of the puncture test, namely, the direction of the force change after the yield point and during penetration of the punch into the food, separates the puncture curves into three types: type A, the force continues to increase after the yield point; type B, the force is approximately constant after the yield point; type C, the force decreases after the yield point.

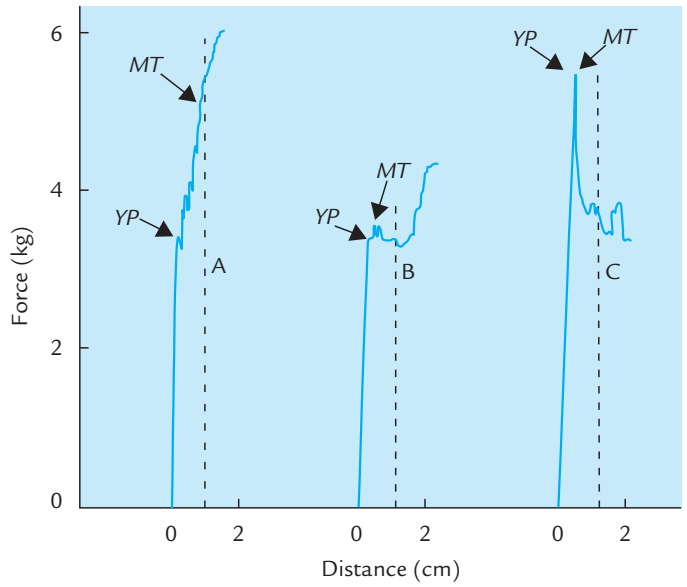


Figure 5.2 Characteristic force–distance curves obtained by mounting the 5/16-in.-diam punch of the Ballauf tester in the Instron. *YP* is the yield point and *MT* the force reading that would have been obtained on a hand-operated puncture tester. The dotted vertical lines represent the depth of penetration to the 5/16-in. inscribed line on the pressure tip. (From Bourne, 1965a; reprinted from *Food Technol.* **19**, 414, 1965. Copyright by Institute of Food Technologists.)

With type A products (typified by freshly harvested apples) the hand tester must be pushed with increasing force after the yield point to make the punch penetrate to the required depth. Each increment in force causes an increment in penetration and no further penetration occurs until the force is increased again. It is easy to control the depth of penetration of the punch tip into a type A commodity.

With type B products (typified by ripe pears and peaches, and apples that have been held in cold storage a long time) the hand tester must be pushed until the yield point is reached, the punch then continues to penetrate the tissue with no further increase in force because penetration occurs at approximately constant force. It is fairly easy to control the depth of penetration into a type B product but not as easily as with a type A product. When the punch penetrates beyond the inscribed line, the force reading can still be used because the puncture force is almost independent of the depth of penetration.

For type C products (most raw vegetables exhibit this type of behavior), the hand tester must be pushed until the yield point is reached, when the punch plunges into the tissue very rapidly until it is stopped by the splash collar. Figure 5.3 shows typical force–distance plots for vegetables. It is very difficult to control the depth of penetration into type C products. When the yield point has been reached, the spring continues to push the punch with yield point force, although the resistance to penetration has become much lower. Consequently the punch accelerates so quickly that even an experienced operator cannot prevent the tip from penetrating into the food past the inscribed line.

Because it is impossible to stop the penetration at the inscribed line on the punch in a type C product, many operators consider the puncture test to be an unsatisfactory test for vegetables, but this is an erroneous opinion. The yield point for a type C product is the maximum force that is encountered during

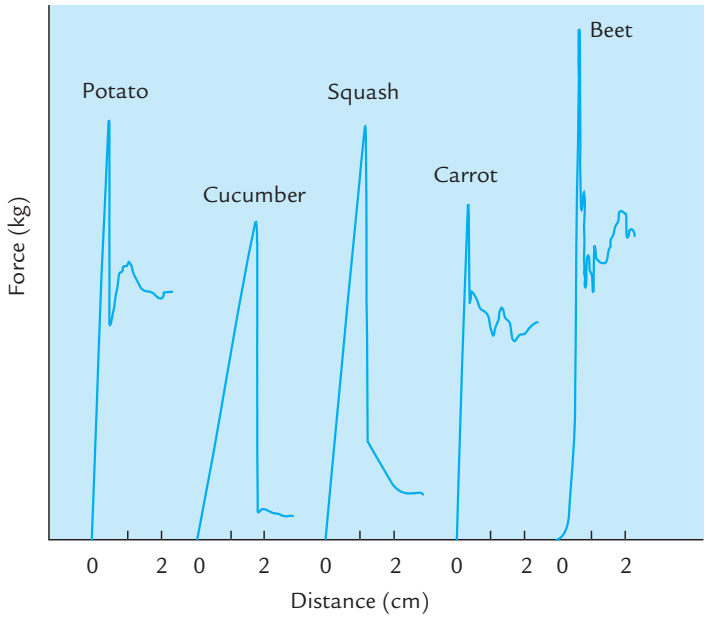


Figure 5.3 Characteristic force–distance curves from puncture tests on raw vegetables. Note that each one is a type C curve. (From Bourne, 1975c; with permission from D. Reidel Publ. Co.)

the test. Since the hand tester uses a maximum force reading dial, it will read the yield point (maximum force) correctly, even though the penetration goes beyond the inscribed line, provided that the test is performed correctly. Therefore, the hand puncture test can be a useful test on raw vegetables and other products that behave in this manner. Table 5.3 shows data in which the puncture test was performed using the same punches in the Effi-Gi puncture tester and in the Instron; the hand tester gives the correct measurement of the yield point of vegetables (within the limits of experimental error), although the punch penetrated up to the splash collar in every test.

There has been considerable discussion as to whether the skin should or should not be removed at the puncture test site. Figure 5.4, which is a

Table 5.3 Comparison of Puncture Test by Hand Tester and Instron

Commodity	Hand tester[a] mean force (kg)	Instron[b] mean force (kg)
Irish potatoes	10.76	10.86
Summer squash	9.78	9.50
Beets	12.23	12.59

Source: From Bourne (1975c); with permission from D. Reidel Publ. Co. 5/16-in.-diam punch; mean of 25 punches.
[a]Effi-Gi tester, 5/16-in.-diam tip, operated by hand, read dial force.
[b]5/16-in.-diam tip mounted in Instron, read off yield point.

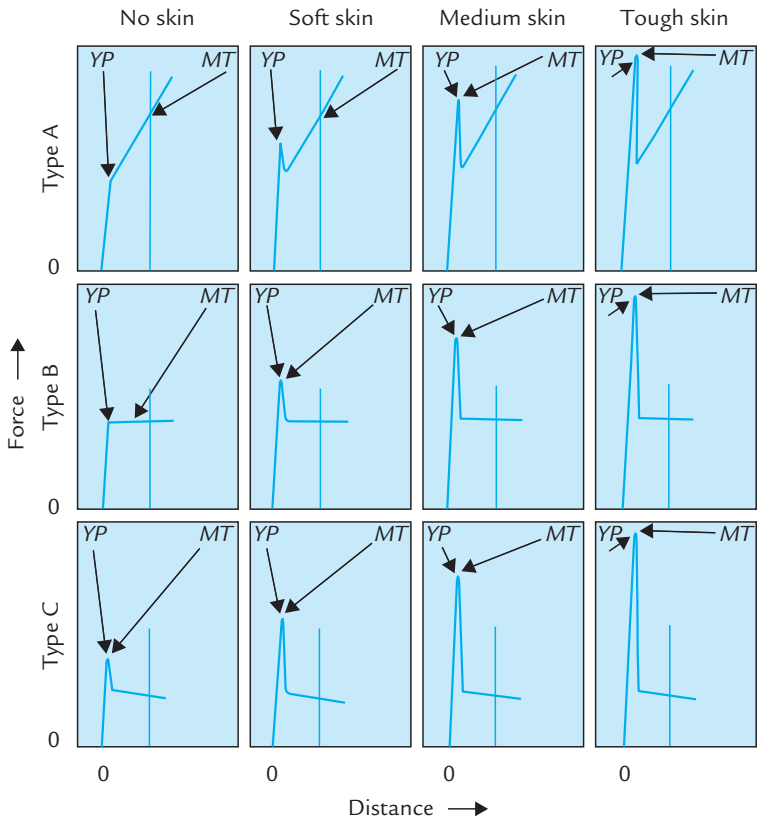


Figure 5.4 Schematic representation of force–distance curves obtained when puncturing horticultural products with and without skin. The left-hand column shows the three types of curves obtained with skin removed at the test site. The next three columns show the effect of soft, medium, and tough skin on each type of curve. *YP* is the yield point and *MT* the force reading that would have been obtained on a hand-operated puncture tester. Note that the only effect of the skin is to increase the yield point. The vertical lines indicate 5/16-in. penetration point. (From Bourne, 1965b; with permission from New York State Agricultural Experiment Station.)

schematic representation derived from thousands of tests with the Instron, clarifies this point. The left-hand column of graphs shows the three different shapes of force–distance curves that are obtained on horticultural products with the skin removed (as discussed above; see Fig. 5.2).

Whenever skin is present it must be ruptured by the punch before any substantial penetration of the punch into the food can occur; the force to rupture the skin is therefore included in the penetration force and this appears as a peak in the yield point force which is superimposed upon a regular type A or type B curve and an increase in the height of the peak of a type C force–distance curve. The height of the superimposed peak depends on the toughness of the skin. In type B and type C products, where the flesh yield point force is the measured quantity, the increase in reading caused by the skin is always reflected in a higher force reading. In some cases (e.g. strawberries) the skin is so soft that the increase is negligible. In the case of a type A commodity with soft skin the force to rupture the skin is less than the force required to penetrate 5/16 in. If the skin is of medium toughness, it generally ruptures at about the same force required as at the 5/16-in. penetration and only a small increase in force reading results. Finally, if the skin is quite tough, the force to rupture the skin is well beyond the normal Magness–Taylor force and the force reading will be noticeably increased. Figure 5.4 explains why the presence of skin sometimes causes an increase in puncture force and at other times it does not.

Since the strength of the skin is not necessarily related to the firmness of the underlying flesh, it is evident that the skin should be removed if a true measurement of flesh firmness is required, unless it has been established that the skin is so tender that it causes a negligible increase or that the product exhibits type A characteristics and does not have a tough skin.

Equation (4.5) in Chapter 4 (page 121) explains the relationship between punch diameter and puncture force and shows that both area and perimeter of the punch are important. This equation demonstrates that the puncture force depends on two different properties of the test material and on both the area and perimeter of the punch. It explains why it is difficult to convert data obtained with one punch diameter into data obtained with another punch diameter. For this reason it is mandatory to standardize the punch diameter in any one set of experiments. It is quite acceptable to change the strength of the spring as one moves into a higher or lower force range, but punch diameter should not be changed.

In general, the 7/16-in.-diam punches are used on most fruits because the force required will be less than 30 lb. The 5/16-in.-diam punch is used on very hard fruits and raw vegetables when the force would exceed 30 lb with the larger punch diameter. The small diameter punches of the Chatillon 516 series are frequently used on commodities such as sweet corn, green peas, and strawberries. Haller (1941) gives a good discussion of fruit puncture testers and their practical applications and typical results for puncture tests on apples, pears, plums, and peaches. Table 5.4 gives typical puncture force figures for some apple varieties, and Table 5.5 gives typical figures for several fruits.

Table 5.4 Range of Firmness Readings of Some Apple Varieties by Puncture Test[a]

Variety	Hard	Firm	Firm ripe	Ripe	Prime eating	Overripe upper limit
Ben Davis	24–17.5	18–14.5	15–12	13.5–8	13–9	9
Delicious	20–16.5	17.5–14	15–11	12–8	12–8	8
Grimes golden	27–18	18.5–15	16–12.5	13.5–9	12–8	8
Jonathan	21–16	16.5–13.5	14–10.5	12–8	12–8	8
Rome beauty	23–18	19–13	16–12.5	13.5–9	13–9	9
Stayman winesap	21–16	16.5–13	14–11	12–7	12–8	8
Wealthy	20–16	17–13	14–10	11–6	—	—
Yellow transparent	22–16	17–13	14–10	11–6	—	—
York imperial	24–18	19–16	17–14	15–9	13–10	10

[a]lb force with 7/16-in.-diam Magness–Taylor tip. Data from Haller (1941).

Table 5.5 Firmness of Various Fruits by Puncture Test[a]

Fruit	Variety	Color Stage	Firmness (lb)
Apricots	Royal	Yellowish green	14.5
		Greenish yellow	10.0
		Greenish yellow to yellow	7.1
		Yellow to orange	4.1
Plums	Beauty	Green to straw tip	13.2
		Straw to slight pink tip	9.0
		Straw to red tip	6.1
		1/2 to 1/4 red	4.9
	Climax	Green to faint straw tip	25.1
		Straw to greenish yellow	20.7
		Greenish yellow to red tip	15.5
		1/4 to 3/4 red	8.9
Peaches	Elberta	Yellowish green, slight blush	17.6
		Cream to light yellow, slight blush	12.4
		Full yellow, 1/3 to 1/2 red	3.7
	Phillips cling	Greenish yellow to yellow	12.0
		Yellow, 1/4 to 1/2 red	8.8
		Golden yellow, 1/4 to 3/4 red	8.4
Pears	Bartlett	Original green	29.2
		Original green to light green	26.9
		Light green to yellowish green	21.0
		Yellowish green	15.2
	Beurre hardy	Original green	12.3
		Light green	10.8
		Light green to yellowish green	8.6

Source: Data from Allen (1932); with permission from Division of Agricultural Sciences, University of California.
[a]Magness–Taylor tester: 7/16-in.-diam tip for apricots and plums; 5/16-in.-diam tip for peaches and pears.

The EPT (Electronic Pressure Tester) uses the standard Magness–Taylor tips and microprocessor to detect the bioyield point. The fruit is cradled on a platform with the skin removed at the test site. The operator pulls down a handle which forces the metal tip into the fruit to a depth judged adequate by the operator. Each reading is displayed as it is performed. When a batch of fruit has been tested the instrument prints the average force and standard deviation for that batch. This instrument greatly decreases the time required to test a number of replicates, record the data, and calculate the mean. DeLong *et al*. (2000) compared the EPT fruit tester with other fruit puncture testers on three cultivars of apples by four operators.

Mechanical and Motorized Puncture Testers

Bloom Gelometer

The Bloom Gelometer (Bloom, 1925) is a puncture test designed to measure the strength of gelatins and gelatin jellies. It consists of a hopper full of lead shot that flows through a tube onto a pan, thus providing the force necessary to make a plunger penetrate into a standard jelly. Borker *et al*. (1966) reviewed the early history of gelatin gel testing and discussed the necessity for frequent maintenance of alignment and adjustment of the Bloom gelometer.

The 2000 edition of *Official Methods of Analysis* (published by AOAC International) gives the details for the preparation of a standard gel. For gelatin it is method 948.21, and for gelatin dessert powders, method 936.09. The standard method for determining the jelly strength of glue is described by DeBeaukelaer *et al*. (1930). The standard jar containing the standard jelly is placed in the Bloom Gelometer and adjusted until the flat face of the probe is just resting on the surface. A 1/2-in.-diameter punch is used for gelatin and a 1-in.-diameter punch is used for gelatin desserts. A lever is tripped allowing lead shot to flow from the hopper into a lightweight aluminum dish on the scale supported by the punch pan at the rate of 200 ± 5 ***g*** per 5 s. When the plunger has penetrated 4 mm into the jelly (which usually occurs suddenly), an electrical contact shuts off the flow of shot. The shot is weighed and the weight of shot in grams is expressed as the Bloom of that gel. The Bloom Gelometer is 18 × 19 × 63 cm high and weighs 13 kg.

DeBeaukelaer *et al*. (1945) showed that the flow rate of 200 ***g*** per 5 s causes errors in soft jellies because the lead shot runs out too fast, and suggested that for soft jellies the flow rate should be reduced to 40–50 ***g*** per 5 s. Borker and Sloman (1969) also found that slowing the flow rate of shot to 45 ***g*** per 5 s gave more precise results and recommended that this flow rate be incorporated as an official standard. As noted above, the 2000 official standard continues to use the 200 ***g*** per 5 s rate of shot flow.

Stevens LFRA Texture Analyzer

This instrument, developed by the Leatherhead Food Research Association (LFRA) in England, was designed to perform the standard Bloom test plus a

number of other tests. The instrument stands about 50 cm high, 24 cm wide, and 23 cm deep, and weighs about 12 kg. It replaces the Boucher Electronic Jelly Tester, which is no longer manufactured.

The standard probe is a 1/2-in.-diam flat-faced straight-sided acrylic punch that has the same dimensions as the punch used for the Bloom test. Punches of other diameters and punches in the form of a needle, ball, or blade are also available. Four speeds of punch travel are available: 12, 30, 60, and 120 mm min^{-1}. The maximum stroke of the punch is 15 cm. The penetration distance is adjustable from 1 to 29 mm in 1-mm steps. In operation, the test sample is placed beneath the punch and the motor activated. The punch moves downward at the maximum speed until a force of 5 ***g*** is registered, when it automatically steps down to the selected set speed and travels at this speed for the selected distance. At the end of the stroke it returns to its original position at maximum speed. An electronic load cell in the base of the instrument senses the force and registers it on a digital readout, which shows the maximum force obtained in the test. The instrument has a capacity of 1000 ***g*** force and reads within 1 ***g***. It can be adapted to a 100-***g*** force capacity and a reading within 0.1 ***g*** for very soft products.

A recorder is an optional accessory giving force–distance plots of the puncture tests. This instrument is a useful general-purpose puncture tester for soft products. It is used on meat pastes, foams, various gels, and some fats.

Maturometer

This instrument, designed to measure the maturity of fresh green peas, was developed in Australia and is extensively used in that country. Its intended purposes were to objectively measure the maturity of fresh peas and to select the optimal harvest time during the growth of the crop that gives the yield and quality required to meet the production objectives of the processor. Its manufacture is covered by Australian Patent No. 143,316. It consists of 143 1/8-in.-diam flat-face punches set in an array of 11 rows by 13 rows with individual punches spaced on 7/16-in. centers. A metal plate containing 143 matching countersunk holes is positioned underneath the punches.

A pea is lodged in each recess. When the plate of peas is driven upward by a motor, the peas are punctured simultaneously by the pins and the maximum force is measured on a force scale at the top of the instrument (Lynch and Mitchell, 1950, 1952; Mitchell *et al*., 1961). A matching perforated plate mounted over the metal plate that holds the peas prevents the peas from sticking to the punches during the return stroke. The instrument has a force capacity of 440 lb in 5-lb graduations.

Based on extensive field testing and sensory evaluation, it was found for Australian conditions that peas harvested at a maturometer reading of 250 lb gave the maximum yield of highest quality peas for canning. A somewhat lower figure is needed for the maximum yield of best-quality peas for freezing. In using the Maturometer Index (MI) as a basis of payment for quality the

following ranges are recommended for field run ungraded peas:

Grade 1 (canning) consists of peas in the range of 230–270 MI.
Grade 2 (canning) consists of peas in the range of 190–230 and 270–320 MI.
Grade 1 (freezing) consists of all peas up to 200 MI.

The MI of peas in the field increases by an average of 20 lb per day. By testing field samples daily it is possible to predict when the figure of 250 lb will be reached. This enables a pea processor to know several days in advance when to harvest a field and the number of fields that will be harvested on a given day.

Casimir *et al*. (1971), using a single-punch Maturometer, found a simple correlation coefficient *r* ranging from 0.96 to 0.99 between puncture force and alcohol insoluble solids of individual peas. Casimir *et al*. (1967) showed that high speed of operation of the pea viner caused some bruising and tenderization of the peas resulting in lower Maturometer readings.

Christel Texture Meter

This instrument (Christel, 1938) consists of a set of 25 flat-faced 3/16-in.-diam punches that are held in a metal plate above a metal cup 2 in. internal diam and $1\frac{3}{4}$ in. deep. A removable metal cover containing a set of holes that match the array of punches above it rests on top of the cup. The food is placed in the cup, the set of punches is driven down by a hand-operated gear and rack assembly, and the force is registered on an hydraulic pressure gauge with a force capacity of 100 or 300 lb.

Armour Tenderometer

This instrument consists of an array of $10\frac{1}{8}$-in.-diam stainless-steel probes, 3 in. long, with the last inch tapered to a point (Hansen, 1972). The instrument and its operation are covered by the basic United States Patent No. 3,593,572 and by several later patents. Morrow and Mohsenin (1976) analyzed the mechanics of a multiple conical probe system of this type. In operation the array of 10 needles is manually pressed 2 in. into the fifteenth rib eye of a beef carcass. The maximum force during penetration is recorded on a portable strain gauge force transducer fitted with a peak force indicator. Measurements of the maximum force on cold rib eyes in the chill room on the day after slaughter were found to correlate well with subjective panel tenderness scores on the same meat cooked after 1 week of aging. Huffman (1974) found the Armour Tenderometer to be superior to USDA quality grade or marbling as a means of placing cattle into homogeneous tenderness groups.

Some researchers have found low correlations between the Armour Tenderometer readings and sensory panels (Carpenter *et al*., 1972; Dikeman *et al*., 1972) whereas others find poor correlation (Henrickson *et al*., 1972; Parrish *et al*., 1973; Campion *et al*., 1975; Harris, 1975). Some of these low

correlations may have resulted partly from incorrect operator technique (Voisey, 1976). Nevertheless, this Tenderometer was granted the Industrial Achievement Award by the Institute of Food Technologists in 1973.

Other Puncture Testers

The suppliers of Universal Testing Machines provide a number of probes of various shapes and sizes that are suitable for puncture tests on many different kinds of foods.

Compression–Extrusion Testers

It was pointed out in the previous chapter that the extrusion principle test cells usually involve complex combinations of compression, extrusion, shear, friction, and perhaps other effects. For the sake of brevity, the word 'extrusion' will be used to describe this type of test, but the reader should remember that this class of test cell usually involves more than extrusion.

FMC Pea Tenderometer

This instrument was developed by the Food Machinery Corporation as an objective means for measuring the quality and maturity of fresh green peas (Martin, 1937; Martin *et al*., 1938). A motor-driven grid of 19 stainless-steel blades 1/8 in. thick and spaced 1/8 in. apart are rotated through a second reaction grid of 18 similar blades. The peas placed in the cavity between the two grids are cut and extruded through the slits between the blades. This is commonly known as a shearing device, but it is evident that most of the action on peas is extrusion. The reaction grid is mounted in bearings and is free to rotate, but its rotation is resisted by a weighted pendulum hanging from the second grid which swings out of the vertical as the reaction grid rotates. The force exerted during extrusion of the peas is reflected in the angular movement of the pendulum and is recorded by a pointer that moves across a sinusoidal scale. The pointer records the maximum force encountered in each test. The machine is rugged, self-contained, easy to clean, and can stand a lot of abuse in a processing plant or at a pea vining station.

Although it is widely used by the pea processing industry as an index of quality and price to be paid for the peas, it has some serious drawbacks, notably the problem of calibration. If the blades become dented or warped, a friction component is introduced. Voisey and Nonnecke (1971) performed a detailed appraisal of the Pea Tenderometer and found serious differences among different Tenderometers being used in industry. The problem of standardizing this instrument has also been discussed by Bourne (1972a). Unilever Research in England have devised a standardization procedure they claim maintains agreement to within ± 1.5 Tenderometer units between all instruments in their continental European and British factories (Pearson and Raynor, 1975). However, Voisey (1975) still considers the Tenderometer to

have serious deficiencies. Despite these problems, this instrument continues to be a widely used method for measuring the quality of peas in the industry.

Texture Press

This versatile and well-known instrument was developed at the University of Maryland (Kramer *et al*., 1951; Decker *et al*., 1957). Although it is commonly known as the 'Kramer Shear Press,' the name of the instrument has undergone several changes. The instrument was first manufactured by the Bridge Food Machinery Co. of Philadelphia, and later made by the Lee Corporation of Washington, DC, and called the Lee Comptroller and later the Lee–Kramer Shear Press. Later, the rights to manufacture the instrument were acquired by Allo Precision Metals Engineering, Inc., of Rockville, Maryland, and was called the Allo–Kramer Shear Press. Presently, it is manufactured by the Food Technology Corporation of Chantilly, Virginia, and is known as the Food Technology Corporation Texture Test System, abbreviated to FTC Texture Test System.

FTC currently produces five variations on the Texture Press design;

The Model TU, for Tenderometer measurements on fresh peas
The Model TM for in plant use on most food products
The Model T-2000 for general plant lab use
The Model TMS-90 computerized system for research labs
The Model TU-12 for field testing using a 12 V dc power source

The Models TU and TM are watertight designs for plant floor use and have a minimum of operator controls for quick on the spot testing. The T-2000, outfitted with the new TG4-E Integrating Texturegage and TMS-90, with the computer control, have more sophisticated hydraulic systems and controls and are not intended for use in harsh environments. The new Model TU-12 allows agricultural field men to do maturity and texture sampling in the crop fields. Model TMS-2000 is shown in Fig. 5.5.

At this time we will discuss only the basic machine (Model T-2000) fitted with one of the presently available force measurement devices, that is, Digital Texture gauge (Model TG4-EI), or a force transducer (loadcell). A number of accessories and various test cells, can be attached to this instrument converting it into a multiple measuring instrument. This mode of operation is discussed on page 228 and in Appendix III, Table 1, page 353.

The basic machine, known as the 'Texture Press,' is 64 cm wide, 60 cm deep, 90 cm high, and weighs about 95 kg (see Fig. 5.5). This is a robust machine that is designed for hard reliable work under wet food processing plant conditions. The system is driven hydraulically. An electrically driven oil pump powers the ram to which the moving parts are attached. Switches control the up and down motion of the ram. The working space for the test cells is 4×4.5 in.

In the older models the force was measured by a proving ring placed between the test cell and the bottom of the ram. In the current models the force

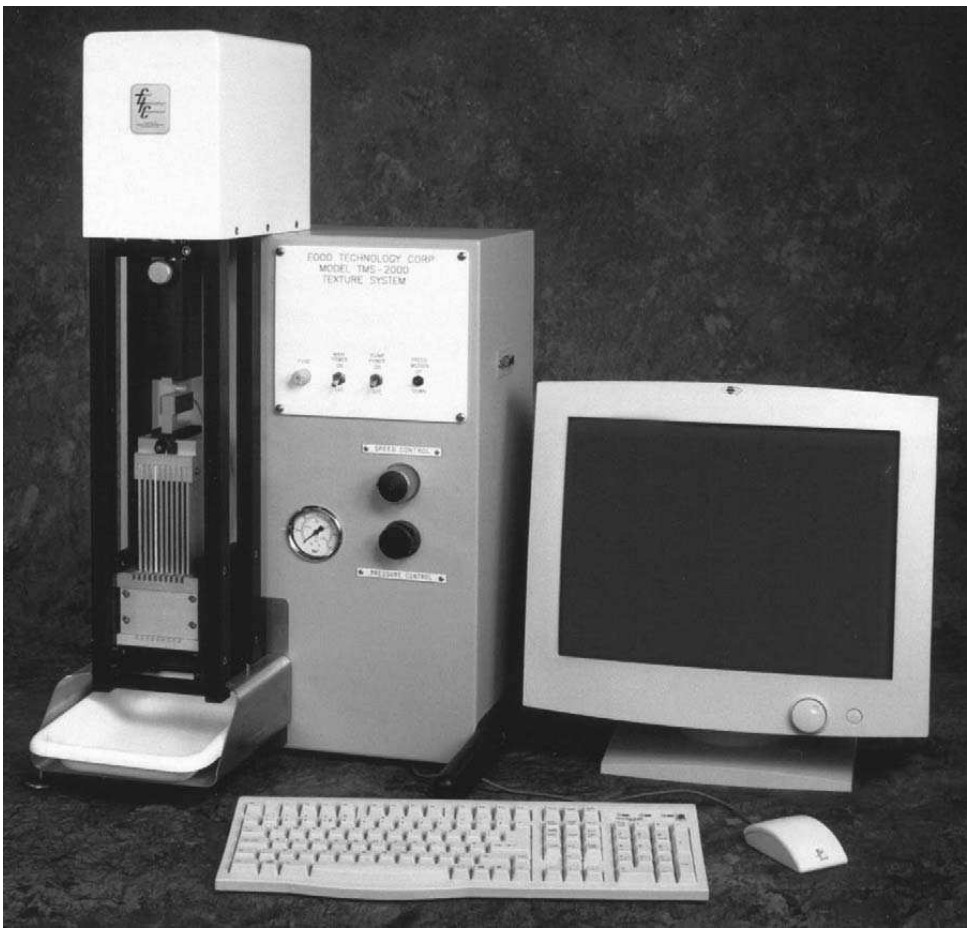


Figure 5.5 The Food Technology Corporation Texture Press ('Kramer Shear Press') Model TMS-2000. (Courtesy of Food Technology Corporation.)

is measured by means of a force transducer placed between the bottom of the ram and the test cell that is electrically connected to either a direct-reading digital texture gauge or a TMS-90 computer, both of which can display results in metric or English units. The force transducers have long-term stability; once calibrated they hold their performance for extended periods of time unless overloaded or abused. Force transducers should be returned to the manufacturer periodically for recalibration and inspection.

Six force transducers ranging from ±50 to ±3000 lb capacity are available. A special force transducer is available for use with fresh peas, which is calibrated directly in Pea Tenderometer units, and covers the range of 0–500 equivalent Tenderometer units. One Tenderometer unit is equivalent to approximately 6.2 lb/force. The digital texture gauge can be used as a maximum force measuring instrument by utilizing the peak holding switch on the front of the texture gauge. It can also be used as a total work calculator by using the integral switch on the gauge. With the switch in the peak position, the digital meter will read the peak maximum force and hold this reading until manually reset at the start of the next test.

The standard test cell of the Texture Press consists of a metal box with internal dimensions $2\frac{5}{8} \times 2\frac{7}{8} \times 2\frac{1}{2}$ in. high (6.6 × 7.3 × 6.4 cm). A set of

1/8-in.-wide bars spaced 1/8 in. apart are fixed in the bottom of the box. Guide ridges from the ends of these bars rise vertically up the sides of the box. A set of ten blades, each 1/8 in. thick and $2\frac{3}{4}$ in. wide, spaced 1/8 in. apart, is attached to the press ram. A metal lid containing a set of bars that match the bars in the bottom fits over the box. In operation, the food is placed in the test cell, the lid is positioned, and the test cell is placed in the machine such that the slits formed by the bars in the lid are aligned with the blades on the ram. When the ram is activated, the set of blades is forced down through the box, first compressing and then extruding the material. Some of the material extrudes upward between the moving blades, and the remainder extrudes downward through the bars in the bottom of the test cell. The moving blades are propelled down until they pass between the bars in the bottom of the test cell. When the ram is reversed, the moving blades ascend and return to their original position. As they ascend, the bars of the stationary test cell lid scrape off into the cell the food lodged between the moving blades.

The first standard test cell was fabricated in stainless steel, and the moving blades were a rigid welded unit with the bottom faces of the blades flat and parallel. This type of cell was manufactured by the Lee Corporation and Allo Precision Metals. The rigid construction posed a number of problems, including that of friction between the fixed bars and moving blades which can cause serious errors in measurement, particularly with soft products (Bourne, 1972a). Also there could be friction if the blades were burred, twisted, bent, or in some other way moved out of strict alignment.

The standard test cell manufactured by the Food Technology Corporation was changed to aluminum alloy, which makes the cell lighter (from almost 6 to 2.4 kg) and easier to handle. In the new design the moving blades are not welded but are pinned together, leaving a small amount of free play of the blades in the attachment connected to the ram. The blades in the new test cell design self-align with the slots in the box. The clearances between the moving blades and the slots in the stationary box have been increased slightly, which reduces the problem of friction between the parts.

A number of variations of this cell design are available. The CS-1A, which is fabricated from stainless steel and Delrin plastic, is designed for use with high acid foods. It is geometrically identical to the CS-1. Another variant is the Model CS-2 with thinner blades and slots; it is better suited for use with smaller-sized products such as rice or minced vegetables.

Voisey (1977b) found that some friction still occurred with the aluminum test cell and that the amount of friction varied greatly from cell to cell. He considered that these errors may be acceptable for samples that require a high force, but noted that errors could become large for samples that require a low force.

The bottom faces of the moving blades are slanted in alternate directions, which eliminates the sudden peak force that sometimes occurred when the flat and parallel blades first engaged the stationary bars at the bottom of the box.

The new design test cell has reduced some of the problems of the old cell and is preferred for general use. Occasionally the old cell may have an

advantage over the new cell. For example, Ross and Porter (1968, 1969, 1971, 1976) used the old design test cell to study the texture of French fries. They were able to obtain good results with the old model cell with squared-off ends on the moving blades, but their results cannot be duplicated with the new type cell with the slanted blades.

The relationship between the weight of material in the cell and the maximum force during the compression stroke was studied by Szczesniak *et al*. (1970), and is shown in Fig. 5.6. For two products (white bread and sponge cake) a linear relationship is found between sample weight and maximum force over a limited range of sample weight. deMan and Kamel (1981) also found a linear relationship between maximum force and sample weight for cooked poultry meat. The relationship for the other foods was nonlinear, tending toward constant force–weight relationship at high fill weights. Some products (e.g. raw apples and cooked dry beans) never reach a linear relationship. Many products attain a constant force independent of sample weight before the cell is filled (e.g. canned beets, peas, carrots, lima beans; frozen peas and lima beans; and raw snap beans and bananas). Thus, for most foodstuffs the force per sample weight is not constant but decreases as the sample weight increases. On these grounds it is advisable to use a constant weight of sample in the test cell unless tests show that there is a linear relationship between sample weight and maximum force for that food. Many researchers report Texture Press data as pounds force per gram weight of product. Figure 5.6 shows that this procedure is likely to introduce errors, and it should be discontinued.

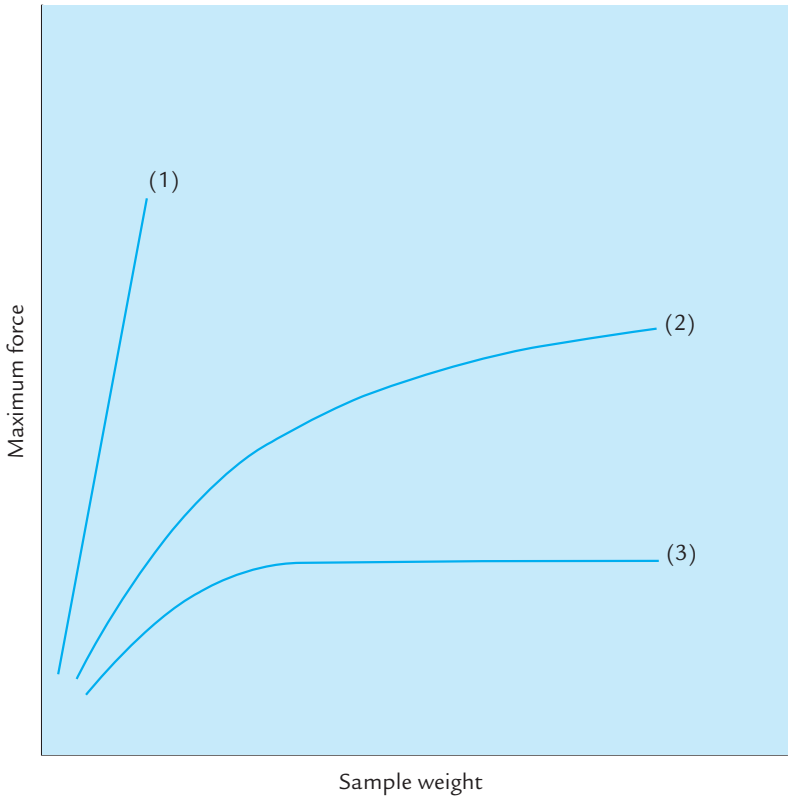


Figure 5.6 Typical maximum force versus sample weight relationship for standard Texture Press test cell. Behavior (1) is exemplified by white bread and cake, (2) by raw apples and cooked dry beans, and (3) by canned or frozen vegetables. (Reprinted from *J. Texture Studies* **1**, page 366, 1970. With permission from Food and Nutrition Press Inc.)

The speed of travel of the hydraulic ram is infinitely variable from 0 to 20 in. min^{-1} by adjusting a flow control valve located in the oil supply pipeline to the ram. Ram speed is usually expressed as seconds to travel its full stroke of 3½ in. This procedure poses the problem of using a reciprocal scale, that is, the higher the number in seconds the slower the speed. The formula for converting seconds to travel full stroke length into inches per minute, assuming constant ram speed, is

$$(3.5/s) \times 60 = \text{inches per minute}$$

The viscosity, which affects the rate of flow of the hydraulic oil, depends on the oil temperature. Hence, at a given setting of the control valve the speed of the ram will change with changing oil temperature. Therefore, the ram speed should be checked after the instrument has been running for some time to compensate for the effect of the heating of the oil. This is particularly important for those commodities that are strain-rate sensitive and for very slow ram speeds. Ang *et al*. (1960) used the Texture Press at a very slow rate of 0.46 in. min^{-1} and found that after 2 h of operation the oil had heated to 165°F, and the speed of travel of the ram had changed. In order to overcome this problem they placed a thermostatically controlled electric immersion heater in the oil bath to preheat the oil to 170°F before testing began. This is the only recorded instance where the temperature of the oil bath needed to be controlled in order to maintain adequate control of the speed of the ram. Voisey (1972) in a study of the Texture Press discusses the problem of speed control and concluded that the early models gave inadequate control of ram speed. Current models incorporate an improved temperature compensator flow control valve in the hydraulic control circuit.

The Food Technology Corporation provide another extrusion cell (Model CE-1 Universal Test Cell) that can be operated in several modes. It consists of a cast-iron cylinder that mounts in the machine frame. A circular piston is attached to the ram. In one mode the piston is a close fit in the cylinder, and all food placed in the cylinder is pushed out before it. There is some friction between the piston and the walls of the cylinder. A grid of metal bars or a flat plate containing a single orifice is inserted in the base of the cylinder, and the food is extruded through the grid or the orifice plate. In the second mode, a piston with a smaller diameter is used and a solid plate is placed in the bottom of the cylinder; in this configuration it acts as a back extrusion cell because the food is extruded upward between the walls of the cylinder and the sides of the piston, moving in the opposite direction to the motion of the piston. The annulus width in this back extrusion cell is 1/8 in. (3.2 mm), and there is no friction between the piston and the cylinder.

Ottawa Pea Tenderometer

The Ottawa Pea Tenderometer is a special version of the Ottawa Texture Measuring System (Voisey, 1971b, 1974; Voisey *et al*., 1972; Voisey and Nonnecke, 1973a,b) that was adapted specifically for measuring the maturity

of fresh peas (Voisey and Nonnecke, 1972a,b, 1973a,b,c). The standard test cell is constructed of 1/2-in.-thick aluminum plate and is square in cross section. The internal cross-sectional area of the cell is 30 cm^2 (55 mm along the edge), and it stands about 13 cm high. A rectangular plunger made of 1/2-in.-thick aluminum plate is attached to a 1-in.-diam shaft. The plunger has a clearance of 0.275 mm from the wall on each side to eliminate friction. The peas are extruded through a replaceable wire grid that slips into the bottom of this cell. The grid consists of nine wires 2.36 mm diam with a gap of 3.3 mm between the wires. The plunger is driven down into the test cell at 18.2 cm min^{-1} by a synchronous motor connected through a gear box to a single vertical screw that moves the crosshead.

Vettori Manghi Tenderometro

This Italian-built instrument is similar to the FTC Texture Press in that it uses an array of metal blades that move down and through slots formed by a set of stationary bars (Andreotti and Agosti, 1965). The instrument is constructed of stainless steel and is driven by a hand-powered crank handle. The capacity of the test cell is 166 ml, which is approximately one third the 450-ml capacity of the FMC Pea Tenderometer. An hydraulic gauge measures maximum force in Tenderometer units on a 0–250 scale. It is used mostly for measuring the maturity of fresh peas. It can be easily disassembled for cleaning.

FirmTech 2

This small instrument, weighing only about 7 kg, is designed to test small fruits such as blueberries, cherries, grapes, plums, and tomatoes. A small platen gently compresses fruits one by one. Two modes of compression are available: (1) measures deformation distance under a standard force; (2) measures force to attain a given deformation. A third option is to perform a puncture test using a probe smaller than the fruit. A turntable has a number of depressions around the perimeter, the size and number of depressions is matched to the size of the fruit. The instrument is controlled by a desktop or laptop computer. A fruit is placed on each depression and the instrument is started. The fruit under the platen is gently compressed, then the turntable automatically rotates to bring the next fruit under the platen and after it has been compressed, it moves on to the next fruit, and this process continues until all the fruits on the turntable have been tested. The load cell capacity is 45 N. Approximately 3 s is required to test each fruit.

Cutting–Shear Test

Warner–Bratzler Shear

The test cell of this apparatus consists of a stainless-steel blade 0.040 in. thick in which a hole, consisting of an equilateral triangle circumscribed around a 1-in.-diam circle, is cut and the edges rounded off to a radius of 0.02 in. (Warner, 1928; Bratzler, 1932, 1949). In some publications the

Warner–Bratzler Shear is misrepresented as having a rectangular-shaped hole in the blade. This confusion probably results from the fact that the first experimental model of the Warner–Bratzler Shear used a blade with a square hole. Also, some researchers are presently experimenting with square blades.

Two sharp-edged borers that resemble cork borers are provided with the instrument and are used to cut a 1/2- or 1-in.-diam sample of meat. This sample is placed through the hole and two metal anvils, one on each side of the blade, move down, forcing the meat into the V of the triangle until it is cut through. A 50-lb capacity spring force gauge with a maximum pointer measures the maximum force encountered during this cutting action. The principle of this test has been described on pages 134–138. Although commercially available, the Warner–Bratzler shear has not been patented (see Fig. 5.7).

This instrument measures approximately $23 \times 30 \times 56$ cm high and weighs 14 kg. The anvil moves downward at 23 cm min^{-1}. However, the actual shearing rate is less than 23 cm min^{-1} because the spring in the gauge is highly extensible and the blade and the meat move downward to some extent as the force increases.

A number of studies have been performed to compare Warner–Bratzler Shear figures with subjective estimates of tenderness of meat. Szczesniak and Torgeson (1965) thoroughly reviewed the subject of meat tenderness and its measurement. In summarizing 38 studies on beef, four on pork, and nine on poultry these authors list correlation coefficients (r) between the Warner–Bratzler shear and some method of sensory testing ranging from -0.001 to -0.942. Of the 51 papers listed in this review, 41 reported good agreement or better, and the remainder indicated that correlation was borderline to poor. Szczesniak and Torgeson (1965) commented on the high degree of variability in the correlation between Warner–Bratzler Shear and sensory testing and point out that many factors come into play, one of which is the reliability of the sensory panel that is used. At the present time there is no other device that consistently gives better correlations, although the FTC Texture Press is about as good (Szczesniak and Torgeson, 1965). The subject of Warner–Bratzler Shear correlations with sensory tests is also discussed on pages 298–300 and 335–336.

Although its reliability has often been questioned, the Warner–Bratzler shear is the most widely used device in the United States for measuring toughness of meat. One serious difficulty with this test is the great variability of meat. Meat toughness varies markedly from animal to animal, from muscle to muscle within an animal, and also from point to point in the same muscle. Meat to be tested should be sheared across the muscle fibers; hence, samples should be cut parallel to the fibers (Hostetler and Ritchey, 1964). The boring tool should be sharpened regularly. Variability in meat is also discussed on pages 305–307.

When cutting the sample core, it is necessary to use a technique that will give a standard diameter sample because the shear force is affected by the diameter of the test sample (see page 137). A steady, moderate pressure should

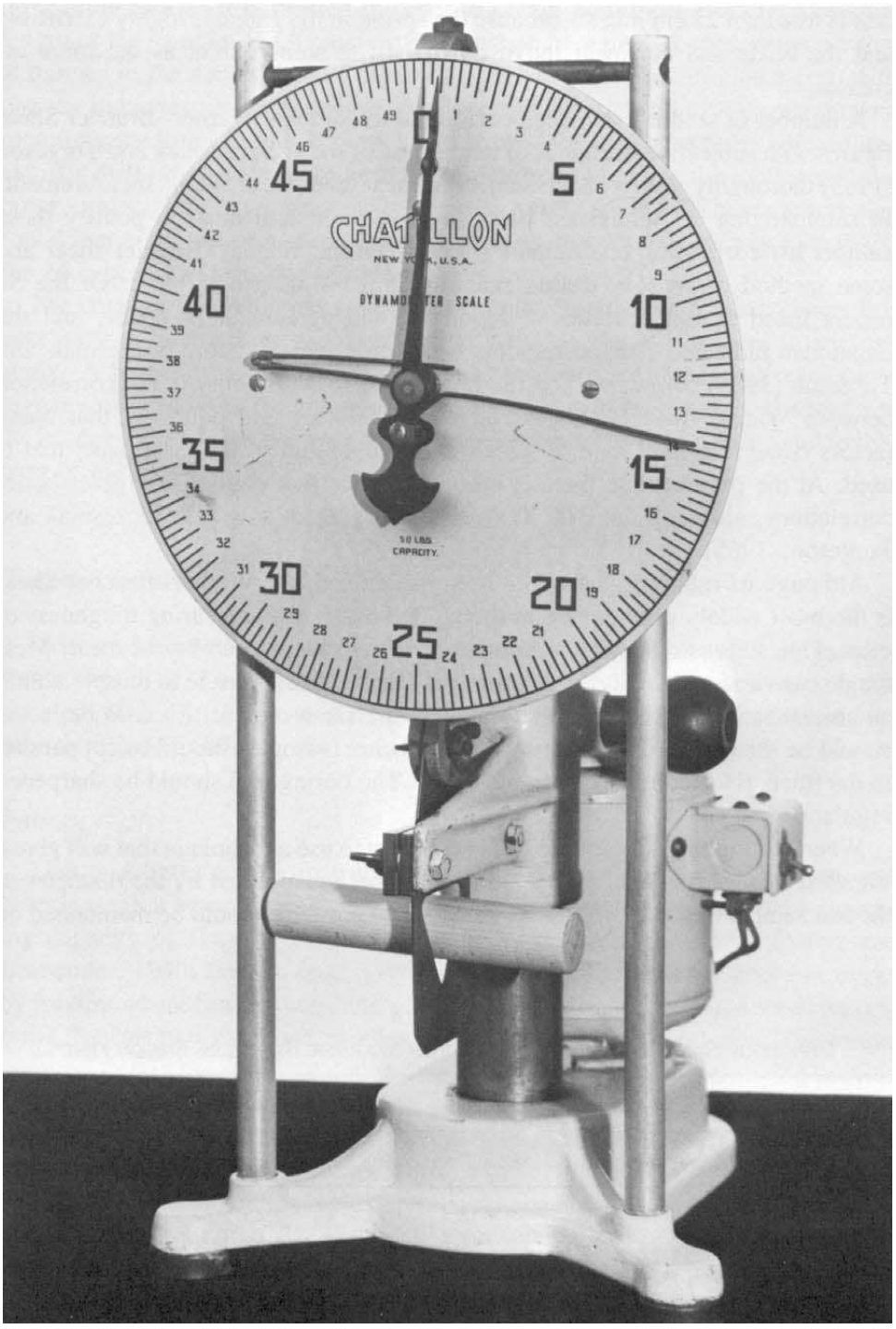


Figure 5.7 The Warner–Bratzler Shear: the cylinder of wood inserted in the triangular blade represents a piece of meat.

be maintained on the cutting tool as it is twisted in order to obtain a uniform diameter along the length of the sample. High pressure will give an hourglass-shaped meat core that is thinner in the center than at the ends. Uneven pressure will give a core with uneven diameter along its length. Kastner and Henrickson (1969) recommend mounting the borer in a drill press because they found that samples cut with the aid of a drill press were more uniform in

Table 5.6 Effect of Sample Cutting Method on Warner–Bratzler Shear Test

Cutting tool diam (cm)	Hand-bored samples		Machine-bored samples	
	Mean diam (cm)	Shear force (lb)	Mean diam (cm)	Shear force (lb)
2.54	2.41	18.4	2.48	19.6
1.90	1.79	11.6	1.88	12.1
1.27	1.21	7.5	1.25	8.4

Source: Data from Kastner and Henrickson (1969). Sample material was porcine longissimus dorsi muscle heated to an internal temperature of 72°C in deep fat at 140°C and chilled for 24 h in a 4°C cooler before cutting.

diameter, closer to the diameter of the borer, and slightly larger than the hand-cut samples (Table 5.6). These authors also found that more uniform cores were obtained when cooked pork was held at 4°C for 24 h before cutting the samples.

The degree of cooking has a great effect on the toughness of meat; hence, it is necessary to have all meat cooked to the same degree of doneness in any one study. A higher final internal temperature (or degree of doneness) results in a higher shear reading. The range of shear readings usually varies from about 5 to 25 lb, depending upon the size of the sample, doneness of the meat, and toughness of the meat. Wheeler *et al*. (1996, 1997) noted that the method of sampling, thawing frozen beef, cooking and coring affects Warner–Bratzler readings (see also pages 335, 336).

Pasta Firmness

Matsuo and Irvine (1969, 1971) used a simulated tooth to deform and cut through single strands of cooked spaghetti. Voisey's group in Ottawa designed a system whereby ten strands of cooked spaghetti were cut by ten 1.5 mm thick blades. This system can be mounted in a universal testing machine or the Ottawa Texturometer. This group reported good results for measuring firmness and chewiness of cooked spaghetti with this device (Voisey and Larmond, 1972, 1973; Voisey *et al*., 1978).

The American Association of Cereal Chemists have a standard method for measuring the firmness of cooked pasta and noodles that uses a small blade to cut through the product (AACC Method 66-50).

Torsion Devices

Most of the torsion measuring instruments are used to measure viscosity of fluids, which will be discussed in Chapter 6 where the subject of viscosity is covered. Three instruments that use the principle of torque and are used on semisolid foods or in intermediate stages of processing are described below.

Farinograph

This is a basic testing instrument that is used in flour mills, bakeries, and cereal research laboratories to determine the baking quality and moisture-absorbing capacity of flour and the handling properties of bread dough (Munz and Brabender, 1940; Locken *et al*., 1960; Brabender, 1965). The instrument works by mixing wheat flour, water, and sometimes other ingredients in a small mixing bowl that has two Z-shaped paddles that rotate on a horizontal axis. The torque required to mix the resulting dough and how this changes during mixing provide a quantitative measure of rheological properties of the dough that correlate well with the way it handles in the bakery. The method is highly empirical and requires strict control of the conditions. The highly standardized conditions of operation are spelled out in AACC Method No. 54-21, ICC Method No. 115/1 and ISO Method 5530-1.

A new model, Farinograph E with a more compact design that works fully electronically with computer-controlled operation and display of the torque–time curve, is now available. It uses the same geometry mixing blades and gives the same results as the standard Farinograph.

The basic instrument occupies approximately 120 × 120 cm of bench space and is about 90 cm high. Three models are available: Model FA2 is powered by a two-speed 0.5-hp electric dynamometer motor that drives the paddles at either 63 or 31.5 rpm. Model FAH is also driven by a two-speed 0.5-hp dynamometer motor that drives the paddles at either 63 or 126 rpm. Model DO-V153 (Do-Corder) is powered by a 0.8-hp dc dynamometer motor that drives the paddles at any speed between 20 and 210 rpm by means of an infinitely variable speed control. The mixing bowl is made of stainless steel with a jacket through which water is circulated from a temperature bath to maintain constant temperature. Two sizes of mixing bowls are available: 50 and 300 g capacity. The capacity refers to the amount of flour that is used. The actual capacity of the bowl is about 50% more than the weight of the flour. A pair of sigma-shaped blades are standard for mixing flour. A pair of delta-shaped blades can be supplied and are used to study ingredients such as shortenings that cause a change in the consistency.

The blades of the Farinograph mixer/measuring head are driven by a motor that is suspended to swing freely between precision bearings to form a dynamometer. As the mixer blades encounter a resistance torque from the test material, the dynamometer reacts by swinging in the opposite direction of the shaft rotation. The reaction torque acts through the lever system of an analytical scale and is simultaneously recorded on a strip chart recorder. The baking and milling industry commonly express their results in Brabender units. One Brabender unit is one meter-gram torque.

The Brabender instruments can be calibrated with weights if needed. Most users of the Brabender instruments have a company serviceman routinely check each machine yearly. Check (standard) flour samples are routinely distributed by the American Association of Cereal Chemists, 3340 Pilot Knob Road, St Paul, Minnesota 55121, to compare instruments.

Mixograph

This instrument is a recording dough mixer that performs substantially the same functions as the Farinograph, using a small sample of flour (30 g). A smaller assembly that accepts a 10-g sample of flour is also available (Finney and Shogren, 1972). The cup contains three pins and four contrarotating pins in the mixing head that knead the dough (Swanson and Working, 1933; Larmour *et al*., 1939). In contrast to the Farinograph, where the mechanical dynamometer measures the reaction of the motor, the Mixograph has the mechanical dynamometer attached to the mixing bowl and measures its reaction as the dough is formed and kneaded. A pen attached to the arm records the movement on strip chart.

The resistance offered by the dough to four vertical pins revolving around three stationary pins in the mixing bowl creates a torque in the bowl that is proportional to the shear strength and elasticity of the dough. The Mixograph is a standard physical dough tester (American Association of Cereal Chemists Method 54–40A). The Mixograph is 80 × 80 × 45 cm high, weighs 50 kg, and uses 15 cm-wide chart paper.

Bending

Structograph

This instrument operates on the triple-beam principle (see p. 145). The sample rests on two parallel support bars that are attached to an elevator platform that is raised at constant speed to contact a sensor bar mounted above the sample and equidistant between and parallel to the two lower knife edges. A strip chart recorder gives a force–time plot.

This instrument is useful for measuring the force to snap brittle foods. It can also be used to measure bending deformation from the slope of the force–distance plot on the chart. For nonbrittle foods, a sharp-edged upper knife or a pointed cone can be used to measure the force to cut through or penetrate the product. This instrument has a variable stroke length up to 70 mm, and a rate of travel variable from 8 to 320 mm min^{-1}. Samples up to 80 mm wide can be accommodated. The strip chart recorder is 180 mm wide and the standard chart speed is 10 mm min^{-1}, but this can be varied by changing gears inside the instrument case. The instrument is approximately 50 cm wide, 28 cm deep, 51 cm high, and weighs 18 kg. The force ranges available are 0–500, 0–1000, and 0–2000 g.

Tensile Testers

All the universal testing machines are equipped to perform tensile tests. They provide a wide range of grips to hold different kinds of foods.

Extensograph

This instrument is used in conjunction with the Farinograph to evaluate the rheological properties of bread dough in laboratories associated with the flour

milling and bread-baking industry. It consists of three parts: (1) the dough-forming devices, which round and roll the dough to standard dimensions, (2) a temperature-controlled fermentation cabinet to allow the dough to relax, and (3) the mechanism that stretches the dough to breaking and reads the changes in force with extension.

Three parameters are obtained from the Extensograph curve: (1) the energy, which is measured as the area under the curve; (2) resistance to extension, which is the force at 50 mm stretching measured in EU force units (Extensograph units); and (3) extensibility, which is the length of the curve, measured in millimeters.

The standard method for using the Extensograph is described in AACC Method No. 54-10, ISO Method No. 5530-2 and ICC Method No. 114/1.

The Extensograph can be modified for computer connection for fully automatic tests and evaluation with Windows software.

FTC Texture Test System

This company provides a tension test cell (model TT-1) comprising a pair of serrated gripping jaws 1-in. wide. It also has available a thin-slice tensile test cell (model ST-1) with a horizontal work table for tensile tests on products such as sliced bologna, cheese, and bread. This is modeled on the accessory developed by Gillett *et al.* (1978).

Distance Measuring Instruments

Bostwick Consistometer

This simple instrument consists of a level stainless-steel trough that is rectangular in cross section and comprises two compartments. The first compartment is 5 × 5 × 3.8 cm high, and it is separated from the second compartment by means of a spring-loaded gate. The second compartment, which is contiguous with the first compartment, is a trough 5 cm wide, 24 cm long, and about 2.5 cm high. The floor of this compartment has a series of parallel lines drawn across it at 0.5-cm intervals beginning at the gate and extending to the far end. It weighs about 800 g (see Fig. 5.8).

In operation, the gate is pressed shut and locked in place by means of a trigger. The first compartment is filled with the material whose consistency is to be tested. This is usually a comminuted fruit or vegetable such as applesauce, carrot puree and other baby foods, tomato catsup and tomato purees. The consistometer is leveled and the trigger is pressed, releasing the gate, which springs up out of the way. The fluid material is then free to flow under the force of gravity from the first compartment into the second compartment. The distance it has flowed from the gate after 30 s is measured in centimeters as the Bostwick Consistometer reading.

When the moving front edge of the flowing product is curved, the distance to the forward edge of the curve is taken. In some products syneresis occurs;

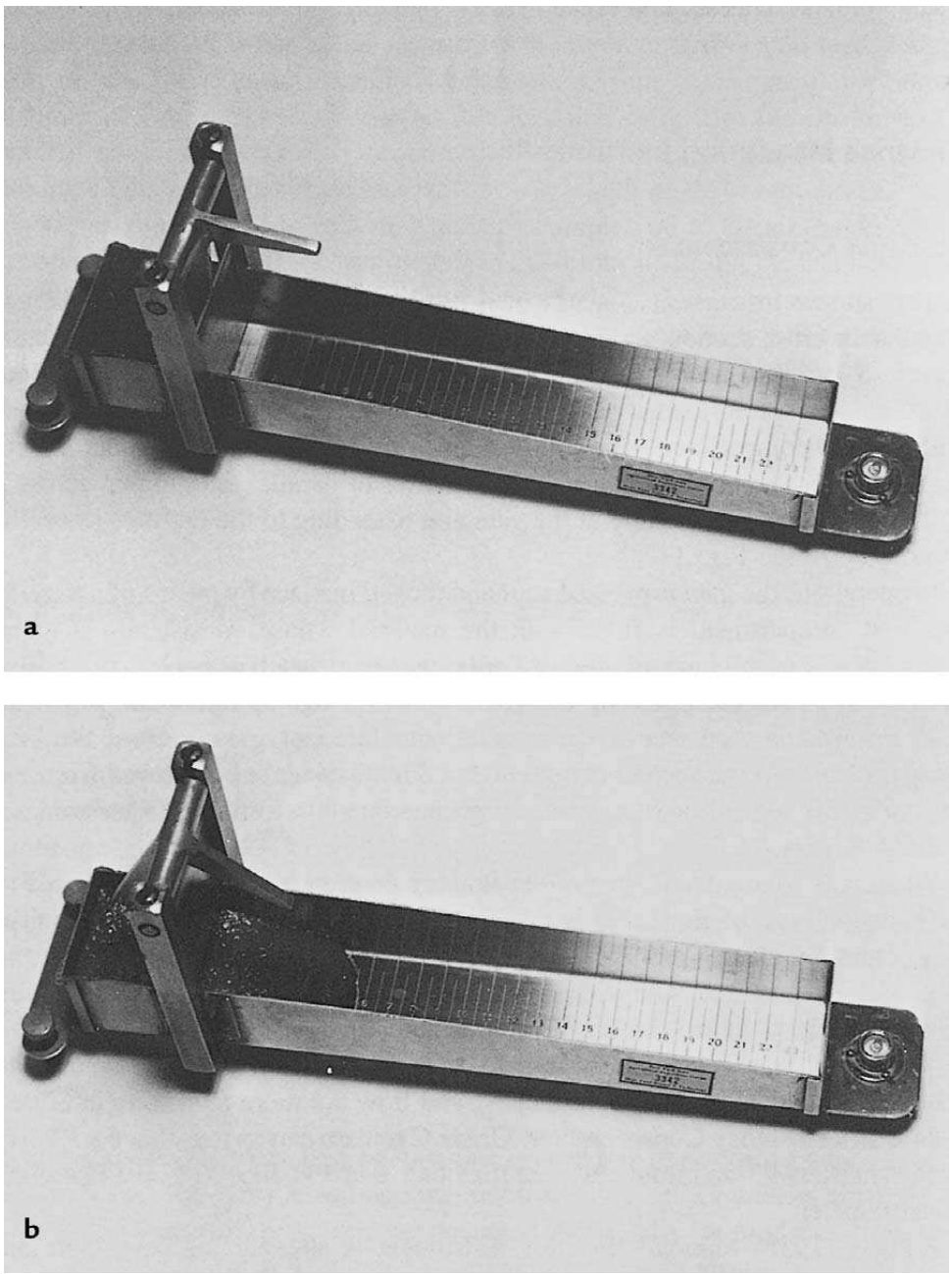


Figure 5.8 The Bostwick Consistometer: (a) sample is in first compartment with gate closed; (b) gate is open and sample has flowed along the second compartment.

in these cases the clear liquid is generally ignored, and the reading is taken at the front edge of the puree. The width of the clear serum is sometimes also measured in those products in which considerable syneresis occurs.

The United States standard for tomato catsup stipulates that grade A and grade B quality should be of good consistency, and flow not more than 9 cm in 30 s at 20°C in a Bostwick Consistometer. Grade C tomato catsup must have a 'fairly good consistency' and flow not more than 14 cm in 30 s at 20°C in a Bostwick Consistometer.

Rutgers (1958) reported that this instrument is suitable for nonthixotropic purees and thick porridges but not for starch-thickened milk puddings.

Bookwalter *et al*. (1968) found the Consistometer to be suitable for processed cornmeals and their protein-enriched blends. Rao and Bourne (1977) found that the Bostwick Consistometer was suitable for fruit and vegetable purees but not suitable for nonpureed foods because they adhered to the gate. It is not suitable for high solids tomato paste because the paste does not flow far enough in 30 s to give measurable differences between samples. However, some laboratories dilute tomato paste with distilled water to reach a standard soluble solids level (°Brix) and then measure its consistency in a Bostwick Consistometer.

Each year the US Agency for International Development donates hundreds of thousands of tons of a precooked corn–soy blend to undernourished people in developing countries. One quality specification for this product is that a slurry of 37 g dry corn–soy blend mixed with 100 ml water at 25°C shall give a Bostwick reading of less than 20 cm one minute after raising the gate (Konstance *et al.*, 1999).

The results from this instrument cannot be converted into fundamental rheological parameters because surface tension, wetting power, and possibly other factors other than viscosity are also involved. Nevertheless, it is a useful, rapid quality control tool for products that have a yield point but is not too stiff. McCarthy and Seymour (1993) showed that the Bostwick Consistometer used the gravity flow current principle (see page 162).

The Hilker–Guthrie Plummet

This simple device was developed to measure the consistency or 'body' of cultured cream, but it can also be used on other products that have a similar consistency (Hilker, 1947; Guthrie, 1952, 1963). The plummet consists of a hollow aluminum tube 1/2 in. diam and $4\frac{1}{2}$ in. long weighing about 15 g. The lower end tapers to 1/8 in. diam and is closed off. A series of inscribed lines numbered 1 to 10 are etched into the tube at 3/8-in. intervals beginning from the top. The plummet is mounted in a stand vertically over the commodity to be tested and with the lower tip exactly 12 in. from the surface of the product. It is released and allowed to fall freely into the product. The depth of penetration into the commodity is read off the scale after 5 s. It is customary to take the mean of three tests.

Hilker (1947) gives the following figures for relating the plummet reading to the viscosity of cultured cream: very thin, 0–2; thin, 2–4; medium, 4–6; good, 6–7.5; slightly heavy, 7.5–8.5; heavy, 8.5–10; very heavy, greater than 10.

Ridgelimeter

This little device was developed for judging the grade of fruit pectins and the stiffness of pectin jellies (Cox and Higby, 1944; Anonymous, 1959). The instrument is essentially a height-measuring gauge. A pectin jelly is made under standard conditions specified by The Institute of Food Technologists Committee on Pectin Standardization (Anonymous, 1959). To make a standard jelly, one assumes a jelly grade and uses (650/assumed grade) grams of

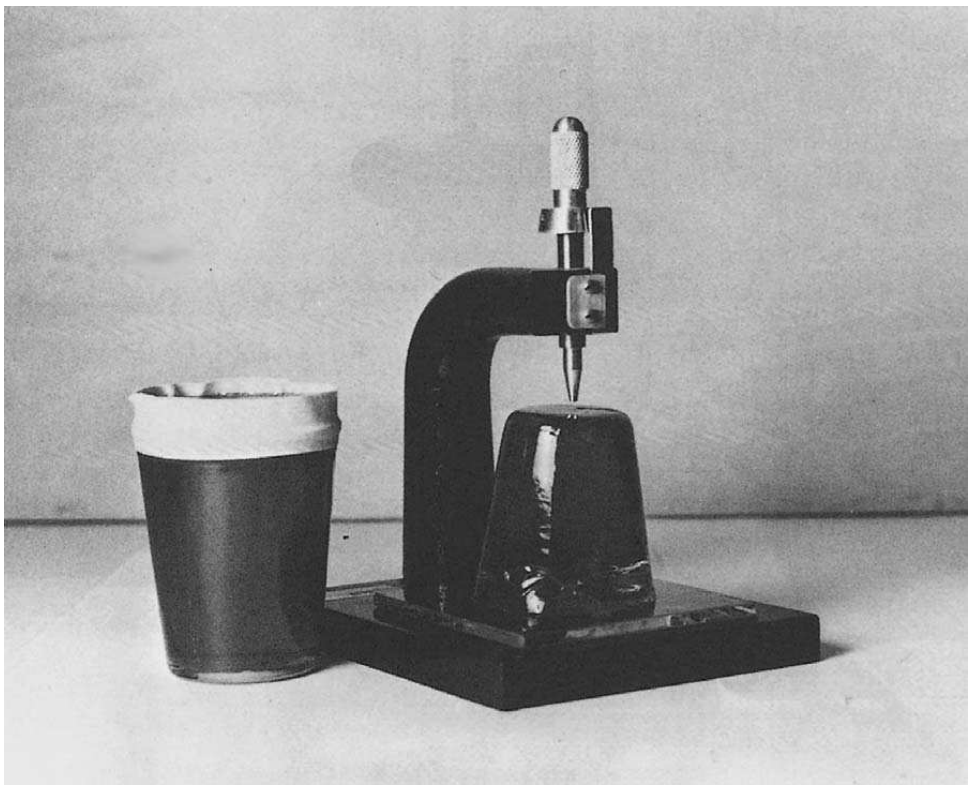


Figure 5.9 The Ridgelimeter.

pectin to make the jelly. The jellies are poured into tapered glass tumblers that are 1.75 in. i.d. at the bottom, 2.5 in. i.d. at the top, and internal height exactly 3.125 in. Masking tape is applied to the top of the jar to protrude at least 1/2 in. above the jar (see Fig. 5.9).

The boiling jelly is poured into the jar until it is 1/2 in. above the top of the jar, the excess being retained by the tape. After standing for 20–24 h at 25 ± 3°C the tape is removed, a wire cutter is moved across the top of the jar to remove the excess jelly, and the jelly is carefully tipped out onto a small square of plate glass that is furnished with the instrument. The pointer of the dial is moved down close to the surface of the jelly. After exactly 2 min the pointer is moved until it just contacts the jelly. The scale gives the percentage sag to the nearest 0.1%. A jelly of 'standard firmness' has a sag of 23.5%. The true grade of the test is obtained from the formula

$$\text{true grade} = \text{assumed grade}\ (2.0 - \%\ \text{sag}/23.5).$$

If a more precise calculation is needed, a conversion curve given by Cox and Higby (1944) may be used.

This is a simple but effective instrument and is the standard test used by the industry for establishing the grade of pectins and fruit jellies.

Penetrometer

This useful instrument was first developed for measuring the firmness or the yield point of materials such as petroleum jelly and bitumen, but it is widely

used for measuring the firmness or yield point of butter, margarine, and other solid fats. The principle is described on pages 148–150.

The Penetrometer manufactured by Precision Scientific is described here (see Fig. 5.10). Penetrometers that are very similar are made by several other manufacturers. The Penetrometer consists of a vertical rod 3/16 in. diam and weighing 47.5 g that can be locked in position and then released to fall freely under the force of gravity. At the lower end is a small chuck that can hold various cones and needles. A 4-in.-diam dial gauge that is connected to a depth gauge is used to measure manually the distance the rod falls after release to within 0.1 mm. The dial is graduated from 0 to 380 in 1/10-mm increments. Penetration measurements can be made to a total depth of 62 mm because the dial pointer can make approximately $1\frac{2}{3}$ revolutions.

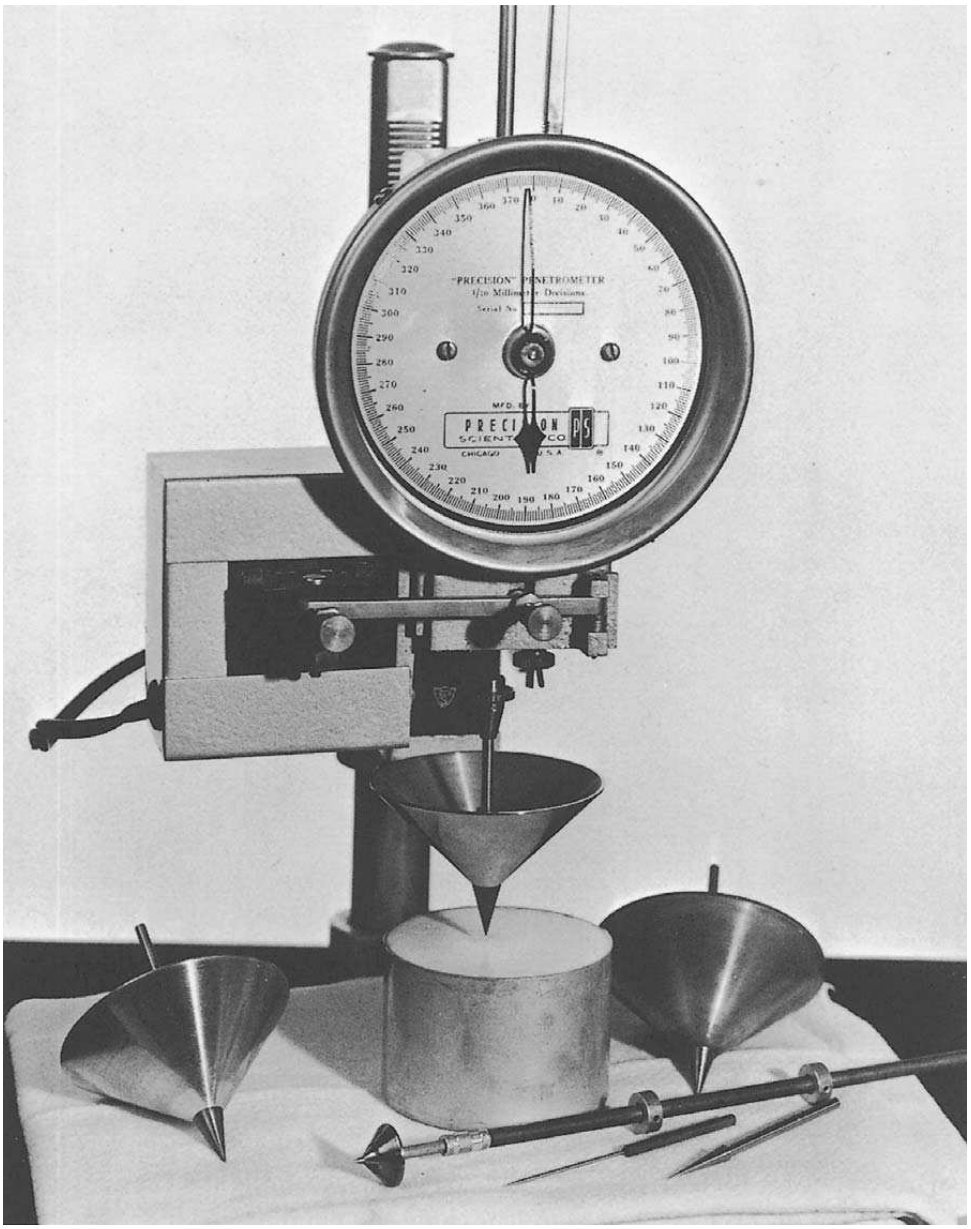


Figure 5.10 The Penetrometer: different types of cones and needles are shown resting on the white cloth.

This assembly is attached to a vertical shaft by means of a rack and pinion to adjust the height above the sample. The vertical shaft is held in a heavy cast aluminum base that has a built-in spirit level and two leveling feet. A trigger normally holds the rod at its highest point in a locked position. When the trigger is pressed, the rod is free to drop. An optional addition is a solenoid trigger assembly controlled by an electrical timer that when switched on releases the trigger and then locks it again after 5 s.

To operate, a suitable cone or needle is placed in the chuck, the trigger is released, and the rod and cone assembly is lifted up until it reaches the upper stop where it is locked. The needle should then read 0. If it is not 0, a small adjusting knob beneath the instrument is turned to bring the needle to 0. The material to be tested is positioned beneath the cone, and the whole cone and dial assembly is lowered by means of the rack and pinion until the point of the cone almost touches the surface of the fat. The rack and pinion assembly is then locked. The final adjustment to bring the point of the cone exactly into contact with the surface of the sample is made by means of a micrometer adjusting screw. The cone and rod assembly is then released and allowed to sink into the food under the force of gravity for 5 s when it is locked again. Weights are provided that can be added to the top of the rod to increase the force on the cone. Then the depth gauge is pressed down gently until it reaches a stop on the rod. The dial reading indicates the depth of penetration directly in tenths of a millimeter. When the dial reading has been recorded, the cone and rod assembly is returned to the 0 position and the instrument is ready to make the next reading.

There is discussion in the literature as to the exact meaning of the Penetrometer reading and whether the reading measures the yield point of the fat, the consistency, or some combination of these (see page 149). Although this matter is not completely settled, the Penetrometer test is a useful test for solid fats. It is common to make measurements on fats at several temperatures in order to determine the range of temperatures over which the fat is workable (i.e. its plastic range).

Maleki and Siebel (1972) used a Penetrometer to measure the deformability of bread and reported a correlation coefficient (r) of 0.88 between Penetrometer units and sensory score of softness. These authors used 5-cm-thick slices of bread, a deforming weight of 203 g for 5 s. Fresh bread gave a mean deformation of 13.5 mm whereas 5-day-old bread gave a mean deformation of 5.3 mm. Underwood and Keller (1948) used the Penetrometer to measure the consistency of tomato paste.

The Penetrometer can be adapted to measure the deformation of many foods by using a flat disk in place of the cone (Bourne, 1973). A small flat disk 5 mm thick and 50 mm diam is cut from a piece of hard plastic and a 1/8-in.-diam brass rod inserted in the center of one side of the disk normal to the plane of the disk. The article of food (e.g., a tomato or other deformable food) is placed in position in the Penetrometer and the disk is brought down close to (but not touching) its surface by means of the rack and pinion. The

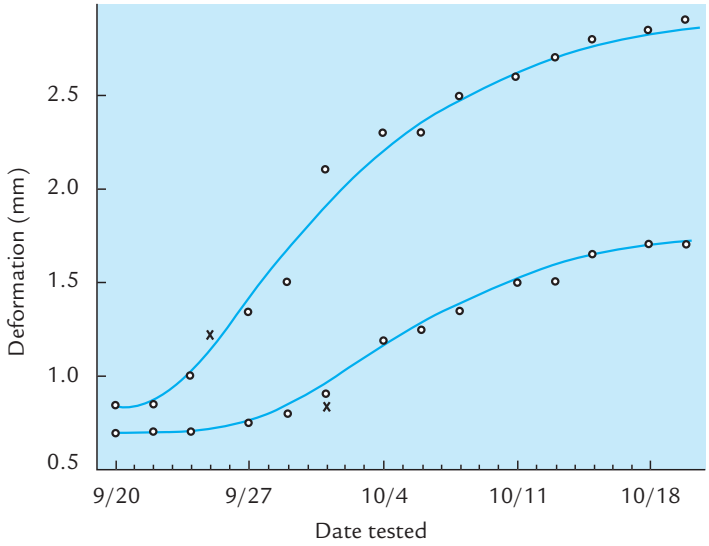


Figure 5.11 Change in deformation of two individual tomatoes during ripening as measured by the Penetrometer. Lower curve is a firm variety and upper curve is a soft variety. The 'x' on each curve denotes the day when the first sign of pink color appeared near the blossom end of the fruit. (From Bourne, 1973. Reprinted from *J. Food Science* **38**, page 721. Copyright by Institute of Food Technologists.)

Penetrometer is turned on and the disk and rod are allowed to drop freely for 5 s and then locked. The distance the rod and disk have fallen is measured on the dial gauge. A selected weight is then placed on the upper end of the rod, and the weighted disk and rod assembly is allowed to drop freely again for 5 s, then locked, and a second reading is taken from the dial gauge. The difference between the two dial readings gives the deformation of the article in units of 0.1 mm for a force change equal to the difference in weight between the rod and disk assembly and the added weight.

In conventional Penetrometer testing with a cone, it is critical that the point of the cone be placed exactly at the surface of the food. In the deformation test the initial placement is not critical, since this is a test by difference. The 64-g weight of the unloaded disk and rod assembly is sufficient to give the small preliminary compression that eliminates those errors that might be caused by intrinsic irregularities in the surface of the food piece (Bourne, 1967a). This technique has the advantage that the Penetrometer is a relatively inexpensive instrument that can easily be adapted for measuring the deformability of foods that are reasonably soft and of reasonable size.

Figure 5.11 shows how this technique measured the change in deformation of two tomatoes as they ripen. Since this is a nondestructive test, the same tomato can be tested repeatedly, eliminating the problem of sample to sample variation, provided the force applied is sufficient to cause no irreversible change at the test site.

SURDD Hardness Tester

This instrument was developed by the Southern Utilization Research and Development Division (SURDD) of the United States Department of Agriculture (USDA) and is designed to determine the hardness and softening

characteristics of fats and waxes. The test is based on the Brinell tester that is used to measure the hardness of metals (see p. 149).

The instrument consists of a vertical rod that is free to move within a stand. The lower end of the rod holds a steel ball having a selected diameter from 0.125 to 0.500 in. The upper end of the rod holds a small platform on which weights may be placed. The force is applied by raising the test sample support platform upward until all the weight of the ball rests on the sample. In operation, a sample of the fat is placed beneath the ball, a suitable weight ranging from 0.2 to 6 kg is placed on the plate, and the ball is allowed to penetrate into the fat under this force for 1 min. The diameter of the ball and the weight are selected so that the diameter of the impression made in the fat is about one third the diameter of the ball. The diameter of the impression in the fat is measured by means of a cathetometer or a magnifying glass with a built-in scale. This measurement can be made to within 0.02 mm.

Haugh Meter

The Haugh meter is used to measure the quality of eggs. It consists of a tripod stand through the center of which a pin is located that can be moved up and down by means of a screw. It is a small instrument, weighing less than 1 kg. The principle of the measurement is based on the fact that high thick albumen (the egg white) indicates good quality, fresh eggs. Figure 5.12 shows in top view and silhouette the relationship between albumen height and egg quality.

In operation, an egg is weighed, the shell is broken gently and the egg is spread out on a horizontal glass plate. The Haugh meter (see Fig. 5.13) is placed such that the center pin is over the thick white about 10 mm out from the edge of the yolk. The screw is turned until the face of the pin just touches ('kisses') the albumen. The gauge measures the height of the albumen above the plate. Haugh (1937) established that the log of the albumen height is directly proportional to the egg quality. The basic equation is

$$\text{Haugh units} = 100 \log H$$

where H is the albumen height in millimeters. The factor 100 is used to remove the decimal.

A correction for the weight of the egg is needed because large eggs will have higher albumen than small eggs of equal quality. The equation correcting for the weight of the egg is

$$\text{Haugh units} = 100 \log \left[H - \frac{\sqrt{G(30W^{0.37} - 100)}}{100} + 1.9 \right]$$

where G is 32.2 and W, the weight of the egg in grams. The dial gauge mounted on the tripod is usually calibrated directly in Haugh units by means of a scale that compensates for variations in egg weight.

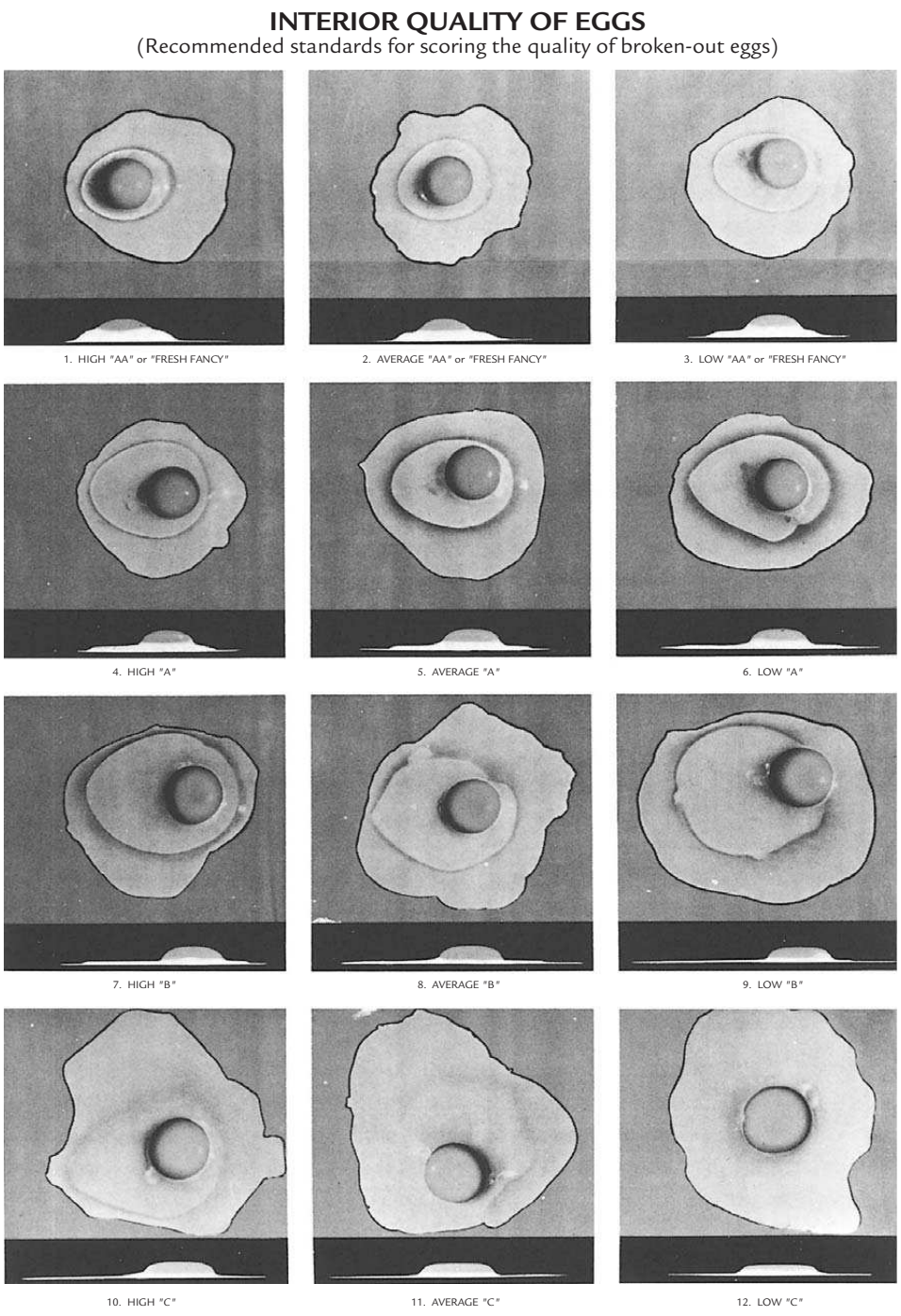


Figure 5.12 Relationship between albumen height and egg quality (USDA photo).

Since egg quality is largely determined by heredity, the Haugh meter is used to identify and breed hens that lay top quality eggs with high albumen. Detailed specifications concerning egg quality have been published, and the Haugh units of the eggs are one index of that quality (USDA Handbook No. 75, 'Egg Grading Manual'). In order for eggs to be graded AA or Fancy, they need to maintain a moving average of 72 Haugh units or higher. For eggs

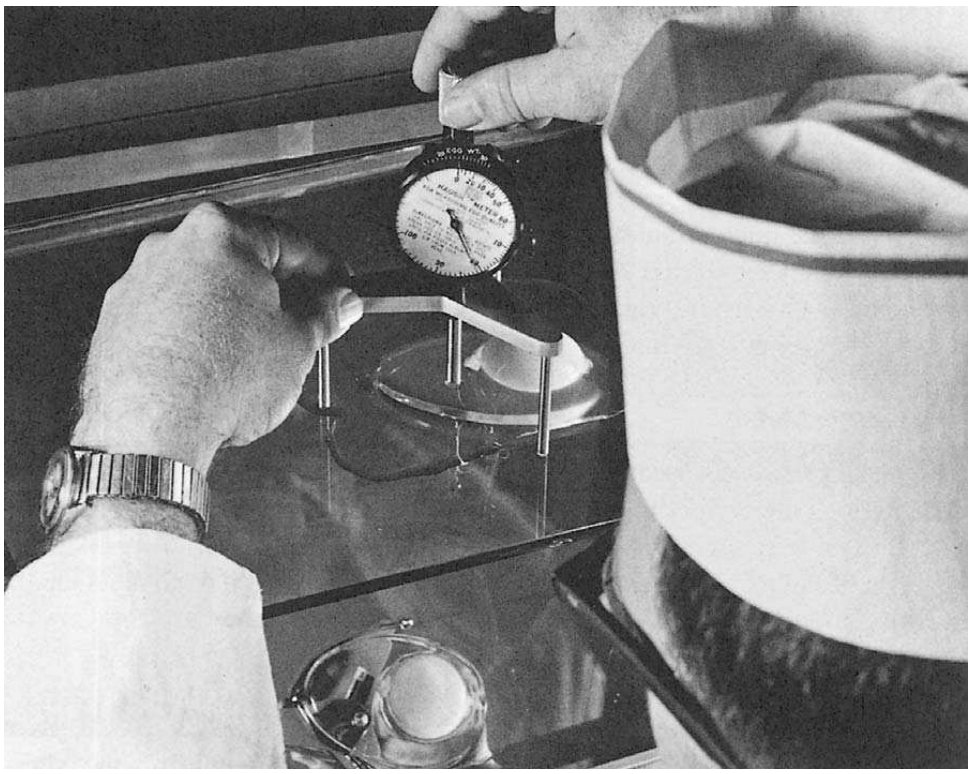


Figure 5.18 The Haugh meter (USDA photo).

that are labeled Grade A, the flock must maintain a moving average of 60 Haugh units or higher.

Baker Compressimeter

This instrument measures the force to press a metal plate onto a 12-mm-thick slice of bread until it has been compressed to 9 mm (25% compression). A small motor gradually applies a force by winding up on a spool a cord attached to the compressing lever. The force and degree of compression are measured on two scales, and it is possible to measure forces and deformations at other than 25% compression. The instrument is also used to measure the softness of buns, rolls, cakes, and other leavened baked goods.

The Baker Compressimeter is a standard method for measuring the staleness of bread (Cereal Laboratory Methods No. 74-10A, published by the American Association of Cereal Chemists). The relationship between the actual Compressimeter reading and degree of staleness and quality of the bread is a matter of discussion among cereal chemists, and some judgment is needed to interpret the results (Platt and Powers, 1940; Bice and Geddes, 1949; Crossland and Favor, 1950; Edelman *et al.*, 1950; Thompson and Meisner, 1950; Bechtel *et al.*, 1953).

Willhoft (1970) developed an empirical equation describing the staling of bread over a period of six days:

$$F_t = A(t/t_i)^B$$

where F_t is the firmness at time t, measured by an objective test; t_i, the time of initial measurement; A, a constant which is equal to firmness at time equal to unity; and B, a constant which is equal to the rate of firming.

He showed that a plot of log F_t versus log t is rectilinear with slope equal to the rate of firming constant B. The same author reviewed the theory and mechanism of bread staling and associated changes in textural properties (Willhoft, 1973).

Adams Consistometer and Tuc Cream Corn Meter

These instruments measure the distance a semifluid food flows across a plate in a standard time (Adams and Birdsall, 1946). They should be known as the Grawemeyer and Pfund Consistometer if priority is recognized (Grawemeyer and Pfund, 1943).

The Adams consistometer consists of a 12-mm-thick sheet of clear hard plastic (Plexiglas) approximately 37 cm square that is leveled by means of adjustable legs. A series of concentric circles are inscribed on the underside of the sheet at 1/4-in. intervals. The frustum of a stainless-steel cone that is 3 in. diam at the lower face, 2 in. diam at the upper face, and 5 in. high is placed in the center of the plate. The Tuc Cream Corn Meter is very similar to the Adams Consistometer.

In operation, the cone is placed in position and filled to the top with the product. The cone is gently lifted up and the product is allowed to flow out in two dimensions across the plate. After a standard time the diameter of the product is measured along two axes at right angles to each other. The USDA specification for standard quality cream-style corn stipulates that the average diameter should not be greater than 30.5 cm after 30 s flow. The product is substandard if the diameter is greater than the 30.5 cm.

USDA Consistometer

This is similar in principle to the Adams Consistometer. The USDA flow sheet #1 consists of a thin flexible plastic sheet over which the product flows. The receptacle holding the food is a Perspex cylinder 3 in. i.d. and 3¼ in. high. The distance of flow is measured from the outer edge of the cylinder in centimeters (see Fig. 5.14). This contrasts with the Adams Consistometer, which measures inches diameter and includes the diameter of the cone.

The USDA standards for canned applesauce measures the distance of flow after 1 min on this sheet. The flow value is taken as the average of the readings at four quadrants of the flow sheet. The readings are taken at the edge of the applesauce and do not include any free serum that exudes from the sauce. The amount of free serum that exudes may also be measured. For grade A applesauce, regular style, the flow should be not greater than 6.5 cm and for chunky style not more than 7.5 cm. For grade B applesauce the flow should not exceed 8.5 cm for the regular style and 9.5 cm for the chunky style.

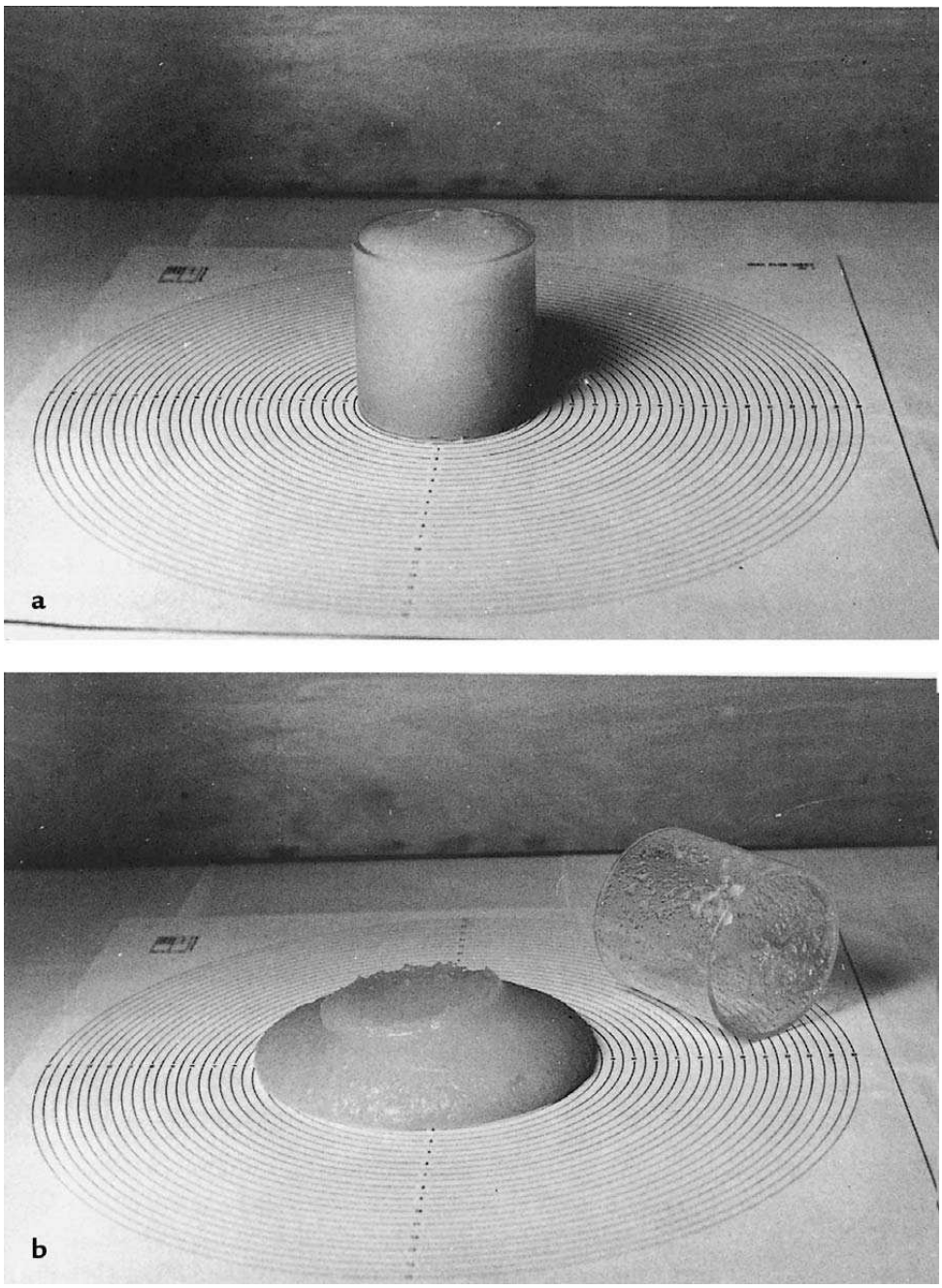


Figure 5.14 The USDA Consistometer: (a) cylinder is filled with applesauce; (b) cylinder is removed, allowing sauce to flow out.

Volume Measuring Instruments

Loaf Volume Meter

This apparatus consists of a metal box connected through a rectangular chute to a hopper containing rapeseed. A loaf of bread is placed in the box, which is closed, a slide in the chute is pulled out, and the rapeseed is allowed to fill the box. A calibrated scale on a Pyralin face of the volumeter column gives the direct reading of the volume of the bread in cubic centimeters. This device is widely

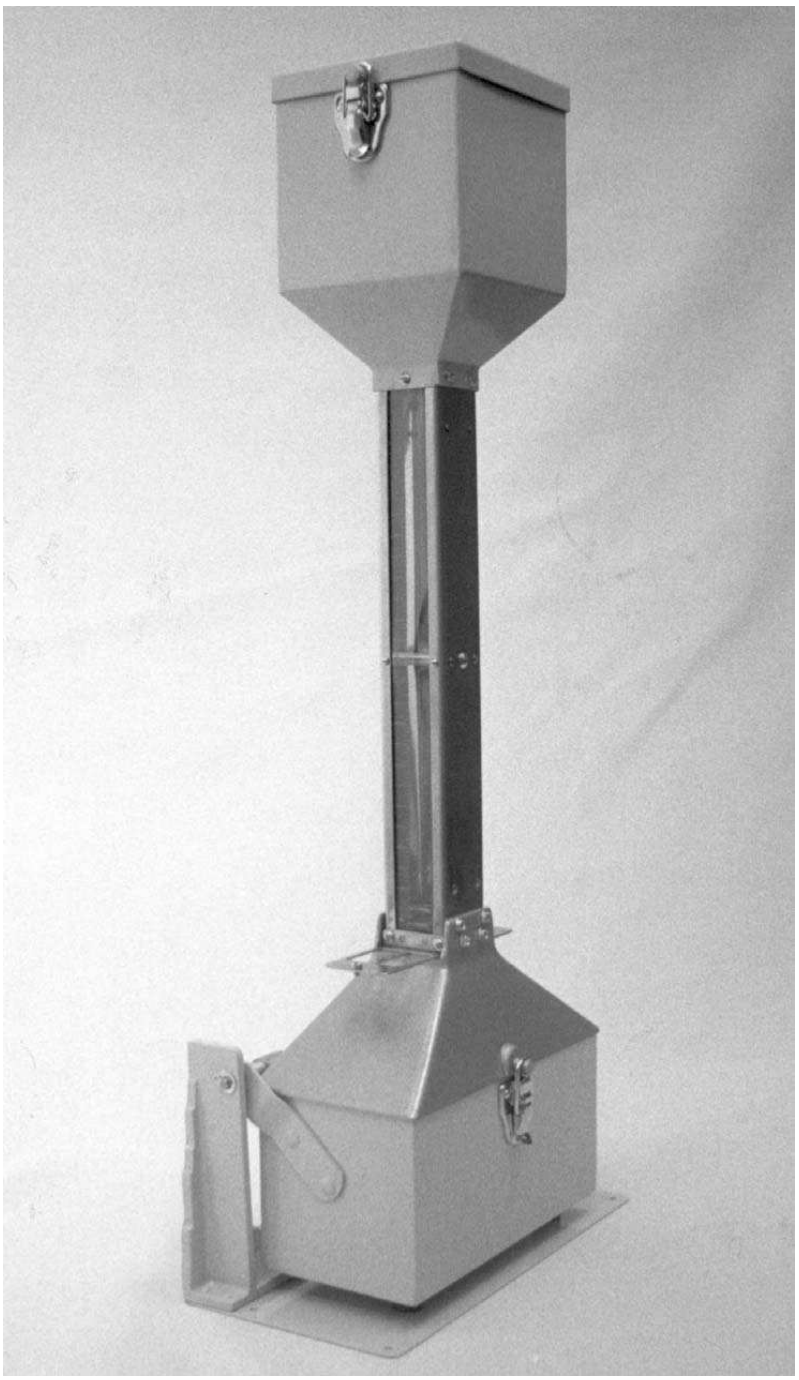


Figure 5.15 The Loaf Volumeter. (Courtesy of National Manufacturing, A Division of TMCO Inc.)

used in the baking industry to measure loaf volume, which is one index of quality of the loaf (Cathcart and Cole, 1938; Funk *et al*., 1969) (see Fig. 5.15).

The standard volumeter consisting of a box $5\frac{5}{8} \times 11\frac{5}{8}$ in. is designed for the 1-lb loaf of bread and can read volumes between 1675 and 3000 cm^3. Other sizes available are the 'Pup size,' measuring 400–1000 cm^3 'micro' size, measuring 100–270 cm^3, 'half-pound' size, measuring 900–1500 cm^3, '$1\frac{1}{2}$-lb' size, measuring 2475–3800 cm^3, and a 'round cake' size, designed for cakes with

measuring volumes of 500–1600 cm^3. A 'dummy' loaf of standard size is provided with each volumeter to calibrate the rapeseed level in the hopper.

Succulometer

This instrument is designed to measure the volume of juice that can be pressed from fresh sweet corn and is used as an index of maturity and quality (Meyer, 1929; Sayre and Morris, 1931, 1932; Kramer and Smith, 1946). In operation, a 100-g sample of cut corn is placed in the sample chamber and pressure is applied through a hydraulic ram that is pumped by hand. A pressure of 500 lb is maintained for 3 min and the juice that flows out is collected in a 25-ml graduated cylinder. The volume of juice decreases as the corn becomes more mature. Kramer and Smith (1946) relate the Succulometer values to quality of sweet corn as follows: fancy quality, more than 22 ml of juice; extra standard, 19–22 ml; standard, 12–18 ml; substandard, less than 12 ml.

The Food Technology Corporation Texture Press is provided with an optional accessory in the form of a succulometer cell (Model CR-1), which allows the succulometer test to be performed in this apparatus.

Time Measuring Instruments

Kinematic viscometers are time measuring instruments. These will be discussed in Chapter 6.

BBIRA Biscuit Texture Meter

The British Baking Industry Research Association (BBIRA) Biscuit Tester is designed to measure the hardness of biscuits (cookies and crackers) (Wade, 1968). A stack of biscuits is placed in the sample holder and pressed with constant force against a small circular saw blade that is rotating at 15 rpm. The time taken to make the saw cut through the stack is recorded by a counter, which stops when the operation is complete. A brush is positioned behind the saw to clean the teeth. The unit is housed in a fiberglass cover with a door to enable the operator to gain access to the working elements. The door has a Perspex window in it to enable the operator to watch the saw cut operation. This instrument is essentially a comparator; standards must be established experimentally for each type of cookie or cracker.

Miscellaneous Methods

Torry Brown Homogenizer

This instrument is an homogenizer that has been especially designed to measure the toughness of fish by the 'cell fragility method' (Love and Mackay,

1962; Love and Muslemuddin, 1972a,b; Whittle, 1973, 1975). A 200-mg sample of fish tissue is dropped into the homogenizer cup with 20 ml of a solution consisting of 2% trichloroacetic acid and 1.2% formaldehyde cooled to below 6°C. The paddle in the cup is rotated at 8750 rpm for 30 s. Muscle from fresh fish breaks up into small particles forming a cloudy soup that has a high optical density whereas muscle from tough fish is shredded into large pieces and has a low optical density. For rough work the optical density of the homogenate can be viewed by eye. For more accurate work the optical density can be read in an absorptiometer.

This method has been shown to give a good index of the deterioration in the texture of frozen fish. Fatty fish and fish in an advanced stage of bacterial decay give spurious readings because of the higher optical density imparted to the homogenized liquid by the bacterial cells or fat globules (Love and Muslemuddin, 1972a,b; Love, 1983).

Multiple Measuring Instruments

GF Texturometer

This Texturometer was developed by the central research group of the General Foods Corporation (Friedman *et al*., 1963; Szczesniak *et al*., 1963). The commercial instrument is manufactured in Japan.

A 1/16-hp electric motor drives an eccentric that is linked to the activating arm of the instrument. Because it is driven by an eccentric, the arm moves through the arc of a circle with the speed varying approximately in a sine wave function. To this arm can be attached a variety of plungers made of Lucite, aluminum, or nickel, ranging in diameter from 3 to 50 mm.

Positioned underneath the moving arm to which the plungers are attached is a platform on which the food sample is placed. This platform rests on a cantilever beam to which strain gauges are attached. Bending of the beam under the application of a force is sensed by the strain gauges and recorded electronically on a strip chart recorder. This instrument is designed for testing 'bite-size' pieces of food. The standard piece is a 1/2-in. cube, but particulate foods (e.g. peanuts) are normally tested as whole units. The mechanics of the movement of the eccentric and compressing arm have been analyzed by Brennan *et al.* (1975). One Texturometer unit is equivalent to approximately 105 ***g*** force ($\simeq$1.03 N), but the actual value can vary to some extent depending on the voltage output of the recorder batteries.

The GF Texturometer was originally used to develop the instrumental texture profile analysis procedure in which a number of texture properties are extracted from the force–time curve when a bite-size piece of food is compressed two times. However, instrumental texture profile analysis is now usually performed in universal testing machines (see pages 182–186). Other applications of the GF Texturometer are discussed by Szczesniak and Hall (1975) and Tanaka (1975).

FTC Texture Test System

These systems are variations on the Food Technology Corporation Texture Press, which was described on pages 201–206 but with a number of additions that give it expanded utilization, more flexibility in operation, and make it attractive for many research purposes. Some additional accessories will also be described below.

The major feature of the laboratory model, the TMS-90 Texture Test System, is the addition of a computer to control and monitor the output signals from the Texture Press. The computer has an integrated 100 mm wide thermal printer, which allows a hard copy output of the graphic and alpha numeric test results. The system will work in either metric or English units and has a preset texture profile analysis mode with automatic calculation of TPA parameters and statistical results of multiple sample runs.

The hydraulic drive mechanism and other characteristics of the ram press have been described previously (see page 202). The force sensor in this model is the strain gauge type force transducer, which provides a continuous signal that is directly proportional to the force applied and is transferred electronically to the computer.

The thermal graphics printer is 100 mm wide. After each test the force/distance or force/time graph can be printed. The computer allows the operator to expand or contract the graphic scaling as desired.

Some additional features standard in the Model TMS-90 Texture Systems are the following:

(1) Automatic ram cycling using the 'Program Mode' that causes the ram to cycle between up to eight preset positions enabling the instrument to be used for customized cyclic tests.
(2) A 'TPA Mode' that allows the operator to perform Texture Profile Analysis and program percentage of compression. The operator can also select from automatic sample height detection or tell the computer the dimensions of the sample under test. The computer will automatically calculate the traditional TPA parameters at the conclusion of the test(s).
(3) The TMS-90 will also calculate the work done, slope of the force curve, time, minimum and maximum forces, and a complete set of statistical results on a series of tests.
(4) A series of six model FTA force transducer load cells with force capacities of ±10, 50, 100, 250, 1000, and 3000 lb that can measure force in both compression and tension.
(5) A number of different test cells, including: (a) a single-blade shear cell with a flat cutting face; (b) a meat shear cell with a V-shaped cutting face that is similar to the Warner–Bratzler Shear blade; (c) compression test accessories that can be used for gentle or extreme compression or cycling compression; (d) a Succulometer test cell for pressing liquid from foods such as sweet corn to measure juiciness; (e) a triple-beam

bending test cell; (f) a drill chuck that holds 3/16 and 5/16 in. diameter punches for puncture tests; (g) a tension test cell; (h) a thin-slice tension test cell.

Table AIII.1 in Appendix III (pages 353–357) provides guidelines for testing various foods in the Food Technology Corporation Texture Test System.

Ottawa Texture Measuring System (OTMS)

This general purpose testing machine was developed by the Engineering Research Service of Agriculture Canada under the direction of P. W. Voisey (Voisey, 1971b; Voisey *et al.*, 1972). It consists of a single screw-operated press that is driven by an electric motor via a gear box. A variable-speed motor with an infinite selection of speeds over the range 2–29 cm min^{-1} is used for research applications. The screw is driven via a brass pin, which breaks when overloaded; forestalling damage to the press. The screw drives a carriage up and down two vertical guide rods. Adjustable stops on the guide rod can be set to stop, start, and reverse the motion of the carriage.

A number of test cells have been developed for this instrument (Voisey and deMan, 1976). In addition, the test cells from most other instruments can be attached to the OTMS by means of an adapter.

Universal Testing Machines (UTM)

The three essential components of UTMs (drive system, test cells and force measuring and recording system) are described on page 177. The first edition of this book described the operation of the Instron in detail because, at that time, UTMs were just beginning to become popular and the Instron was the first UTM to be widely used for foods. The description of UTMs in this edition will be brief for several reasons.

(1) UTMs are now used in most laboratories, so a detailed description is no longer needed.
(2) Manufacturers of UTMs bring out new models from time to time. They periodically develop new attachments to perform new kinds of tests.
(3) The software to drive UTMs is becoming more important. Ease of use, and ease of setting up new tests and a wide range of different kinds of tests is becoming as important as the basic instrument itself. The software for UTMs is being upgraded regularly.

Therefore, any detailed description in this book is likely to become obsolete within a few years. The addresses of the major suppliers of UTMs for food purposes are given in Appendix I. The reader is advised to consult their websites for the latest information on their offerings.

There are many manufacturers of strength of materials UTMs, and most of these machines can be adapted to work with foods in the same way that the

Instron was adapted to work with foods (Bourne *et al*., 1966). However, many of them do not provide test cells for food applications, and the researcher will have to design and make his/her own accessories and computer software. All the UTMs listed below supply a range of cells appropriate for foods. Any instrument that uses a rectilinear motion to measure food texture can be duplicated in a UTM by fitting the appropriate test cell components into it. Instruments that use a rotary or blending movement cannot be duplicated in UTMs because they work on the principle of uniaxial compression or extension.

One precaution that should always be taken when setting up a test cell in a UTM is to ensure that the crosshead travel stops are set in positions that positively prevent accidental metal-to-metal contact of the test cell parts. Most food tests involve compression in which metal parts approach each other, often at high speeds. Unless the crosshead travel stops are properly set, the metal parts may collide and, since there is no 'give' in these 'stiff' machines, the load cell will be broken. Repair of a damaged load cell is expensive and time consuming. Many UTM suppliers have minimized this problem by designing the control mechanism and drive mechanism so that the crosshead will either stop or reverse direction quickly as soon as an overload is sensed.

Since a number of different test principles are used in UTMs (puncture, extrusion, shear, compression, bending, etc.), any reports of results obtained should carefully specify the type of test and the conditions that were used. For example, it is not satisfactory to report 'the Instron test correlated highly (or poorly) with sensory scores.' The test principle and all the operating conditions must also be stated. Another type of test performed in the same Instron may have given a better (or worse) correlation. UTMs will give poor results if an inappropriate test principle or the wrong conditions (e.g. speed of travel) are used. (See Chapter 9 for more discussion on this point.)

Instron

This was the first UTM adapted to food use (Bourne *et al*., 1966). The Instron Corporation make a wide range of UTMs for a wide range of products, most of which are nonfood. Table AIII.2 in Appendix III (pages 358–361) lists details of food applications of the Instron that have been used in the author's laboratory using a floor-model machine with a force capacity of 50,000 N.

Figure 5.16 shows the single screw model No. 5542 that is often used for foods. It has a force capacity of 500 N and crosshead speeds cover the range 0.05–1000 mm min^{-1}. Other models with twin screws are available that have a force capacity up to many tonnes. A wide range of accessories are available for food texture analysis including fixtures for the Kramer Shear Press and Ottawa Texture Measuring System.

TA.XT2 Texture Analyzer

The standard TA.XT2 Texture Analyzer is a single screw machine that was developed especially for food work. It has a force capacity of 250 N and

Figure 5.16 A model of the Instron often used on foods. (Courtesy of Instron Corporation.)

crosshead speeds of 6–600 mm min^{-1}. Heavy-duty twin screw models are available up to 5000 N force. The TA.XT2 Plus model offers speeds up to 2400 mm min^{-1}.

Figure 5.17 shows the TA.XT2 Texture Analyzer and Table AIII.3 in Appendix III (pages 362–368) lists details of applications to many kinds of foods. Stable Micro Systems, and their US Distributor, Texture Technologies Corp., have developed an extensive library of food applications and have established a reputation for personally helping customers with their day-to-day texture measurement problems and to work with them to develop new test methods and applications in operating their instruments.

QTS Texture Analyzers

This line of single-screw machines was developed from concepts originally established by the Leatherhead Food Research Association in the United Kingdom as the Stevens Texture Analyzer. It has a force capacity of 250 N and crosshead speeds from 5 to 1000 mm min^{-1} in 1 mm increments. A number of accessories for food applications are available. It can be utilized as stand alone but also can be controlled by a computer.

This company also supplies the LFRA Texture Analyzer which is a small instrument with a force capacity of either 1 N or 10 N and comes with probes for testing gelatin gels and similar products. It has five choices of crosshead speed from 0.1 to 2.0 mm s^{-1} and is used for testing soft foods such as gelatin gels, yogurt, butter and margarine. It includes the 12.5 mm diameter probe for

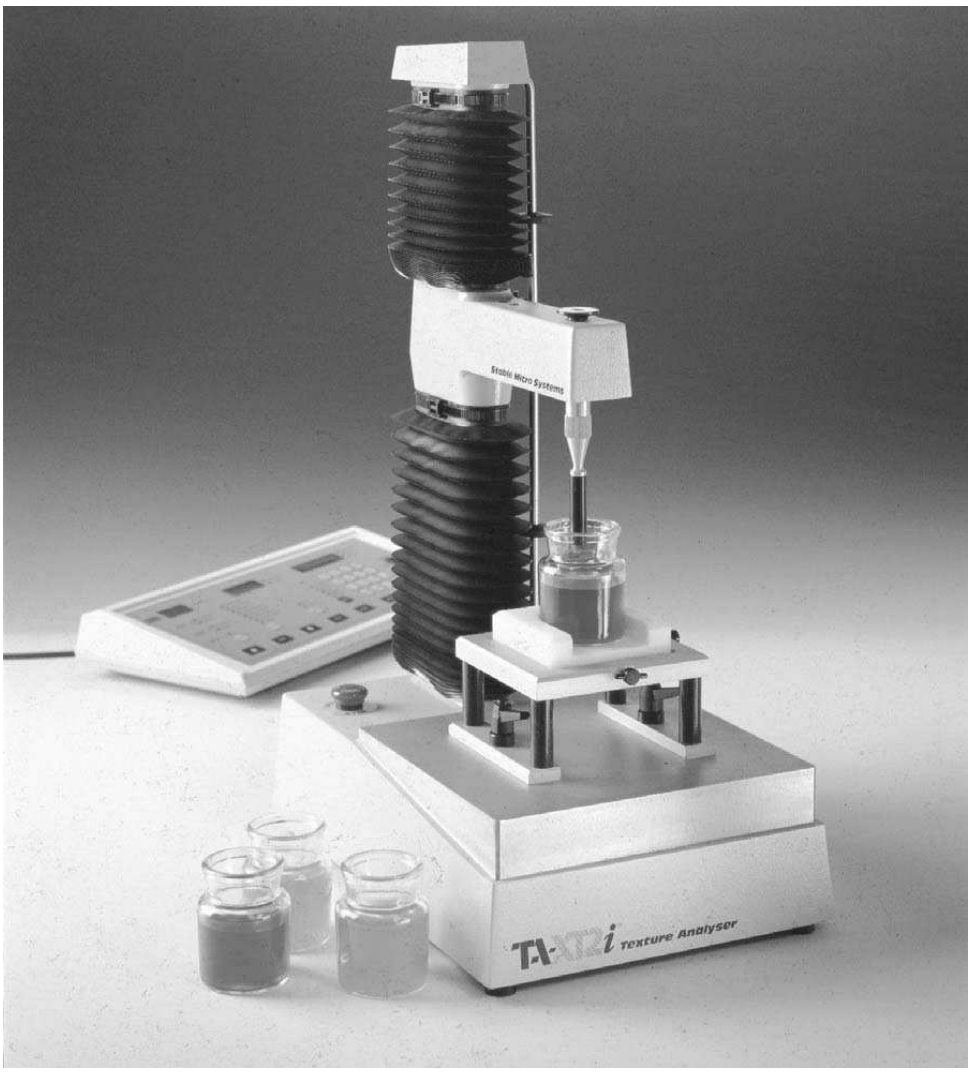


Figure 5.17 The TA.XT2 Texture Analyzer. (Courtesy of Stable Microsystems Ltd.)

performing the Bloom test in gelatin and the 25 mm diameter probe for the Bloom test on gelatin desserts. It can be utilized as stand alone or with computer software to analyze the data.

Lloyd Texture Analyzer

A number of accessories for testing foods can be attached to Lloyd machines. The commonly used basic machine is the model TA500 which is chain driven, has a force capacity of 500 N and speed range of 1–1000 mm min^{-1}. Models with a higher force capacity are driven by a single screw or double screw depending on the force level required.

Tensipresser

This instrument, designed and manufactured in Japan, is intended for testing of foods, chemicals, and packaging materials in compression or tension. It features components that are particularly well suited for performing texture profile analysis under a wide range of test conditions. Model (TTP-50BX) was

first manufactured in 1973. The latest model (TTP-50BXII) has been produced since 1993. It is a single screw machine with a force capacity of 500 N and crosshead speeds of 6–600 mm min^{-1}. It has attachments to perform a wide range of texture tests on foods. One interesting feature of Model TTP-50BXII is that it can be programmed to operate either with a uniform crosshead speed or a sinusoidal crosshead speed that approximates the action of the human mandible. The software is in Japanese and English. The operator's manual is available in Japanese but not in English.

This Page Intentionally Left Blank

Viscosity Measurement

CHAPTER 6

Introduction

The definition of viscosity and description of the different types of viscosity were given in Chapter 3. It is assumed that the reader has already read Chapter 3 because the foundation it provides is needed to gain a full understanding of the material in this chapter.

The first thing to remember in measuring viscosity is that the viscosity of fluids is highly temperature dependent (see page 78). The Brookfield Engineering Laboratory points out that No. 50 motor oil will change its viscosity about 10% for a 1°C temperature change at 25°C. This company has encountered materials whose viscosity changed 50% per degree centigrade. The viscosity of water at 20°C changes 2.5% per 1°C temperature change. Hence, it is impossible to measure the viscosity of water with an accuracy of 0.1% unless the temperature is controlled to within 0.04°C. Therefore, in all viscosity measurements it is essential that the temperature be closely controlled.

The effect of temperature on viscosity of sucrose syrups is shown in Fig. 3.10 (page 78) and Fig. 3.11 (page 79) and for depectinized apple juice in Fig. 8.11 (page 310). The temperature at which viscosity measurements are taken should be stated with all viscosity data because the data are meaningless unless the temperature is known. It is assumed that close temperature control is an essential feature of each system described below.

The various types of viscometers can be classified according to the principle on which they work.

Capillary Type

The time for a standard volume of fluid to pass through a length of capillary tubing is measured. The underlying theory behind capillary viscometers is

developed fully by a number of authors (see, e.g., Oka, 1960; VanWazer *et al.*, 1963) and will not be given here. This type of flow is described by the Poiseuille equation, which is also known as the Hagen–Poiseuille equation (Hagen, 1839; Poiseuille, 1846):

$$\eta = \pi P r^4 t / 8 V l$$

where η is the viscosity; P, the driving pressure; r, the radius of capillary; t, the time of flow; V, the volume of flow; and l, the length of capillary.

The driving pressure is usually generated by the force of gravity acting on a column of the liquid, although it can be generated by the application of compressed air or by mechanical means (as in the Instron Capillary Rheometer). The discussion here will be restricted to glass capillary viscometers.

The Ostwald viscometer is one of the simplest of the glass capillary types and is shown schematically in Fig. 6.1. There are a number of variations in the design of glass capillary viscometers, each with its own specific name and each claiming certain advantages (VanWazer *et al.*, 1963). For example, the Ostwald–Cannon–Fenske Viscometer, which is a widely used modification of the Ostwald viscometer, has both arms bent at an angle that brings the center

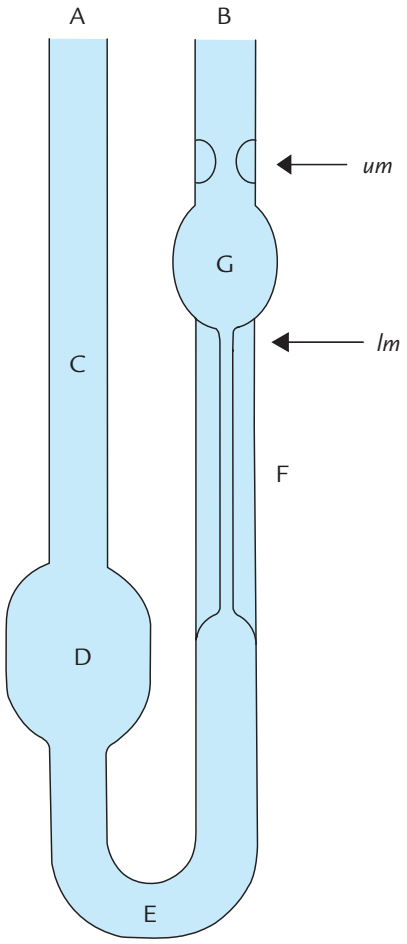


Figure 6.1 Schematic representation of the Ostwald viscometer.

of the upper bulbs directly over the center of the lower bulb, thus displacing the capillary from the vertical position.

The operation of the Ostwald Viscometer will now be described. Other styles of glass capillary viscometers are operated in a similar manner, the exact details should be provided by the supplier when it is purchased.

In operation, a standard volume of fluid is pipetted into arm A of the Ostwald Viscometer, which should be held in a vertical plane (see Fig. 6.1). It is not essential that the capillary be exactly vertical but it should be held reproducibly at the same angle. The fluid runs down the wide-bore tube C into bulb D and U-tube E. The apparatus is immersed in a constant temperature water bath until the viscometer and liquid in it reach the standard temperature (about 30 min). Suction is then applied at the top of arm B to draw the fluid through the capillary F into bulb G until the upper meniscus is above the mark *um*. The suction is removed and the fluid flows from bulb G through the capillary tube F under the force of gravity. A stop watch is started when the meniscus crosses the upper mark *um* and stopped when it crosses the lower mark *lm*. The viscosity is calculated from the elapsed time.

The AVS/N viscometer is a sophisticated glass capillary that uses light barriers to record the time the meniscus passes the set points and displays the elapsed time on a digital indicator to the nearest 0.01 s. This eliminates errors in operating the stopwatch and allows the operator to attend to other duties once the test has been started.

For a given viscometer of this type, the dimensions of the radius and length of the capillary are constant and the volume is kept constant. The driving pressure P is proportional to the hydrostatic head and the density of the fluid. The head decreases as the liquid falls in reservoir G. This viscometer is designed to minimize the change in head during the measured portion of the efflux time, and the shape of the bulb G is such that most of the efflux time occurs when the head is close to its mean value. Variations in the pressure head have no effect on the viscosity measurement of Newtonian fluids but they do affect measurements on non-Newtonian fluids, the magnitude of the deviations depending on the degree to which the fluid departs from Newtonian behavior. For a Newtonian fluid the driving pressure P can be replaced by $h \times g \times \rho$, where h is the mean head; g, gravity; and ρ, the density of the fluid. Since h is constant for a given viscometer, the Hagen–Poiseuille equation can be simplified to

$$\eta = K\rho t$$

where K is the instrument conversion factor ($\pi hgr^4/8Vl$) and is a constant for each instrument. This equation can be rearranged to

$$\eta/\rho = Kt \quad \text{or} \quad \nu = Kt$$

since kinematic viscosity $\nu = \eta/\rho$.

Hence the kinematic viscosity ν of the fluid is obtained by multiplying the measured efflux time by the instrument conversion factor K. Most laboratory supply houses will provide the K value for each viscometer at a small additional cost over the price of the viscometer.

If the instrument conversion factor K is not provided or has been lost, it can be obtained by measuring the efflux time for a fluid of known viscosity:

$$\nu_s = Kt_s$$

where ν_s is the kinematic viscosity and t_s is the efflux time for a standard fluid of known viscosity.

Rearranging this equation gives

$$K = \nu_s/t_s$$

The Cannon Instrument Co. (PO Box 16, State College, Pennsylvania 16801) supplies a wide range of Newtonian viscosity standards in the form of a series of oils of calibrated viscosity. These are useful for calibrating kinematic viscometers.

Glass capillary viscometers are widely used for measuring low to medium viscosity Newtonian fluids because of their high degree of accuracy, ease of operation, and low cost. Priel *et al*. (1973) developed a system for a Ubbelohde glass capillary viscometer that yielded data with an absolute accuracy within three parts per million. An essential part of their system was a thermostat with a long-time thermal stability of $\pm 2 \times 10^{-4}$°C over a period of 4 weeks.

Because of their low cost it is usual to purchase several glass capillary viscometers if a large number of measurements need to be made. This allows several units to be reaching equilibrium temperature while a measurement is being performed on one unit. It is advisable to purchase a series of viscometers with a range of capillary diameters when a wide range of viscosities are encountered. A capillary diameter should be selected that gives an efflux time between about 200 and 800 s. Figure 6.2 shows some typical glass capillary viscometers.

The American Society for Testing and Materials (1918 Race Street, Philadelphia, Pennsylvania 19103) has published a standard test method for use of capillary viscometers on Newtonian fluids: ASTM D445–79, 'Kinematic Viscosity of Transparent and Opaque Liquids (and the Calculation of Dynamic Viscosity).' This organization has published another useful document: ASTM-D446–79, 'Standard Specifications and Operating Instructions for Glass Capillary Kinematic Viscometers.'

A number of corrections need to be made when very accurate results are needed from glass capillary viscometers. These include correction for the kinetic energy lost in the stream as it issues from the bottom of the capillary, and effects due to the change in the meniscus size and shape as it enters or leaves the capillary, possible turbulence in the capillary, and inadequate drainage due to liquid adhering to the walls of the viscometer. These errors, and methods for their correction, are discussed in detail by VanWazer *et al*. (1963). The same authors show how the capillary viscometers may be used for certain non-Newtonian fluids.

The AOAC Official Methods of Analysis Handbook (2000) uses an Ostwald or Cannon–Fenske capillary viscometer for measuring the viscosity of beer

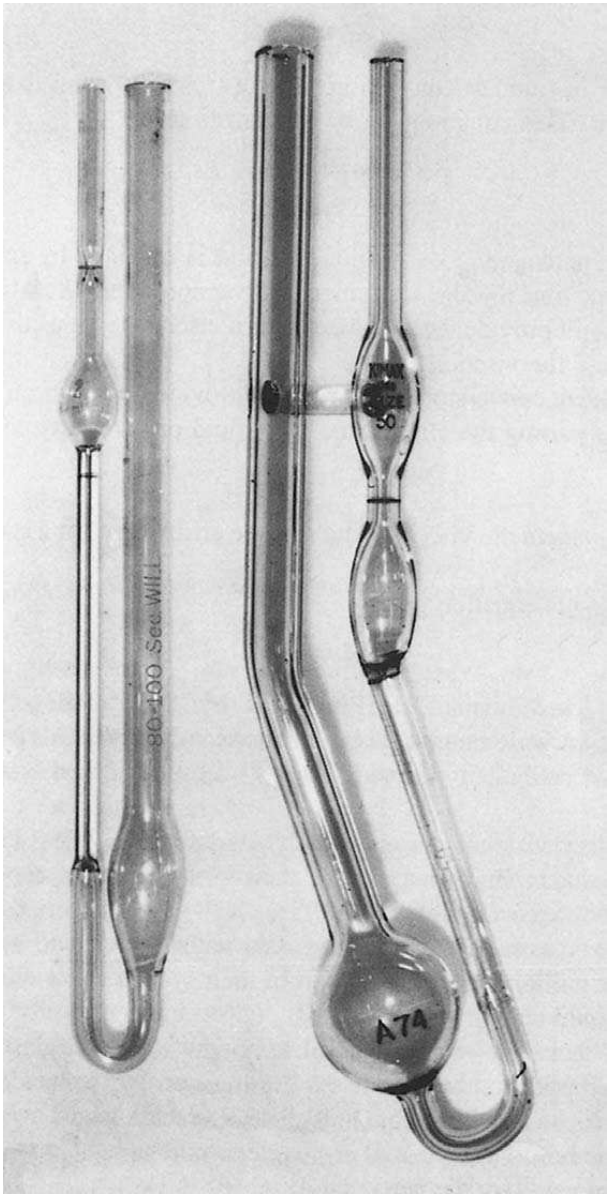


Figure 6.2 Some glass capillary viscometers.

(Method 974.07). The method specifies that a capillary be selected that gives a time range between 50 and 150 s, the temperature adjusted to 20.00 ± 0.05°C, and that the viscometer be cleaned with chromic acid cleaning solution and rinsed and drained before use.

The Lamb–Lewis Capillary Viscometer was developed by the National Food Processors Association (formerly known as the National Canners Association) as a low-cost quality-control instrument for use on tomato juice, fruit nectars, and similar fruit or vegetable juices and blends (Lamb and Lewis, 1959). It is used by the fruit and vegetable juice industry as an internal quality standard (Lamb, 1967). It consists of a 3.8 cm i.d. × 17.8 cm long Lucite chamber from the bottom of which protrudes a precision Pyrex glass tube 3 ± 0.01 mm i.d. and 29 cm long (see Fig. 6.3). The chamber is filled with liquid, which is

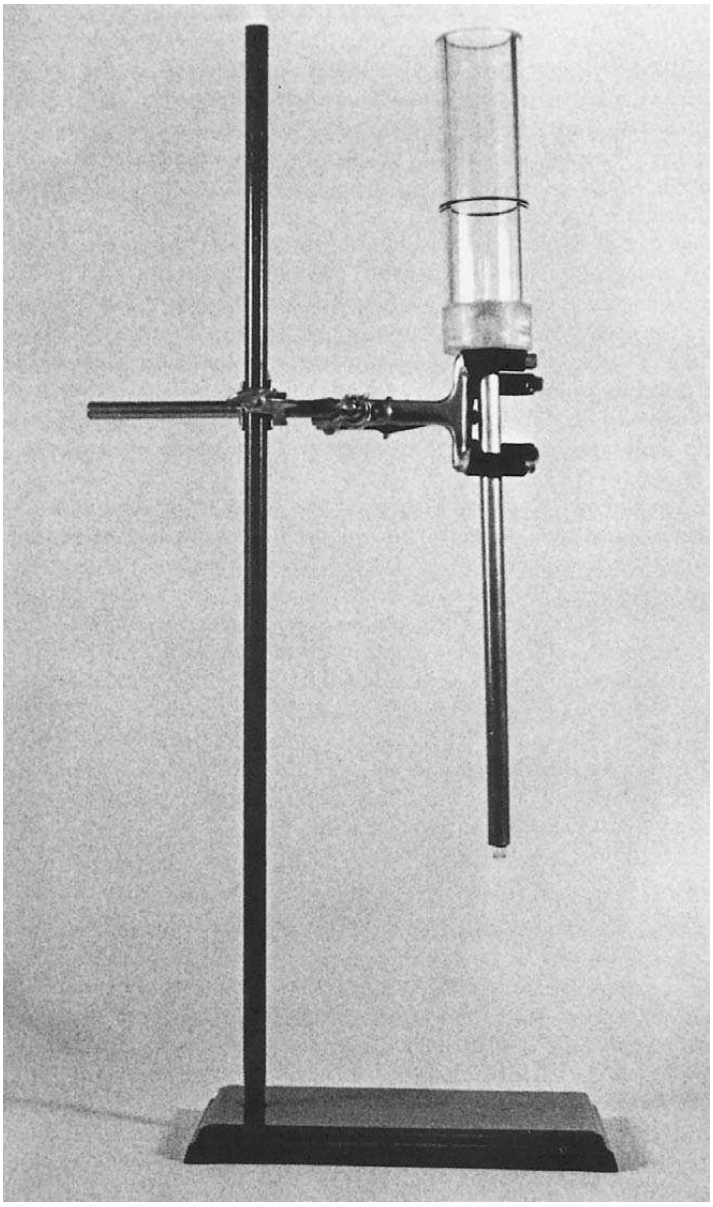


Figure 6.3 The Lamb–Lewis Capillary Viscometer. (Courtesy of National Food Processors Assoc.)

allowed to flow through the capillary until a steady flow is obtained. A finger is placed over the capillary outlet to stop flow, the chamber is filled level with the top, the finger is removed as a stopwatch is started, and the time for the meniscus to reach the calibration line is recorded to the nearest 0.1 s.

The instrument is calibrated so that the time for water at 24 ± 2°C to reach the calibration line is 13.0 ± 0.2 s.

This simple instrument can be made in the laboratory. The exact specifications for the composition and dimensions of the parts are given in AOAC Official Methods of Analysis (2000) as Method 967.16. The advantages of this instrument are:

(1) Low cost
(2) Simple operation

(3) Rapid
(4) Handles Newtonian fluids and non-Newtonian fluids
(5) The end point is unambiguous. For some efflux viscometers it is sometimes difficult to decide exactly when to stop the timer as the last few drops of fluid drip out.

Tube Viscometry

This might be considered as a wide-bore capillary viscometer with a special capability to handle suspensions. It consists of a horizontal tube of uniform cross-sectional area that is usually 0.5 m long and may be even longer. The internal diameter typically ranges from 6 mm to 30 mm. Two pressure transducers are attached to the pipe to record the pressure drop (ΔP) over a given length of pipe (L). A constant pressure is maintained at the entrance of the tube that ensures laminar flow occurs and the volumetric flow rate (Q) is measured (see Fig. 6.4).

For a non-Newtonian fluid obeying the power law equation the viscosity is given by the equation:

$$\eta a = \left(\frac{\Delta P}{8LQ}\right)\left(\frac{4n}{3n+1}\right)\pi R^4$$

where ηa is the apparent viscosity, ΔP is pressure drop over distance L, Q is volumetric flow rate, R is the radius of tube, and n is the flow behavior index of a power law fluid.

Care needs to be taken in operation to ensure that the effects of entrance and exit flow are negligible. Steffe (1992) gives a thorough account of the theory behind the tube viscometer.

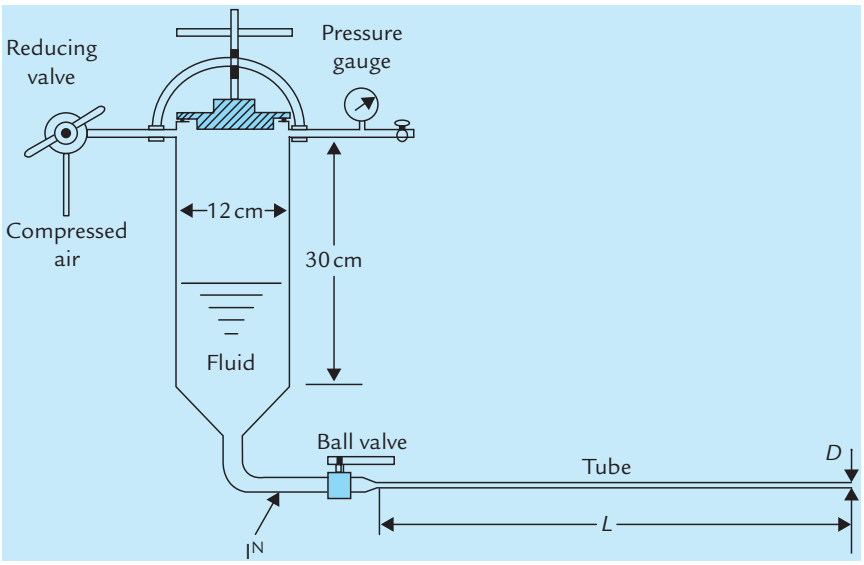


Figure 6.4 Tube viscometer. (From Saravacos, 1968. Reprinted from *Food Technology* **22** (12), page 1589. Copyright by Institute of Food Technologies.)

Saravacos (1968) used a tube viscometer to study the viscosity of pear, apricot and peach purees, applesauce, and grape juice, apple juice and their concentrates. Rao *et al*. (1974) used one to study the flow behavior of banana, guava, mango and papaya purees. Xu and Raphaelides (1998) used a tube only 30 mm long and 2.05 mm i.d. to study the flow of concentrated starch dispersions at 95°C. Zimmer *et al*. (2001) reported that although a tube viscometer had the advantages of being well adapted to measuring in-line viscosity, able to handle fluids containing particulate matter, and amenable to cleaning-in-place (CIP), it was unable to accurately measure viscosity of a 60% sucrose solution, a Methocel solution or a xanthan gum dispersion without additional calibration effort. Two aspects of tube viscometry that sometimes cause difficulties are: (1) maintaining a constant temperature along the whole length of the tube; and (2) large quantities of test material are required compared to most other viscometers.

Orifice Type

This can be considered as a very short capillary type of viscometer. The time for a standard volume of fluid to flow through an orifice is measured. This is a simple, inexpensive rapid method that is widely used in quality control of Newtonian or near-Newtonian liquids where extreme accuracy is not needed.

Possibly the best known of the orifice viscometers in the food industry is the dipping-type Zahn Viscometer. These consist of a stainless-steel 44 ml-capacity cup attached to a handle with a calibrated circular hole in the bottom. In operation, the cup is filled by dipping it into the fluid and withdrawing it. A stopwatch is started as soon as it is withdrawn and stopped when the first break occurs in the issuing stream. The elapsed time gives an empirical value of viscosity. Table 6.1 gives specifications for the five standard models of Zahn viscometers, and Fig. 6.5 shows a set of four Zahn viscometers.

Coaxial Rotational Viscometers

These are also known as concentric cylinder or couette viscometers, in honor of the developer of the first practical viscometer of this type (Couette, 1890).

Table 6.1 Specifications for Zahn Viscometers

Zahn No.	Orifice diameter (mm)	Approximate viscosity range (mPa•s)
1	2.0	14–40
2	2.7	21–196
3	3.8	88–614
4	4.3	148–888
5	5.3	345–1265

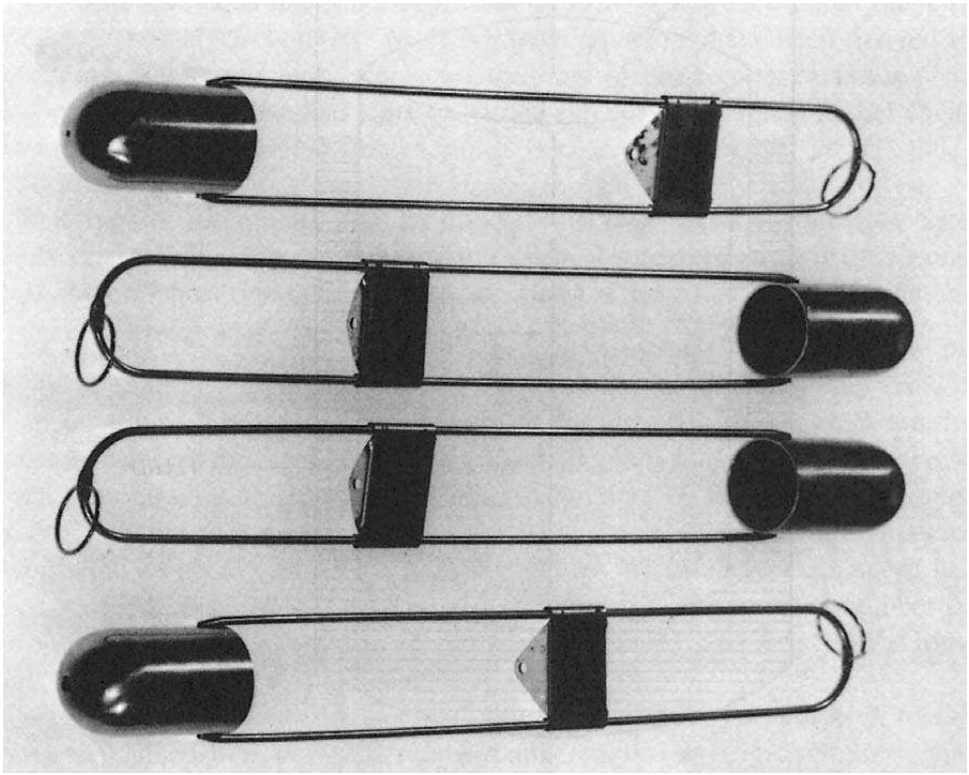


Figure 6.5 Some Zahn viscometers (dipping orifice type).

The principle is shown schematically in Fig. 6.6. A bob that is circular in cross section is placed concentrically inside a cup containing the test fluid. Either the cup or the bob is rotated and the drag of the fluid on the bob is measured by means of some kind of torque sensor. The shear rate–shear stress relationship is the same whether the bob is rotated and the cup held stationary or vice versa. This type of viscometer permits continuous measurements to be made under a given set of conditions and allows time-dependent effects to be studied. By changing the rate of shear or magnitude of stress it is possible to obtain viscosity measurements over a range of shearing conditions on the same sample. It can be used for both Newtonian and non-Newtonian foods. This is the most common type of viscometer that is used in the food industry. It might be called the 'workhorse' viscometer.

The Margules equation (Margules, 1881) applies to the flow of Newtonian fluids in coaxial rotational viscometers:

$$\eta = (M/4\pi h\Omega)\,(1/R_b^2 - 1/R_c^2)$$

where η is the absolute viscosity; M, the torque on the bob or cup; Ω, the angular velocity of rotating member; h, the length of bob in contact with the fluid; R_b, the radius of the bob; and R_c, the radius of the cup. For a given instrument with a given geometry and fill of container this equation reduces to

$$\eta = KM/\Omega$$

where K is the instrument constant $(1/4\pi h)\,(1/R_b^2 - 1/R_c^2)$.

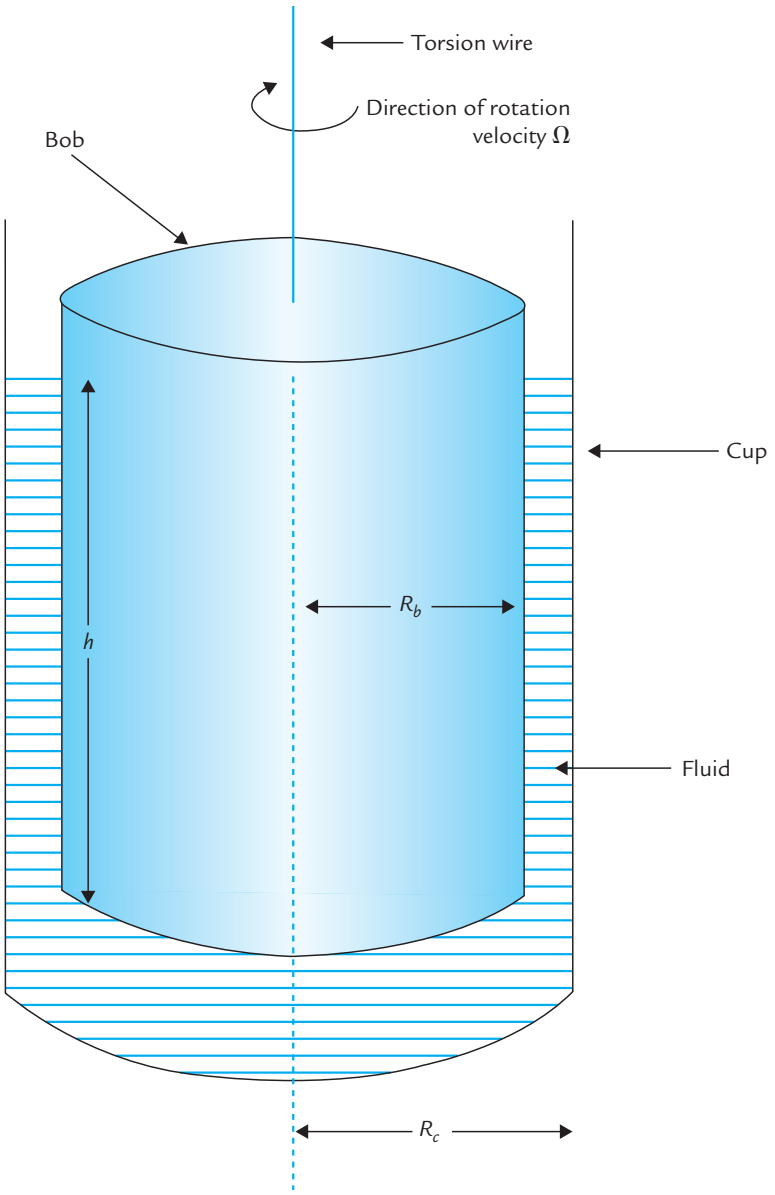


Figure 6.6 Principle of the coaxial rotational viscometer.

The Margules equation is not applicable to flow of non-Newtonian fluids in coaxial rotation viscometers. More complex equations have been derived to represent, or approximately represent, the flow of these complex fluids. The reader is referred to standard texts on viscometry for the development of equations applicable to non-Newtonian fluids (see, e.g. VanWazer *et al.*, 1963; Whorlow, 1980).

This type of viscometer may be divided into two classes.

Class 1. Stormer type. The shear rate is measured under a controlled torque. A constant torque was maintained in the original stormer viscometer by a falling weight attached to a thin cord that passes over a pulley and is wrapped around a drum that is connected to the rotor bob. Modern electronics have rendered obsolete this method of achieving a constant

torque although the stormer viscometer can still be found in some catalogs.

Class 2. MacMichael type. The torque is measured at a controlled shear rate which is a function of the number of revolutions per minute of the rotating member and the geometry of the test cell. The first successful viscometer of this type was developed by MacMichael (1915).

The major error that occurs in coaxial viscometers is the 'end effect,' which arises from the drag of the fluid on the ends of the bob. The derivation of the Margules equation (and other similar equations) assumes an infinitely long bob with no ends. The end effect of the top of the bob is easily eliminated by filling the cup to a level below that necessary to cover the bob. Since the top of the bob is not in contact with the liquid there is no drag. The end effect of the bottom of the bob can be determined experimentally by measuring the torque/angular-speed ratio with the cup filled to several different heights. A rectilinear plot should be obtained when the data are plotted (see Fig. 6.7). The plot is extrapolated to zero on the torque/angular-speed ratio axis. The negative intercept on the horizontal axis (h_o) gives the end effect in terms of the equivalent length of bob with no ends. In any mathematical exercise the depth of immersion h should be replaced by $h + h_o$ in order to account for the end effect. The effect is practically eliminated when bobs with concave top and bottom are used, because air replaces most of the metal end surfaces of the bob.

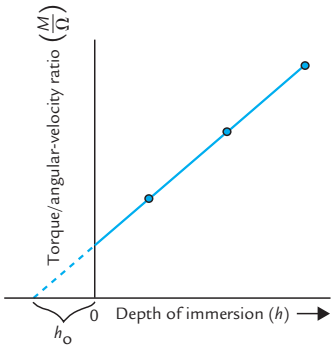


Figure 6.7 Measurement of the end effect in a coaxial rotational viscometer. The torque/angular-velocity ratio (M/Ω) is plotted against the depth of immersion of the bob in the fluid h. The intercept of the extrapolated line on the horizontal axis gives the numerical value of the end effect (h_o).

Cone and Plate and Parallel Plate Viscometers

The fluid is held by its own surface tension between a cone of small angle that just touches a flat surface (Fig. 6.8). The torque caused by the drag of the fluid on the cone is measured as one of the members is rotated while the other member remains stationary. For a Newtonian fluid the following equation applies:

$$\eta = 3\alpha M/2\pi R_b^3 \Omega$$

where η is the absolute viscosity; α, the angle of cone (usually less than 2°); M, the torque; R_b, the radius of the cone; and Ω, the angular velocity of the rotating member. For a given instrument with a given geometry this can be reduced to

$$\eta = KM/\Omega$$

where K is the instrument constant $3\alpha/2\pi R_b^3$.

A more detailed analysis of the cone and plate viscometer is given by Slattery (1961).

The special feature of the cone and plate viscometer is that the shear rate is uniform at all points in the fluid, provided that the angle of the cone is small.

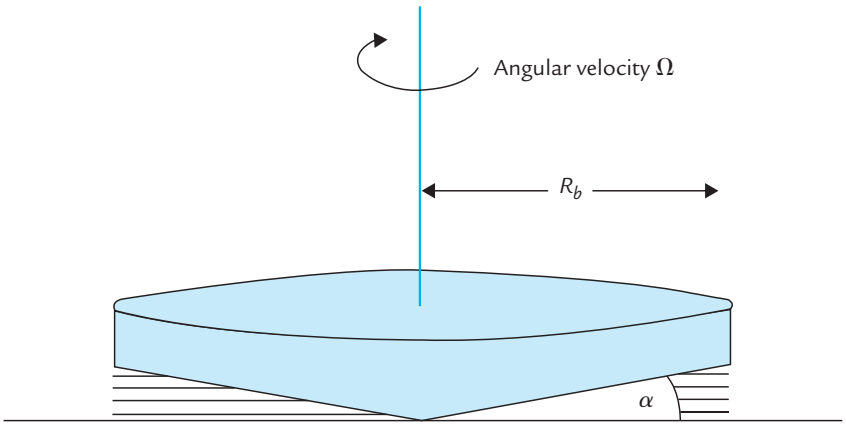


Figure 6.8 Schematic of cone and plate viscometer.

This makes the cone and plate viscometer of particular use for non-Newtonian fluids because the true rate of shear can be obtained comparatively easily. Other features of this type of viscometer are (1) end effects are negligible, (2) a small amount of fluid is needed (usually less than 2 ml), and (3) the thin layer of fluid in contact with temperature-controlled metal base plate enables measurements to be made at high rates of shear without the need to compensate for the heating effect of the high shear rate.

Parallel-plate geometry is used when the presence of suspended matter in the fluid does not allow representative fluid to enter into the narrowest part of a cone and plate viscometer.

Because of the small volume of fluid contained in cone-and-plate, and parallel-plate viscometers there can be a problem with evaporation of the solvent which results in a concentration of the nonvolatile components. This problem becomes more acute as the test temperature is increased because the vapor pressure of liquids increases as the temperature increases. This problem can be ameliorated by enclosing the cone and plate or parallel plate with a cage designed to reduce the loss of solvent vapor without interfering with the rotation. Some researchers coat the exposed edge of the fluid around the perimeter of the cone and plate with a thin layer of low-viscosity oil to retard evaporation.

Modes of Operation of Rotational Viscometers

It has already been explained that there are two types of rotational viscometers. Type 1 measures the shear stress at a controlled shear rate and Type 2 measures the shear rate at a controlled shear stress. Both of these can be operated in several modes.

Mode 1: Ramp increase. The shear rate (or shear stress) is steadily increased and the resultant shear stress (or shear rate) is measured. This gives

a shear stress–shear rate curve. Usually the shear stress–shear rate curve is measured up to the maximum when the test is stopped (ascending curve) but sometimes it continues to be measured as the shear rate (or shear stress) is ramped down again to zero (descending curve). An ascending–descending curve is needed to measure hysteresis.

Mode 2: Step increase. The shear rate (or shear stress) is steadily increased by set amounts and the shear stress (or shear rate) is recorded after each increase. The test can be performed ascending only, or ascending and descending.

Mode 3: Continuous operation at a constant setting. The shear stress is measured at a constant shear rate or shear rate at constant shear stress over a period of time. This mode is used whenever time dependency effects need to be measured (see pages 92–94).

Mode 4: The rotating member is caused to cycle a small angle, clockwise and counterclockwise over a period of time. This is small-amplitude oscillation viscometry and is used to measure the storage modulus G', loss modulus G'', and loss tangent, tan Ø (see pages 98, 99).

There are some more exotic geometries that have been used in coaxial rotational viscometers including cone–cone, double cone and plate, conicylindrical, and disk. These will not be discussed here as they are not widely used in the food field.

Other Rotational Viscometers

There are some empirical viscometers in which a paddle, a cylinder, or bars rotate in a container, usually with large clearances between the rotating member and the wall. The geometry of these viscometers is complex and usually not amenable to rigorous mathematical analysis. These instruments are generally rugged, moderate in cost, and fairly easy to manipulate. They have their place, particularly for quality control purposes in the plant where detailed mathematical analysis is not needed. They are widely used in industry. Examples of this type are some Brookfield Viscometers, and the FMC Consistometer.

The *Brabender Viscograph* is designed specifically to measure the apparent viscosity of starch suspensions and record how the viscosity changes as the temperature of the water–starch slurry is raised past the gelatinization temperature, held at this elevated temperature for a period, and then cooled again.

The *FMC Consistometer* was originally designed by the Food Machinery Corporation to measure the consistency of cream-style corn. It is now distributed by C. W. Brabender Instruments and has been used for routine quality control purposes for catsup, tomato paste, strained baby foods, and other products that have a similar consistency. The product is placed in a stainless-steel cup, the paddle is lowered into the cup, the motor is switched on causing the cup to rotate at a single fixed speed of 78 rpm, and the torque on the

paddle is read from a scale on top of the instrument. Four paddles with different dimensions are provided with this instrument. The instrument is approximately 38 cm high, 26 cm wide, 31 cm long, and weighs about 16 kg; the four paddle sizes available are 2 in. × 1.4 in., 2 in. × 1 in., 2 in. × 0.75 in. and 1.5 in × 1 in.

The *Corn Industries Viscometer* CIV was once widely used to measure changes in viscosity of corn syrup and starch pastes, but this instrument is no longer commercially available.

The *Brookfield Dial Reading Viscometer* is an instrument that may be held in the hand or supported on a stand. A synchronous induction type motor gives a series of speeds of rotation that are constant. Various spindles that take the form of cylinders, disks, and T bars are attached to a small chuck. When the spindle is immersed in the liquid and the motor switched on, the viscous drag of the fluid on the spindle is registered as torque on a dial. A Factor Finder scale provided by the manufacturer enables the operator to quickly convert the dial reading into apparent viscosity.

The company can supply a Helipath stand that automatically lowers the Brookfield Viscometer, thus ensuring that the spindle is continuously moving into previously undisturbed material. This accessory is useful when studying fluids that exhibit time effects or that have a tendency to settle.

The Brookfield Engineering Laboratories have over 60 years experience with viscosity measurement and have a good reputation for helping potential customers identify the precise model of instrument and optimum mode of operation for their own applications.

Brookfield Dial Reading Viscometers are widely used in the food field. They have the advantages that they are of moderate cost, portable, simple to operate, well adapted to many viscosity problems, give results quickly, can be used to measure viscosity in almost any container ranging from a 200-ml beaker to a 1000-gal tank, can be used on Newtonian and non-Newtonian liquids, can be used to measure time dependency and hysteresis, are not affected by large particles in suspension, and require minimum maintenance. The disadvantages are that there is a limited range of shear rates, the shear rate can only be changed stepwise, the shear rate varies across the fluid, there can be problems in obtaining shear rate and apparent viscosity for non-Newtonian liquids, and the geometry and flow pattern do not lend themselves to rigorous mathematical analysis.

Paddle Viscometry

This type of viscometer consists of two or more paddles attached to a shaft that is caused to rotate at one or more speeds while the torque resistance is measured. They may resemble a flag or a star-shaped geometry. They are sometimes called ‘mixer viscometers’ because the paddles stir and mix the product as they rotate. The stirring action makes them particularly useful for

food suspensions containing particulates that settle out. This is an empirical instrument; all test conditions must be kept constant to achieve reproducible results. Researchers are now analyzing the action of this class of instrument and extracting useful rheological parameters even though the shear-rate varies from point to point around the paddles.

Rao (1975) pointed out that the average shear stress is directly proportional to the torque and the average shear rate is directly proportional to rotational speed. Hence, the slope of the plot of log (torque) versus log (rpm) will give the value of the flow behavior index n of power law fluids. The consistency index K can be found by testing a fluid with known values of K and n under identical test conditions using the equation:

$$M_x/M_y = K_x/K_y$$

where M_x is the measured torque for the test fluid and M_y the measured torque for the fluid whose properties are known, K_y is the consistency index for the known fluid. K_x can then be computed since M_x, M_y and K_y are known. One restriction for this method is that the flow behavior index n of the known fluid should be about the same value as is n for the test fluid.

Rao and Cooley (1984) showed that an 'effective shear rate' can be experimentally determined for flag and star impeller viscometers by comparing measurements on a known Newtonian fluid with measurements on a test material that fits the power law flow behavior. Yoo and Rao (1994) used this procedure to study the rheological properties of tomato puree and Missaire *et al.* (1990) to study the rheology of apple pulps.

Steffe and Ford (1985) used mixer viscometry to study the rheology of starch-thickened strained apricot baby food. Castell-Perez *et al.* (1987) found good agreement between a low-cost mixer viscometer and a Rheometrics Fluids Spectometer for apricot puree and guar gum solution. Briggs and Steffe (1997) used the Mitschka method (Mitschka, 1982) to calculate average shear stress and shear rate of a paddle mounted in a Brookfield RV viscometer and found the results for banana puree, salad dressing, enchilada sauce and pancake syrup compared favorably with those obtained with a cone and plate viscometer. Castell-Perez and Steffe (1992) provide a good review of the theory and practice of mixer viscometry.

The *Rapid Visco-Analyzer* is a useful example of mixer viscometry (Ross *et al.*, 1987). It consists of a molded plastic stirring paddle attached to an electric motor whose shaft rotates at constant speed and the current required to drive it is constantly monitored by a microprocessor. A disposable aluminum sample container is filled with 4 g of flour and 25 ml of water and placed to surround the paddle, and the motor is started. A split copper block at 96°C rapidly heats the mixture through the gelatinization temperature of the starch. The test takes 3 minutes to perform. The power output correlates with the apparent viscosity. This has become a routine screening test to detect sprout damage to wheat quality when wheat is delivered to grain storage sites.

Falling-Ball Viscometers

This type of viscometer operates on the principle of measuring the time for a ball to fall through a liquid under the influence of gravity. The falling ball reaches a limiting velocity when the acceleration due to the force of gravity is exactly compensated for by the friction of the fluid on the ball. Stokes (1819–1903) was one of the first to study the limiting velocity of falling balls and the following equation is named the 'Stokes equation' in his honor:

$$\eta = \left[\tfrac{2}{9}(\rho_s - \rho_l)gR^2\right] \Big/ V$$

where η is the viscosity; ρ_s, the density of the falling ball; ρ_l, the density of the fluid; R, the radius of the falling ball; g, gravity; and V, the limiting velocity.

This is a simple type of instrument that is useful for Newtonian fluids but has limited applicability to non-Newtonian fluids. It cannot be used for opaque fluids because the ball cannot be seen. Stokes' law applies when the diameter of the ball is so much smaller than the diameter of the tube through which it is falling that there is no influence of the wall on the rate of fall of the ball.

A falling-ball viscometer can be easily improvised in the laboratory (see Fig. 6.9). Fill a large graduated glass cylinder with the test fluid and gently drop a steel ball in the center of the cylinder. Allow sufficient distance of fall for the ball to reach the limiting velocity, then time the fall of the ball with a stopwatch. Steel ball bearings with a range of precisely controlled diameters can be obtained from engineering supply houses. The larger the ball, the faster it falls. Therefore, it is necessary to select a diameter ball that is small enough to fall at a rate that can be measured with some degree of accuracy with a stopwatch. The lower the density of the ball, the slower it falls. It is possible to obtain balls of material other than steel that have a different density. For example, glass marbles have a density of about 2.6 compared with 7.8 for steel. A glass marble will fall more slowly than a steel ball of equal size.

The *Gilmont Viscometer* is a falling-ball viscometer in which a glass or stainless-steel ball falls down a vertical tube slightly larger than the ball. The interior of the tube is beaded to ensure that the ball stays centered as it falls. Gilmont (1963) used the theory of flow rotameters with spherical floats to derive the following two equations:

$$\eta = K(\rho_f - \rho)t$$

where η is the viscosity, ρ_f is the density of ball (2.53 for glass and 8.02 for stainless steel), ρ is the density of liquid, t is the time for ball to fall between two sets of fiduciary lines etched into the tube as measured by stopwatch, and K is the instrument constant;

$$K = \frac{8.80 D_f^2}{L} \cdot R^{5/2}\left(2 + \frac{R}{100}\right)$$

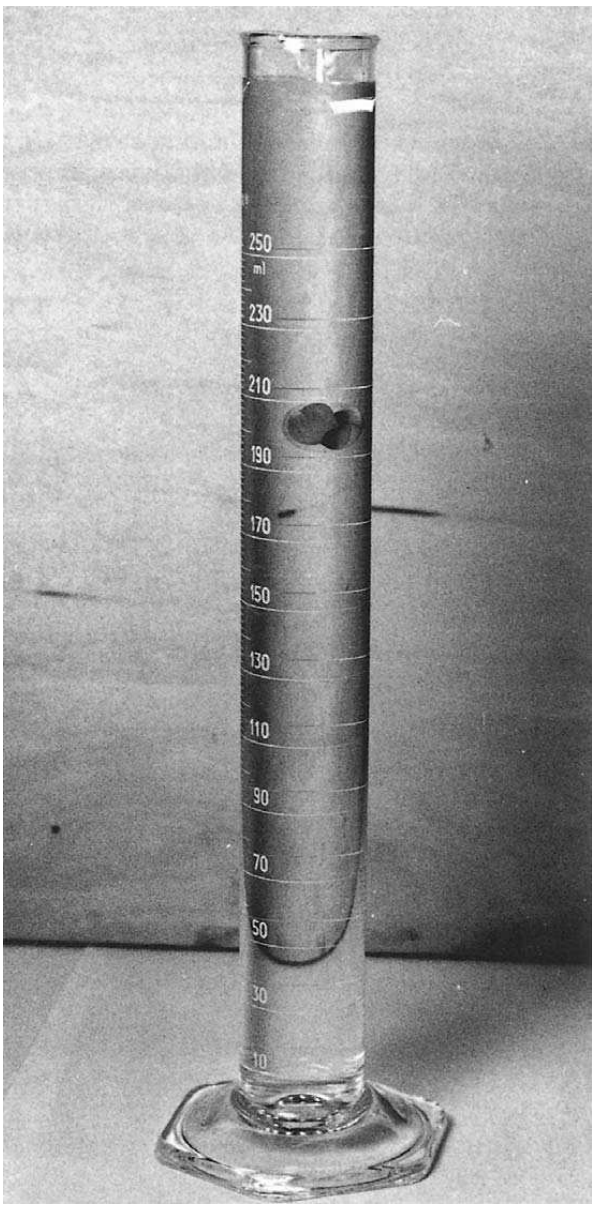


Figure 6.9 A falling-ball viscometer improvised in the laboratory (note the glass marble falling through the liquid).

where D_f is the diameter of falling ball, L is the distance the ball falls between fiduciary marks, $R = 100(D_t - D_f)/D_f$, and D_t is the tube diameter.

In practice, the value of K is usually obtained by measuring the time of descent for a liquid of known viscosity and rearranging the viscosity equation into the form:

$$K = \frac{\eta_s}{\rho_f - \rho} \cdot t$$

where η_s is the viscosity of liquid of known viscosity.

The Gilmont Viscometer uses a 10 ml sample. Two sizes of tubes and two balls (glass and stainless steel) are available. It is suitable for Newtonian liquids in the viscosity range of 0.25–300 mPa·s.

A variation of the falling-ball viscometer is the rolling-ball viscometer in which a ball falls through the liquid in a tube inclined at an angle of about 10° from the vertical. The tube is only slightly larger in diameter than the ball, and there is a strong influence of the wall on the ball.

The best-known rolling-ball apparatus is the *Hoeppler Viscometer*. The instrument consists of a heat-resistant chemically inert 20 cm-long glass tube with a precision bore about 16 mm diam. It is enclosed in an 80 mm-diam. glass tube through which water from a constant temperature bath is circulated. A screw cap at the top of the tube is removed, the tube is filled with sample (about 30 ml), a designated ball is placed in the tube, all air is removed, and the cap is replaced. When the system has reached equilibrium temperature, the tube assembly is inverted and the rate of fall of the ball between markings on the glass tube is measured with a stopwatch.

Hubbard and Brown (1943) developed general relations between the variables involved in the streamline region of fluid flow for rolling-ball viscometers which led to the equation

$$\eta = \frac{5\pi}{42} K \cdot \frac{d^2 \rho g \sin\theta}{V} \cdot \frac{\rho_s - \rho}{\rho} \cdot \frac{D + d}{d}$$

where K is a dimensionless correlation factor; d, the diameter of the ball; D, the internal diameter of the tube; V, the terminal rolling velocity of the ball; g, acceleration of gravity; ρ, the density of the liquid; ρ_s, the density of the ball; and θ, the angle of inclination of the tube to horizontal.

For a given instrument operating under standard conditions, D, d, θ, and K are constant and the above equation reduces to

$$\eta = C(\rho_s - \rho)/V$$

where C is the instrument coefficient, which is equal to $(5\pi/42)Kg \sin\theta D(D + d)$.

By selecting balls of different composition and different diameters it is possible to measure viscosities over the range of less than 1 mPa·s to about 200 Pa·s. The Hoeppler viscometer can give results reproducible to 0.5% or better with Newtonian fluids.

Oscillation Viscometry

A vibrating surface in contact with a liquid experiences 'surface loading' because the shear waves imparted to the liquid are damped at a rate that is a function of the viscosity of the liquid. The power required to maintain a constant amplitude of oscillation is proportional to the viscosity of the fluid. Oscillation viscometers usually take the form of a stainless-steel ball immersed in the fluid and vibrated at high frequency and low amplitude. This type of viscometer has the advantages of high precision, high sensitivity

to small changes in viscosity, rapid accumulation of data, and the equipment is easy to clean. The disadvantages are that it operates at one shear rate only.

The size of the test sample is not critical so long as it exceeds that volume below which reflection from the walls of the container occurs. This distance is usually less than 5 mm. Roth and Rich (1953) give the following equation for the propagation distance for the amplitude of the shear waves to fall to $1/e$ of their value in a Newtonian fluid:

$$\delta = (2\eta)^{1/2}/\omega\rho$$

where δ is the propagation distance; η, the viscosity of the fluid; ρ, the density of the liquid; and ω, the vibrational frequency.

A commercial viscometer of this type is available from the Nametre Company (Fitzgerald and Matusik, 1976; Ferry, 1977). It consists of a $1\frac{1}{4}$-in.-diam polished stainless-steel ball attached to a stainless-steel rod. The ball is immersed in the liquid and vibrated at a frequency of 646 Hz and an amplitude of 25 μ. A digital readout dial displays the viscosity. A viscosity range from about 1 mPa·s to 100 Pa·s can be measured. Minimum sample size is 35 ml up to 10 Pa·s and 70 ml up to 100 Pa·s. The author has not seen reports of the use of this instrument for foods, but it appears to have possibilities for many liquids, including in-line quality control (Oppliger *et al.*, 1975).

The SOFRASER is another type of oscillation viscometer. It immerses a thin vibrating rod into the fluid to be tested. A constant power input imparts a rapid low-amplitude oscillation to the rod and the damping effect is measured by the change in amplitude of the vibration. The amplitude decreases as the viscosity of the test fluid increases. The instrument can be customized to measure viscosities between 0–10 mPa·s up to 0–1000 Pa·s.

Imperfect Lubricated Squeezing Flow

In this procedure the fluid or semifluid is placed in a wide, shallow container and compressed under a platen mounted in a universal testing machine. Since this uses a uniaxial compression it is described in Chapter 4 (see page 175).

Back Extrusion Viscometry

The principle of the back extrusion test for solids described on page 127 refers to compressing solid foods until they disintegrate sufficiently to flow through a narrow annulus. The same principle can be applied to fluids when it may be described as a ‘back extrusion’ test, but is also often termed ‘annular pumping’ by rheologists. In both cases, the food is held in a container that is placed

on the base of a universal testing machine (UTM), a rod or platen attached to the UTM crosshead is driven down into the container and the change in force over time is recorded. There are several differences between back extrusion of solids and liquids:

(1) There is no initial packing down for liquids as there is for solids (see section A–B in Fig. 4.15, page 128).
(2) With solids, the force usually becomes approximately horizontal once extrusion begins (see section C–D in Fig. 4.15, page 128), whereas, with liquids the force increases linearly as long as the rod continues to descend into the fluid.
(3) A correction for buoyancy force and velocity imparted to the fluid needs to be made for liquids. These factors are ignored with solids because the force to disintegrate solids is so high.

Steffe and Osorio (1987), and Osorio and Steffe (1987) pointed out that the total force on the descending rod is given by the sum of three factors:

$$F_T = 2\pi aL\tau w + \pi a^2 \Delta P + \gamma gL\pi a^2$$

where F_T is the total force on the descending rod; a, radius of the rod; L, depth of immersion of the rod in the fluid; τw, shear stress at wall of the rod; ΔP, pressure at depth L; γ, sample density; g, gravity. The first term in the equation is the force due to the shear stress at the wall ($2\pi aL\tau w$), the second term is the force responsible for fluid flow in the upward direction ($\pi a^2 \Delta P$) and the third term represents the buoyancy or hydrostatic force ($\gamma gL\pi a^2$).

If a power-law fluid is tested in a back extrusion cell using two different speeds of the descending rod, its flow behavior index n is given by the equation:

$$n = \ln\left(\frac{F_{cb2} \cdot L_1}{F_{cb1} \cdot L_2}\right) \Big/ \ln\left(\frac{V_2}{V_1}\right)$$

where n is the flow behavior index; F_{cb} is the force connected for buoyancy; L is the depth of immersion of the rod in the fluid; and V is velocity of travel of the rod. The suffixes 1 and 2 refer to the first and second test.

The consistency coefficient for a power-law fluid is given by the equation:

$$K = \frac{PR}{2}\left(\frac{\Phi R}{V_p (R/a)^2}\right)^n$$

where K is a consistency coefficient; P, the pressure drop per unit length; Φ, a dimensionless flow rate; R, radius of container; a, radius of the descending rod, and V_p, velocity of the plunger.

This test procedure, although mathematically complex, has great potential for the food industry because the experimental procedure is simple, rapid, and uses robust attachments to a universal testing machine.

Imitative Viscometers

These empirical instruments imitate the flow of non-Newtonian fluid foods under practical conditions. They are simple instruments that usually give a one-point measurement. Although they have their limitations they can be useful for quality control purposes. Examples of this type of viscometer are the Bostwick Consistometer, the Grawemeyer and Pfund Consistometer (also known as the Adams Viscometer), and sag meters. These types were discussed in the previous chapter.

Use of One-Point Measurements for Non-Newtonian Fluids

Throughout this chapter and in Chapter 3 the severe problems associated with attempts to describe a non-Newtonian fluid by means of a one-point measurement have been emphasized. However, having expressed these cautions, it is now time to point out that under certain conditions it is possible to use a one-point measurement as a quality control technique for non-Newtonian fluids. In some highly standardized systems the change in viscous properties during processing moves in a reproducible manner along a predetermined path. A one-point measurement may satisfactorily determine the endpoint in such a system.

An example of this can be found in the concentration of tomato juice to make catsup. Tomato catsup is essentially tomato puree that has been flavored with salt, sugar, vinegar, and spices. It is manufactured by adding these ingredients to tomato juice and boiling until a satisfactory consistency is obtained. Close control of this endpoint consistency is critical. If slightly too thin, the catsup gushes out of the bottle too fast, whereas if slightly too thick, it becomes difficult to make it flow from the bottle. Figure 6.10 plots the apparent viscosity of tomato puree as a function of the solids content in the puree. Although the flow properties of the puree at each concentration are complex (see Rao *et al.*, 1981), the viscous properties do move in a reproducible way along this complex path. Hence, a single-point apparent viscosity measurement can be used successfully to determine the finishing point for tomato catsup.

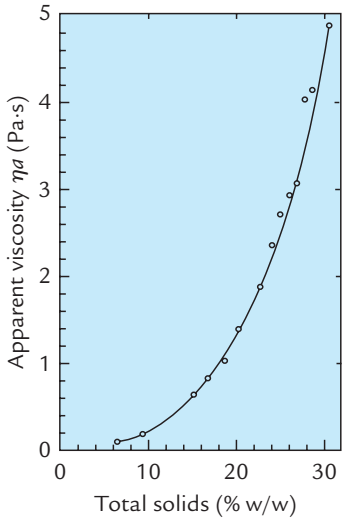


Figure 6.10 Apparent viscosity of tomato juice and concentrates as a function of solids concentration measured at a constant shear rate of 100 s^{-1}. Nova cultivar. (From Rao *et al.*, 1981. Reprinted from *J. Texture Studies* 12, page 521. With permission of Food and Nutrition Press Inc.)

Suppliers of Rotational Viscometers

Although description of the rotational viscometers most commonly used for food products was included in the first edition they will not be described in this edition for several reasons.

(1) Most manufacturers now provide a wide array of viscometer types whereas in the past many manufacturers made only one type. One

manufacturer would specialize in controlled shear rate viscometers, another in controlled shear stress viscometers and yet another would concentrate on designing equipment to measure the normal force. Nowadays most manufacturers provide almost every type of viscometer.

(2) Manufacturers continuously upgrade and expand the number of models available. They also upgrade their software programs on a regular basis.

(3) Companies are being bought and sold more often. A well-known brand name of viscometer this year may be marketed by a different Corporation next year.

A list of the suppliers of the rotational viscometers most widely used for foods is given in Appendix I, pages 341–345. This list is up-to-date at the time of writing. The reader is encouraged to contact suppliers directly because they can provide the most up-to-date information on their offerings.

CHAPTER 7

Sensory Methods of Texture and Viscosity Measurement

Introduction

Sensory evaluation is the measurement of a product's quality based on information received from the five senses: sight, smell, taste, touch, and hearing. Sensory texture measurement is perceived primarily by touch (the tactile sense), although the eyes and ears can provide information on some important components of the total texture profile of a product. The signals generated at the nerve endings of the senses are transmitted via the central nervous system to the brain where they are integrated with past experience, expectations, and other conceptual factors before the opinion of the response is summarized (Amerine *et al*., 1965; Larmond, 1970).

Sensory methods of measuring food quality may appear to lack the precision that is desirable in scientific research because of the variability from person to person and variability from hour to hour and day to day in likes and dislikes of each person. In spite of these obstacles, sensory measurement of texture is a very important aspect of food quality that cannot be ignored. Later in this chapter it will be shown that some sensory testing methodology can be as reproducible and precise as physical tests when properly performed.

Importance of Sensory Evaluation

Instruments are calibrated in absolute units such as newtons force, millimeters distance, pascal-seconds viscosity, and so on, but these readings mean little unless correlated with sensory judgments of quality. Correlating measurements of physical properties with sensory assessments of texture is the subject of the next chapter. There is no point in measuring properties that are not perceived or not judged important by the human senses. People will not purchase or consume food unless it has high acceptability according to their perception of quality.

Sensory methods are the ultimate method of calibrating instrumental methods of texture measurement. Even though sensory methods are generally time consuming, expensive, and not subject to absolute standards, the fact remains that eventually all instrumental measurements have to be calibrated against the human senses. We have to face the fact that if the palate sends a value judgment message that says the food has undesirable textural properties, then the texture is undesirable regardless of the readings given by our instruments.

There is a large body of literature in which excellent reports of physical testing and chemical and biochemical analyses have been matched with sensory testing that was not performed in a scientific manner. It is regrettable that so much work of potentially high value is of limited use because it was paired with inadequately designed and poorly executed sensory studies. The most common deficiencies have been use of untrained or inadequately trained judges, use of hedonic scaling instead of intensity scaling, and inadequate or no definition of the exact meaning of the sensory terms presented to the panel.

Sensory evaluation offers the opportunity to obtain a complete analysis of the textural properties of a food as perceived by the human senses. A number of processes occur while food is being masticated, including deformation, flow, comminution, mixing and hydration with saliva, and sometimes changes in temperature, size, shape, and surface roughness of the food particles. All of these changes are recorded with great sensitivity by the human senses, but many of them are difficult to measure with instruments. The entire complex of events that occurs during mastication cannot be measured completely by instruments. There is no instrument available that has the sophistication, elegance, sensitivity, and range of mechanical motions as the mouth or that can promptly change the speed and mode of mastication in response to the sensations received during the previous chew.

Sensory evaluation is important for product development. It is the best method for evaluating texture of new types of foods in the early stages of development, especially fabricated foods, and for providing a basis on which instrumental methods might later be designed for use as a quality measure and production control.

Sensory analysis of the textural quality of food has been used in practice ever since the first human being walked on the face of the earth; and food researchers have performed sensory texture studies for many decades. However, the comprehensive foundation on which modern sensory texture analysis is built was laid by Dr Szczesniak's group at the General Foods Corporation Technical Center in Tarrytown, New York in the early 1960s. (General Foods Corporation has since become part of Kraft Foods.) Therefore, the sensory texture profiling procedure developed by that group will be described in detail first. Additions, modifications, and spin-offs from the basic procedure will then be described.

Sensory Texture Profiling

Since texture is a multiparameter attribute, its full description must address the identification and quantification of all the textural properties of a food. The most complete system of sensory texture measurement is the General Foods Sensory Texture Profiling technique (Brandt *et al*., 1963; Szczesniak *et al*., 1963; Civille and Szczesniak, 1973; Civille and Liska, 1975). The following description is based on the material in these references. This technique is an extremely powerful tool and is highly recommended. Most other methods for sensory analysis of texture may be viewed as partial texture profile techniques. The best way to learn the procedure and have confidence in it is to do it; it is less satisfactory to describe it because verbal or written descriptions do not give the sense of the strength, accuracy, flexibility, and reproducibility of the technique that is obtained by actually doing it. One might liken this to learning to drive a car by sitting behind a steering wheel and actually driving the car versus learning to drive a car by reading about how to drive cars but never driving one.

The major steps in the operation of establishing a sensory texture profile are (1) selection of panel, (2) training the panel, (3) establishing standard rating scales, (4) establishing a basic texture profile analysis (TPA) score sheet, and (5) developing a comparative TPA score sheet for each commodity. These steps will now be described in sequence.

Selection of Panel Members

A properly trained panel leader is needed to start the sensory texture profiling. It is best for this person to have been trained in a formal training workshop conducted by people who are well experienced with the procedure. The panel leader should possess all the attributes needed for panel members described below and in addition should have (a) the type of personality that puts people at ease and encourages them to put forth their best efforts as a group; (b) some scientific training and understanding of the scientific method, although it is not necessary to have advanced training in these areas; (c) leadership qualities that will bring the panel to a consensus of opinion without imposing personal ideas.

The general requirements for texture profile panelists are listed in Table 7.1. At least twice as many persons as needed should be chosen for preliminary selection because not all persons meeting the requirements in Table 7.1 will be found suitable. A panel normally comprises five to seven persons. In order to have a complete panel at all times, it is necessary to start with two to three times this number to allow for those who cannot pass the preliminary selection test and for attrition due to absences, relocations, and retirements.

In the preliminary selection process each candidate is given four consecutive samples from the hardness scale presented in random order and asked

Table 7.1 Requirements for Texture Profile Panelists[a]

1. Ability to work cooperatively and harmoniously with a group and develop a feeling of team identity with the group.
2. Able to spare the time for training (2–3 h a day for several weeks) and the regular operation of the panel for an indefinite period.
3. Their supervisor must approve this expenditure of time willingly, not reluctantly.
4. Panel members should be very interested in their work, and dedicated to developing a team that can give results with the precision and reproducibility of a scientific instrument.
5. Panel members must have common sense and reasonable intelligence. A high I.Q. is not essential. No special education is necessary. In fact, laboratory technicians and office staff (for example) frequently make the best panel members because they can more readily spare the time; they are always available; they are less likely to be preoccupied with other matters (as are senior scientists and administrators), and hence are able to devote their whole interest to the work at hand.
6. Panel members should be able to discuss the tests with the other members of the panel and be able to reach a consensus. People with a domineering or bossy attitude, and people who are excessively timid or cannot express an opinion are unsuited for panel work.
7. They should be able to develop a professional attitude toward their work, and take pride in it.
8. They should have good dental health and no dentures because false teeth may restrict the perception of some texture attributes.
9. People involved in the development of the product to be tested should not be on the panel because they tend to come to the panel with preconceived ideas of the textural quality of the products to be examined.
10. It is desirable to have members of both genders represented, although the panel can comprise predominantly one gender.

Source: Civille and Szczesniak (1973).
[a]The panel leader should possess the above attributes and in addition should have the following: (1) the type of personality that puts people at ease and encourages them to put forth their best efforts as a group; (2) leadership qualities that will bring the panel to a consensus opinion without imposing personal ideas; and (3) some scientific training and understanding of the scientific method.

to grade them in order of increasing hardness. Peanuts, carrot slices, peanut brittle, and rock candy are easy to obtain, fairly standard in hardness, not highly perishable, and are a good set to present to the panel. Those persons who can rank these four commodities with complete success in increasing order of hardness are used for further training. Those who are unsuccessful in this preliminary test are excluded from further participation.

Rousset-Akrim *et al*. (1995) used a series of 20 tests on 25 subjects to find efficient assessors for sensory texture profiling and concluded that the ability to complete a complex profile could be discerned through simple selection tests. This study supports the adequacy of the procedure described above.

Training of the Panel

The panel should be located in surroundings that are conducive to concentration: a place that is well lighted (not glary), quiet, and free from odors and distractions that might lower the concentration of the panel from the task at hand. Successful sensory texture profiling requires much concentration. The temperature of the surroundings should be comfortable. The panel is seated around a large table and provided with score sheets as needed, a glass of water for rinsing the mouth, and a paper cup for spitting out any material that is no longer needed for the test. There should be room in the center of the table to hold the samples that are currently being tested. A blackboard, a set of large flip sheets of paper, or other form of visual display should be available for recording scores and any comments made by the panel.

The first step in the training is to familiarize the panel with the standard rating scales described in detail in the next section. The panel is presented with one complete standard rating scale at a time. The panel leader gives a full explanation of the scale and then the panel samples each item on the scale in ascending order of magnitude. This is followed by discussion of the scale and further sampling of the commodities on that scale until the panel feels they have mastered the scale. At that time, a food of unknown intensity on the scale being considered is presented and the panel is asked to rate it to the nearest quarter point on the scale. The scores are called out to the panel leader who writes them on the board. When all the scores have been recorded, any differences in the scores are discussed, and sampling of the unknown and the standards is repeated until the entire panel gives a score within ±¼ point of the mean. The panel should work on each standard rating scale until they can obtain this degree of consistency between panelists. When this has been satisfactorily completed, the panel moves on to the next standard rating scale and repeats the procedure. This is continued until all of the scales have been covered, and the panel has a clear impression of the type of property being measured in each scale and the intensities that can be experienced in that scale using the standard items as anchor points.

When the panel has thoroughly grasped the standard scales, including the geometrical scales, they develop (as an exercise) a complete texture profile on a simple product such as soda crackers using the basic TPA score sheet, which is described in detail below. The complete texture profile is developed in one session without the presence of any of the food items on the standard scales. When it is found that panel members show substantial disagreement in some areas, the exercise is repeated in the following session with the items from the standard scales available for reference on the disputed points. The panel now repeats the evaluation of the disputed points on the scale using the standard scales for reference and continues to do this until they resolve their differences to within ±¼ point. This exercise generally makes the panel realize the value of having the standard scales for reference as anchor points.

Having successfully developed a reproducible texture profile for a simple product the panel turns its attention to the commodity of interest and develops a texture profile for it. The time required to develop a texture profile for the product of interest varies. With a simple product a good profile may be developed in two or three sessions. A difficult product may take a number of sessions before a complete, reproducible, and satisfactory profile is developed.

When the basic texture profile for the commodity of interest has been completed, the panel leader develops the comparative texture profile ballot, which is discussed on p. 273. The panel then uses the comparative texture profile ballot and perfects it by means of discussions between the panel and the leader, and by referring to the standard rating scales when questions or differences of opinion arise.

The panel has now been trained and is ready for routine work on the commodity for which the comparative texture profile ballot has been prepared.

Whenever a new commodity is to be studied, the panel utilizes the basic training it has already received. They first develop the basic texture profile for the new product and then move on to develop and perfect the comparative texture profile for that product.

Establishing Standard Rating Scales

Textural characteristics are divided into three classes (Szczesniak *et al*., 1963).

Mechanical Characteristics

The mechanical characteristics are related to the reaction of the food to stress and are made quantitative by means of standard rating scales, analogous to Mohs scale of hardness used by mineralogists. The standard hardness scale consists of nine food products ranging from low hardness (Philadelphia cream cheese) to high hardness (rock candy).

Other standard scales are fracturability (originally termed 'brittleness') (7 points), chewiness (7 points), gumminess (5 points), adhesiveness (5 points), and viscosity (8 points). The original standard scales are listed in Tables 7.2–7.7.

The items selected to be used for the standard rating scales are chosen on the basis of having that particular textural property as a dominant characteristic coupled with fairly uniform intervals between points in the desired characteristic. A panel of five to eight people with adequate training can rate the mechanical properties of a sample on each of the six standard scales to within about one fifth of a point with a high degree of reproducibility.

The items listed in the standard scales shown in Tables 7.2–7.7 were used to construct the original scales because they were available in eastern United States.

Table 7.2 Original Hardness Scale

Panel rating	Product	Brand or type	Manufacturer	Sample size
1	Cream cheese	Philadelphia	Kraft foods	½-in.
2	Egg white	Hard-cooked, 5 min	—	½-in. tip
3	Frankfurters	Large, uncooked, skinless	Mogen David Kosher Meat Products Corp.	½-in.
4	Cheese	Yellow, American, pasteurized process	Kraft foods	½-in.
5	Olives	Exquisite, giant size, stuffed	Cresca Co.	1 olive
6	Peanuts	Cocktail type in vacuum tin	Planters Peanuts	1 nut
7	Carrots	Uncooked, fresh	—	½-in.
8	Peanut brittle	Candy part	Kraft foods	—
9	Rock candy	—	Dryden and Palmer	—

Source: Szczesniak *et al*. (1963); reprinted from *J. Food Sci*. **28**, 398, 1963. Copyright by Institute of Food Technologists.

Table 7.3 Original Fracturability Scale[a]

Panel rating	Product	Brand or type	Manufacturer	Sample size
1	Corn muffin	Finast	First National Stores	½-in.
2	Angel puffs	Dietetic, heated for 5 min at 190°F (88°C)	Stella D'Oro Biscuit Co.	1 puff
3	Graham crackers	Nabisco	National Biscuit Co.	½-in. cracker
4	Melba toast	Inside piece	Devonsheer Melba Corp.	½-in.
5	Jan Hazel cookies	—	Keebler Biscuit Co.	½-in.
6	Ginger snaps	Nabisco	National Biscuit Co.	½-in.
7	Peanut brittle	Candy part	Kraft foods	½-in.

[a]This was originally known as the 'brittleness' scale.
Source: Szczesniak *et al*. (1963); reprinted from *J. Food Sci.* **28**, 399, 1963. Copyright by Institute of Food Technologists.

Table 7.4 Original Chewiness Scale

Product rating	Average no. of chews	Product	Brand or type	Manufacturer	Sample size
1	10.3	Rye bread	Fresh, center cut	Pechter Baking Co.	½-in.
2	17.1	Frankfurter	Large, uncooked, skinless	Mogen David Kosher Meat Products Corp.	½-in.
3	25.0	Gum drops	Chuckle	Fred W. Amend Co.	½-in.
4	31.8	Steak	Round, ½-in.-thick broiled on each side for 10 min	—	½-in. square
5	33.6	Black crows candy	—	Mason Candy Corp.	1 piece
6	37.3	Peanut chews	—	Whitman Co.	1 piece
7	56.7	Tootsie rolls	Midget size	Sweets Co. of America	1 piece

Source: Szczesniak *et al*. (1963); reprinted from *J. Food Sci.* **28**, 399, 1963. Copyright by Institute of Food Technologists.

Table 7.5 Original Gumminess Scale

Panel rating	Product	Brand or type	Manufacturer	Sample size
1	40% flour paste	Gold Medal	General Foods	1 tbs
2	45% flour paste	Gold Medal	General Foods	1 tbs
3	50% flour paste	Gold Medal	General Foods	1 tbs
4	55% flour paste	Gold Medal	General Foods	1 tbs
5	60% flour paste	Gold Medal	General Foods	1 tbs

Source: Szczesniak *et al*. (1963); reprinted from *J. Food Sci.* **28**, 400, 1963. Copyright by Institute of Food Technologists.

Table 7.6 Original Adhesiveness Scale

Panel rating	Product	Brand or type	Manufacturer	Sample size
1	Hydrogenated vegetable oil	Crisco	Procter and Gamble Co.	½ tsp
2	Buttermilk biscuit dough	—	Pillsbury Mills	¼ biscuit
3	Cream cheese	Philadelphia	Kraft Foods	½ tsp
4	Marshmallow topping	Fluff	Durkee-Mower	½ tsp
5	Peanut butter	Skippy, smooth	Best Foods	½ tsp

Source: Szczesniak *et al*. (1963); reprinted by *J. Food Sci.* **28**, 400, 1963. Copyright by Institute of Food Technologists.

Table 7.7 Original Viscosity Scale

Panel rating	Product	Brand or type	Manufacturer	Sample size
1	Water	Spring	Crystal Springs Co.	½ tsp
2	Light cream	Sealtest	Sealtest Foods	½ tsp
3	Heavy cream	Sealtest	Sealtest Foods	½ tsp
4	Evaporated milk	—	Carnation Co.	½ tsp
5	Maple syrup	Premier 100%	Francis H. Leggett and Co.	½ tsp
6	Chocolate syrup	—	Hershey Chocolate Corp.	½ tsp
7	Mixture: ½ cup mayonnaise and 2 tbs heavy cream	Hellman's Sealtest	Best Foods Sealtest Foods	½ tsp
8	Condensed milk	Magnolia, sweetened	Borden Foods	½ tsp

Source: Szczesniak *et al*. (1963); reprinted from *J. Food Sci.* **28**, 401, 1963. Copyright by Institute of Food Technologists.

Some of them may not be available in other areas of the United States and many of them are not available in other countries. Under these conditions substitute commodities must be selected to fill out these scales. Each scale should encompass the full range of intensity of that textural characteristic encountered in foods. Other factors to be considered in selection of the standard commodities are:

(1) select well-known brands that have good quality control and give a consistent quality of the product;
(2) use products that require the minimum amount of preparation in order to eliminate recipe variables;

(3) use products that do not change greatly with small temperature variations or with short-term storage.

The reference items should be standardized as much as possible with respect to size, temperature, brand name, and handling to ensure the stability of each scale point.

With these criteria in mind it is possible to change any commodity in the standard scales. An example of this is shown in Table 7.8 where the hardness and viscosity scales developed for a texture profile panel in Colombia are shown and contrasted with the original scales developed by the General Foods Group in eastern United States. Similar scales have been developed in Colombia for the other mechanical characteristics using different commodities than in eastern United States (Bourne *et al*., 1975).

When necessary, the scales can be expanded in selected areas to allow for a more precise description of differences between closely related samples. For example, when working with semisolids such as puddings and whipped

Table 7.8 Hardness, Gumminess and Viscosity Scales in New York and Bogota

Scale value	New York[a]	Bogota[b]
Hardness		
1	Philadelphia cheese (Kraft)	Philadelphia cheese (Alpina)
2	Cooked egg white	Cooked egg white
3	Frankfurters (Mogen David)	Cream cheese (Ubaté)
4	Processed cheese (Kraft)	Frankfurters (Suiza)
5	Pickled olives (Cresca)	Mozzarella cheese (LaPerfecta)
6	Peanuts (Planters)	Peanuts (LaRosa)
7	Carrot (raw)	Carrot (raw)
8	Peanut brittle (Kraft)	Candied peanuts (Colombina)
9	Rock candy	Milk candy (Colombina)
Viscosity		
1	Water	Water
2	Light cream (Sealtest)	40% sucrose syrup
3	Heavy cream (Sealtest)	50% sucrose syrup
4	Evaporated milk	60% sucrose syrup
5	Maple syrup	Maple syrup
6	Chocolate syrup (Hershey)	96% sweetened condensed milk + 4% water
7	Mixture: ½ cup mayonnaise and 2 tbs heavy cream	Sweetened condensed milk
8	Sweetened condensed milk	
Gumminess		
1	40% Gold Medal flour	41% Comapan flour
2	45% Gold Medal flour	45% Comapan flour
3	50% Gold Medal flour	49% Comapan flour
4	55% Gold Medal flour	53% Comapan flour
5	—	57% Comapan flour
6	60% Gold Medal flour	—

Sources: [a]Szczesniak *et al*. (1963); [b]Bourne *et al*. (1975).

toppings the lower end of the scale may require the addition of softer standards than cream cheese, which ranks number one on the standard scale.

The scales can also be expanded between points by adding other selected foods to serve as intermediate anchor points. For example, if a given formulated food always has a hardness between 3 and 5, then a new hardness scale can be constructed just for that food using 5 to 10 anchor points. In this case there is no need to use points 1, 2, 6, 7, 8, and 9 of the standard hardness scale because they will never be used for this food.

For panel use, the definitions of the mechanical characteristics are given in terms that are closely related to the actual perception.

Hardness is the force required to compress a substance between the molar teeth (in the case of solids) or between the tongue and palate (in the case of semisolids). To evaluate the hardness of solid foods, the item is placed between the molar teeth and the panelist bites down evenly, evaluating the force to compress the food. For semisolids, hardness is measured by compressing the food against the palate with the tongue.

Fracturability is a parameter that was initially called brittleness. It is the force with which a sample crumbles, cracks, or shatters; for example, peanut brittle shatters with greater force than graham crackers. Foods that exhibit fracturability are products that possess low cohesiveness and some degree of hardness. To evaluate fracturability the food is placed between the molar teeth and the panelist bites down evenly until the food crumbles, cracks, or shatters. The degree of fracturability of a food is measured as the horizontal force with which a food moves away from the point where the vertical force is applied. Another factor that helps determine fracturability is the suddenness with which the food breaks.

Chewiness is the length of time required to masticate a sample at a constant rate of force application to reduce it to a consistency suitable for swallowing. An alternative way to use this scale is to record the actual number of chews instead of using the numbers from the scale. To evaluate chewiness the standard is placed in the mouth and masticated at the rate of one chew per second. Chewiness is the number of chews required for a standard-sized piece before the product is swallowed. There may be a wide range in the number of chews from person to person, but the average number of chews for the whole panel represents a range for each scale value and adjacent ranges should not overlap. Even though there may be a wide range in the number of chews different panelists give the same product, each panelist should give the same rank order for the seven foods in the standard chewiness scale. Note that chewiness should be used for solid foods but not for semisolid foods (Szczesniak, 1995).

Adhesiveness is the force required to remove material that adheres to the mouth (generally the palate) during the normal eating process. The technique for evaluating adhesiveness is to place the food in the mouth, press it against the palate, and evaluate the force required to remove it with the tongue. Since the amount of saliva in the mouth affects the degree of adhesiveness, it is desirable to rinse the mouth with water immediately prior to each evaluation.

Gumminess is the denseness that persists throughout mastication or the energy required to disintegrate a semisolid food to a state ready for swallowing. The technique for evaluating gumminess is to place the sample in the mouth and move it between the tongue and the palate. The degree of gumminess is judged as the extent of manipulation required before the food disintegrates. Note that gumminess should be used for semisolid foods and not for solid foods (Szczesniak, 1995).

Viscosity is the force required to draw a liquid from a spoon over the tongue. The technique for evaluating viscosity is to place the spoon containing the food directly in front of the mouth and draw the liquid from the spoon over the tongue by slurping. The degree of viscosity is measured as the force required to draw the liquid over the tongue.

Geometrical Characteristics

Geometrical characteristics are related to the arrangement of the physical constitutents of the food product such as size, shape, arrangement of particles within a food, surface roughness, etc.; they are qualitative and partly quantitative.

These characteristics relate to particle size, shape, orientation, and surface roughness. Some standards for geometrical characteristics are given in Table 7.9. Geometrical characteristics do not lend themselves to as clear-cut scaling as do the mechanical characteristics. They may be divided into two general groups of qualities: size and shape, and shape and orientation.

(1) Those related to size and shape are perceived as discrete particles that are relatively harder than the surrounding medium or the carrier.

Table 7.9 Geometrical Characteristics of Texture

Descriptive term	Example
A. Characteristics relating to particle size and shape:	
Powdery	Confectioner's sugar
Chalky	Raw potato
Grainy	Farina, Cream of Wheat
Gritty	Pear stone cells, sand
Lumpy	Cottage cheese
Beady	Tapioca pudding
B. Characteristics relating to shape and orientation:	
Flaky	Boiled haddock
Fibrous	Base of asparagus shoot, breast of chicken
Pulpy	Orange sections
Cellular	Raw apples, white cake
Aerated	Chiffon pie filling, milk shake
Puffy	Puffed rice, cream puffs
Crystalline	Granulated sugar

Source: Brandt *et al*. (1963); reprinted from *J. Food Sci.* **28**, 405, 1963. Copyright by Institute of Food Technologists.

This group can be scaled in the same manner as the mechanical characteristics. For example, chalky, gritty, grainy, and coarse comprise a scale of increasing particle size. Note that this is particle size evaluation; the hardness of the particles must be evaluated independently.

(2) Characteristics related to shape and orientation represent highly organized structures of different geometrical arrangements within each product. For example, a puffy texture is an organization of hard or firm outer shells filled with large, often uneven, air pockets (e.g. puffed rice), whereas an aerated texture is a network of relatively small even cells filled with air and surrounded by cell walls (e.g. whipped egg white). The geometrical characteristics are sensed primarily by the tongue but may be sensed to some extent on the palate and on the teeth.

Other Characteristics

Other characteristics are properties related to the moisture and fat content of the food as perceived by the human senses; they are qualitative and partly quantitative. These are sometimes called chemical characteristics because they measure the factors of moistness, dryness, oiliness, and fattiness. No standard scales for these characteristics were published in the original texture profile method (Brandt *et al*., 1963), but it should be possible to develop standard scales for these properties. These terms are not the same as moistness or fat content as determined by chemical analysis. For example, two apples may have the same moisture content as determined by chemical analysis but in a sensory test one might be found to be dry and mealy while the other is moist and juicy. It is possible to have two cuts of beef that have been shown to have equal moisture contents by chemical analysis, and yet one cut will be termed juicy because of the sensation of moisture in the mouth while the other cut will be determined dry because the sensation of moisture is lacking.

It is worth emphasizing that it is the *sensation* of moistness or oiliness in the mouth that must be assessed. There is often a poor correlation between the release of oil or moisture during mastication and the amount determined by chemical analysis.

On one occasion the author was training a panel to work on a semiliquid product with a high content of emulsified soybean oil. The panel insisted the product had a 'greasy mouthfeel.' After tasting pure soybean oil ('oily') and Crisco shortening ('greasy') the panel confirmed the product was greasy. In this case the homogenized oil droplets gave the sensory impression of a solid fat even though no solid fat was used in the formula.

Developing the Basic TPA Score Sheet

A systematic method of recording all the texture characteristics of a given food is based upon the 'order of appearance' principle, which relates to the time sequence in which the various attributes of the product appear. Unlike flavor, where the order of appearance of the notes cannot be anticipated, texture

BASIC TEXTURE PROFILE BALLOT

Product: Date: Name:

I. *INITIAL (perceived on first bite)*
   (a) Mechanical
      Hardness (1–9 scale)
      Fracturability (1–7 scale)
      Viscosity (1–8 scale)
   (b) Geometrical
   (c) Other characteristics (moistness, oiliness)

II. *MASTICATORY (perceived during chewing)*
   (a) Mechanical
      Gumminess (1–5 scale)
      Chewiness (1–7 scale)
      Adhesiveness (1–5 scale)
   (b) Geometrical
   (c) Other characteristics (moistness, oiliness)

III. *RESIDUAL (changes induced during mastication and swallowing)*
   Rate of breakdown
   Type of breakdown
   Moisture absorption
   Mouth coating

Figure 7.1 The basic texture profile score sheet. (Courtesy of Dr A. S. Szczesniak.)

perception follows a definite pattern regarding the order in which the various characteristics are perceived. These are subdivided into initial (first bite), masticatory, and residual phases. The basic texture profile score sheet is shown in Fig. 7.1. This should be consulted frequently during the discussion that follows:

1. *Initial*. In the first bite the product is placed between the molars and a single bite is made. On this bite the mechanical properties of hardness, fracturability, and viscosity are measured and also geometrical properties and other properties (moistness, oiliness). The mechanical characteristics are graded to within 0.2 units on the standard scale, although some particularly sensitive people can grade to within 0.1 of a unit. The geometrical characteristics and other characteristics, if present, are listed without assigning a number to them, but adjectives such as slight, moderate, or strong may be appended to these characteristics at this time. There are four potential measures of geometrical properties: (1) number of particles present; (2) size of particles; (3) shape of particles; and (4) hardness of the particles. It is worth noting that some characteristics may be absent and should be given a score of 0. For example, the fracturability scale and viscosity scale are mutually exclusive. If a food is fracturable, it is a brittle solid and is not a liquid. A food that has a fracturability component will have no viscosity component. Conversely, viscosity refers to liquid foods that have no fracturability, so if a product is given a score on the viscosity scale the fracturability score will be zero.

2. *Masticatory*. The second or masticatory phase is performed by placing a piece of food between the teeth and chewing at a standard rate, approximately

60 chews per minute, and determining the mechanical properties of gumminess, chewiness, and adhesiveness, and also assessing any geometrical and other characteristics that appear during chewing. As noted above, chewiness may be graded on the 1–7 scale or it can be listed simply as the total number of chews to swallowing. There will always be a score for chewiness of solid foods. If gumminess and adhesiveness are absent, they should be given a score of 0.

Chewiness is used for solid foods and gumminess for semisolid foods. However, some foods, e.g. crackers and cake, become semisolid during mastication. In these cases, chewiness is reported early, and gumminess late in the masticatory cycle.

3. *Residual characteristics*. The third or residual phase measures the changes induced in chemical, mechanical, geometrical, and all the characteristics throughout the course of mastication up to the completion of swallowing. These are divided separately into the rate of breakdown, type of breakdown, moisture absorption, and mouth coating. In the two previous phases (initial and masticatory), numbers are used to describe the mechanical characteristics and words or phrases are used to describe geometrical and chemical characteristics. In contrast, in the residual phase, numbers are rarely used but phrases and short sentences are used to describe these residual characteristics. To the person who has only read about sensory profiling, the residual characteristics may seem to be of minor importance. In fact, the parameters developed in the residual characteristics are one of the most important aspects of texture profile analysis. The fact that these parameters cannot have numbers assigned to them should not be interpreted as a sign of minor importance. These characteristics are usually impossible to duplicate in instrumental tests. The residual characteristics section of the texture profile is the section where textural parameters are least likely to be measured or detected by any instrumental method. It is an essential part of the total texture profile procedure.

When the panel has completed the basic texture profile ballot for a food, the leader asks each person in turn to call out the scores they have written on their sheet and these scores are written on the board for the rest of the panel to see. Then the leader and the panel examine the scores together. Whenever the score for any parameter that has a standard rating scale varies by more than ± 0.2 of a point, the leader and the panelists discuss the problems that were experienced. After discussing the situation with the other panelists and leader, the panelists repeat that section of the ballot and by means of discussion and repeated testing generally reach a consensus. For those parameters for which words, phrases, or sentences are used, the panelists discuss among themselves any differences and by tasting and discussion (led by the leader) reach a consensus. The sampling–discussion–reference to standard scales–sampling–discussion sequence continues until a consensus or near consensus has been reached. Occasionally one panelist will not agree with the rest of the panelists. The score of that panelist is rejected from the final report. At first

glance this seems to be a nonscientific approach to reject some of the data, but since the texture profile is built around the concept of consensus following adequate discussion, an out-of-line datum must be rejected if it deviates far from the consensus. However, before it is rejected that panelist must be allowed to explain the reason for their odd score. It sometimes happens that this person has experienced a sensation that the others have missed, but recognize it after it has been explained, in which case that sensation is added to the score sheet.

Figure 7.2 shows a basic texture profile ballot for meatballs, and Fig. 7.3 shows a basic texture profile ballot for soda crackers, two products with entirely different textures.

The following similarities and differences between these two foods during the mastication sequence are found by comparing Figs 7.2 and 7.3.

1. *Initial*. Mechanical characteristics show that soda crackers have a little more hardness than the Swedish meatballs and more fracturability, but viscosity is absent in both commodities. Geometrical properties of the crackers are flaky and puffy whereas the meatballs are lumpy with a grainy surface. Other characteristics show that the crackers are dry whereas the Swedish meatballs are moist. The surface of the meatball is slippery, but the uncut surface is not slippery.
2. *Masticatory*. Mechanical characteristics indicate the soda crackers have no gumminess, whereas the meatballs have a gumminess of 1.2. The number of chews for mastication is approximately the same for both commodities and both have a small amount of adhesiveness. The geometrical characteristics of the soda crackers continue to be flaky whereas the meatballs are coarse and grainy and fibrous particles begin to be felt. Other characteristics show that the soda crackers continue to be dry and the meatballs continue to be moist.
3. *Residual sensations*. The rate of breakdown is high for soda crackers. The meatballs break down fast, forming grains that break down at a medium rate. In the type of breakdown, the crackers break down into little rough sheets that change into a smooth dough, whereas the meatballs become a nonhomogenous paste that is grainy and the grain size steadily decreases; some stringy fibrous grains are present but become more noticeable toward the end and require more effort to chew. With moisture absorption, the soda crackers absorb a lot of saliva at a slow rate and gradually change into a moist dough; the saliva mixes easily with the Swedish meatballs to form a slurry, and the bolus becomes progressively more moist, leaving residual grains that feel dry. With mouth coating little pieces of cracker stick to the mouth and gums; there is some slight residual oiliness with the meatballs, and a few fibrous particles stick between the teeth and around the mouth.

These two foods, although very different in nature, have many similarities in the texture profile for the initial and masticatory phases. The major differences between these two commodities show up in residual sensations, illustrating their importance in the texture profile.

Figure 7.2 The basic texture profile score sheet for meatballs.

Basic Texture Profile Ballot for Meatballs

Product: *Swedish meat balls* Date: Name:

I. *INITIAL (perceived on first bite)*
- (a) Mechanical
  - Hardness 3.4
  - Fracturability 0.7
  - Viscosity *Not applicable*
- (b) Geometrical *Lumps, with a grainy surface*
- (c) Other characteristics *Moist, uncut surface is slippery and cut surface is not slippery*

II. *MASTICATORY (perceived during chewing)*
- (a) Mechanical
  - Gumminess 1.2
  - Chewiness 17.7 *chews*
  - Adhesiveness 1.2
- (b) Geometrical *Coarse, grainy, some fibrous particles present*
- (c) Other characteristics *Moist*

III. *RESIDUAL (changes induced during mastication and swallowing)*

Rate of breakdown – *Large lumps break down fast. Grains break down at a medium rate.*

Type of breakdown – *Lumps turn into a nonhomogeneous paste that is grainy, and grain size decreases. Some stringy fibrous grains are present that become more noticeable towards the end and require more effect to chew.*

Moisture absorption – *Initially moist. Saliva mixes easily with slurry and the bolus becomes progressively more moist. Residual grains feel dry.*

Mouth coating – *Slight residual oilness. A few fibrous particles stick between the teeth and around the mouth.*

Figure 7.3 The basic texture profile score sheet for soda crackers.

Basic Texture Profile Ballot for Soda Crackers

Product: *Soda Crackers* Date: Name:

I. *INITIAL (perceived on first bite)*
- (a) Mechanical
  - Hardness 4.0
  - Fracturability 2.5
  - Viscosity *Not applicable*
- (b) Geometrical *Flaky and puffy*
- (c) Other characteristics *Dry*

II. *MASTICATORY (perceived during chewing)*
- (a) Mechanical
  - Gumminess 0
  - Chewiness 16
  - Adhesiveness 0.7
- (b) Geometrical *Flaky*
- (c) Other characteristics *Dry*

III. *RESIDUAL (changes induced during mastication and swallowing)*

Rate of breakdown – *High.*

Type of breakdown – *In the beginning it breaks down into little rough sheets, then it changes into a smooth dough.*

Moisture absorption – *It absorbs a lot of saliva slowly and changes into a moist dough.*

Mouth coating – *Little pieces stick to the mouth and gums.*

Developing the Comparative Texture Profile Analysis Ballot

The final step in texture profile analysis is to develop from the standard score sheets a comparative texture profile ballot for each commodity. The basic ballot can be used for any commodity. Each comparative ballot is especially designed for a particular commodity and enables one to identify and quantify small differences in textural properties of similar materials caused by differences in quality of ingredients, formulation, storage, or processing. In the comparative ballot one material is selected as the 'target' material whose textural properties are desirable to reproduce. It acts as the control and is assigned a score of zero for every textural parameter.

A basic texture profile ballot for arepa is shown in Fig. 7.4, and a comparative ballot is shown in Fig. 7.5. These should be referred to frequently in the following discussion. Arepa is a corn-based staple food that is widely used in Colombia and other countries in Latin America. The textural properties that have been identified during the initial, mastication, and residual phases are listed in the order of appearance and the experimental samples are graded equal to, less than, or greater than the control sample in that particular quality factor. The control in this case was arepa made fresh each day by the traditional village method (Bourne *et al*., 1975). The grading is made semiquantitative by grading from 1 to 5 plus and 1 to 5 minus. One plus means that the sample is slightly greater than the control in that particular textural property; five plus means it is much greater than the control in that particular textural property. The minus score is used to indicate slightly less than to much less than the control sample.

The comparative texture profile ballot identifies those formulations and processing variables that bring the experimental samples closer to the target. It is definitely the best technique for identifying desirable textural properties and eliminating undesirable textural properties in product formulation and measuring deviations in texture from a control, standard sample or a competitor's product. A study of Figs 7.4 and 7.5 shows that 28 different textural characteristics were derived from the basic texture profile ballot. These figures show how complete a texture analysis can be developed by a trained sensory panel. There is no instrumental method or group of methods available that could give as complete an analysis of texture profile as is seen in Fig. 7.5.

Figure 7.6 shows the results from comparative texture profile for meatballs that was developed from the basic ballot shown in Fig. 7.2. The target product was Swedish meatballs made from pure ground beef and it was given a score of 0 for every texture note listed in Fig. 7.6. Initial sensations list the mechanical properties of hardness and fracturability whereas viscosity does not appear. Geometrical properties list lumpiness and scratchiness of the grains; and other characteristics list slipperiness of the uncut surface and moistness. Masticatory sensations list the mechanical properties of gumminess, chewiness, and adhesiveness; geometrical properties list coarseness, graininess, and

Figure 7.4 The basic texture profile score sheet for arepa. (From Bourne *et al.*, 1975. Reprinted from *J. Texture Studies* 6, page 50, 1975, with permission of Food and Nutrition Press.)

BASIC TEXTURE PROFILE SHEET FOR AREPA

Product: *Arepa de Peto* Date: Name:

I. *INITIAL (perceived on first bite)*
- (a) Mechanical
  - Hardness 4.2
  - Fracturability 2.5
  - Viscosity 0
- (b) Geometrical *Tough skin and coarse center. Sandwich-like structure with thin tough skin and doughy matrix. Black patches are crispy and located only on the surface*
- (c) Other characteristics *Dry surface and moist center*

II. *MASTICATORY (perceived during chewing)*
- (a) Mechanical
  - Gumminess 0
  - Chewiness 16
  - Adhesiveness 0.5
- (b) Geometrical *Surface is coarse and center is doughy with little pieces*
- (c) Other characteristics *Dry surface and moist center*

III. *RESIDUAL (changes induced during mastication and swallowing)*

Rate of breakdown – *Moderate.*

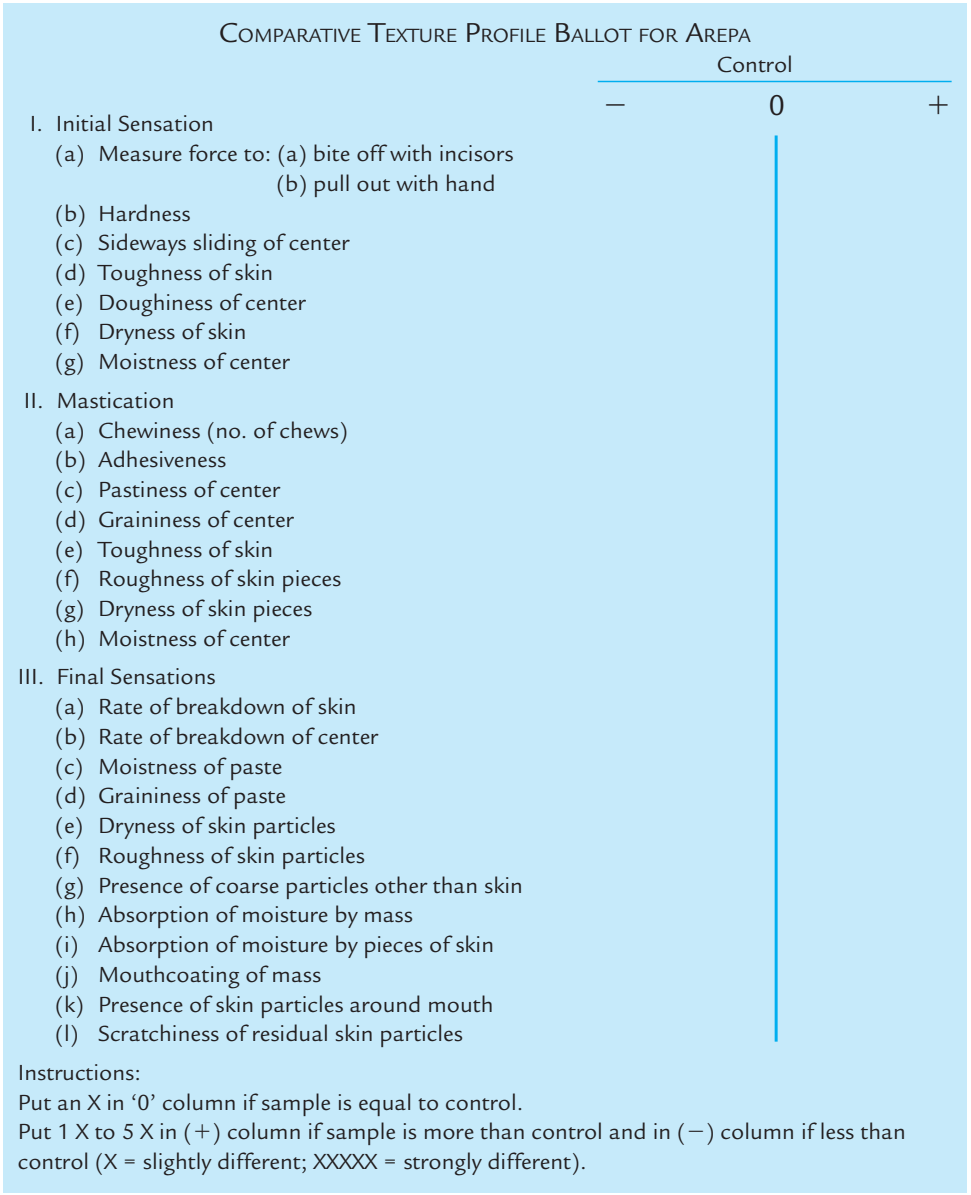
Type of breakdown – *Skin breaks in little sheets. Center breaks in little pieces to form a nonuniform dough.*

Moisture absorption – *Center absorbs moisture more quickly than the surface. Bolus has some little, hard and rough pieces.*

Mouth coating – *Little pieces leave a coating in the mouth, especially on the gums and teeth. After swallowing, the mouth is dry.*

amount of fibrous grains; and other characteristics list moistness. Residual sensations are listed under the rate of breakdown heading, the rate of breakdown of the grains, and rate of loss of cohesiveness between the particles; under type of breakdown heading are listed the homogeneity of the bolus, appearance of stringy fibrous grains, and chewiness of the fibrous grains; under moisture absorption heading are listed dryness of residual grains, and ease of mixing of saliva and slurry; under the mouth coating heading are listed oily mouth coating, presence of residual fibrous particles, and presence of residual sandy particles.

The right-hand side of Fig. 7.6 plots the texture profiles of fish balls against meatballs. Sample X is made from fish instead of beef. Sample O is fish balls in which 10% of the fish was replaced with textured soy protein. The figure shows that the fish balls have lower hardness, higher fracturability, less lumpiness, more scratchiness of the grains, less slipperiness, and more moistness than the meatballs in the initial sensations; less gumminess, chewiness, adhesiveness, and coarseness than the meatballs, more graininess, less amount of fibrous grains, and higher moistness in the masticatory phase; a higher rate of breakdown of the lumps, a higher rate of breakdown of the grains, a higher rate of loss of cohesiveness between the particles, and a higher homogeneity of the bolus in residual sensations. The fish balls have fewer stringy fibrous grains, lower chewiness, and less dryness than the meatballs. The fish balls



Comparative Texture Profile Ballot for Arepa

	Control		
	−	0	+
I. Initial Sensation			
(a) Measure force to: (a) bite off with incisors (b) pull out with hand			
(b) Hardness			
(c) Sideways sliding of center			
(d) Toughness of skin			
(e) Doughiness of center			
(f) Dryness of skin			
(g) Moistness of center			
II. Mastication			
(a) Chewiness (no. of chews)			
(b) Adhesiveness			
(c) Pastiness of center			
(d) Graininess of center			
(e) Toughness of skin			
(f) Roughness of skin pieces			
(g) Dryness of skin pieces			
(h) Moistness of center			
III. Final Sensations			
(a) Rate of breakdown of skin			
(b) Rate of breakdown of center			
(c) Moistness of paste			
(d) Graininess of paste			
(e) Dryness of skin particles			
(f) Roughness of skin particles			
(g) Presence of coarse particles other than skin			
(h) Absorption of moisture by mass			
(i) Absorption of moisture by pieces of skin			
(j) Mouthcoating of mass			
(k) Presence of skin particles around mouth			
(l) Scratchiness of residual skin particles			

Instructions:
Put an X in '0' column if sample is equal to control.
Put 1 X to 5 X in (+) column if sample is more than control and in (−) column if less than control (X = slightly different; XXXXX = strongly different).

Figure 7.5 Comparative texture profile score sheet for arepa. (From Bourne *et al.*, 1975, reprinted from *J. Texture Studies* 6, page 51, 1975, with permission of Food and Nutrition Press.)

mix with saliva to form a slurry better than the meatballs, have less oily mouth coating, less residual fibrous particles, but more residual sandy particles.

The product in which 10% of the fish was substituted with soy protein has a similar texture profile to the one made entirely from fish; however, there are a few exceptions, namely, the substitution of the soy gives a product that has higher moistness, chewiness, adhesiveness, graininess, and amount of fibrous grains, and less sandy particles. If this were a project in product development, various other formulations and processing variables would be tried; in each case the changes in the texture profile would be noted, particularly whether the change in formulation or processing brought the experimental sample closer to the target or further away from the target with certain textural properties.

Figure 7.6 Comparative texture profile score sheet for meatballs and fish balls. Unpublished data from M. C. Bourne.

COMPARATIVE TEXTURE PROFILE FOR MEATBALLS AND FISH BALLS

I. INITIAL SENSATIONS
- (a) hardness
- (b) fracturability
- (c) lumpiness
- (d) scratchiness of grains
- (e) slipperiness (uncut surface)
- (f) moistness

II. MASTICATORY
- (g) gumminess
- (h) chewiness
- (i) adhesiveness
- (j) coarseness
- (k) graininess
- (l) amount of fibrous grains
- (m) moisture

III. RESIDUAL SENSATIONS
- (n) rate of breakdown of lumps
- (o) rate of breakdown of grains n.a.
- (p) rate of loss of cohesiveness between particles
- (q) homogeneity of bolus
- (r) appearance of stringy, fibrous grains
- (s) chewiness of fibrous grains x = n.a.
- (t) dryness of residual grains
- (u) ease of mixing of saliva and slurry
- (v) oily mouthcoating
- (w) residual fibrous particles
- (x) residual sandy particles

Swedish meatballs were used as control. Sample 'X' is fish balls. Sample 'O' is fish balls with 10% replacement of fish with soya protein.

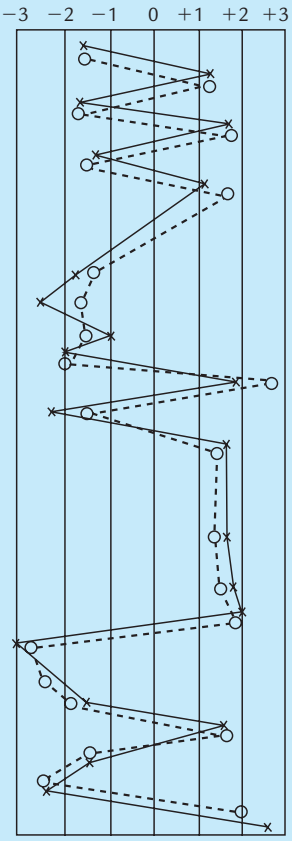


Figure 7.7 shows a texture profile ballot developed for cooked rice. This is a particularly difficult food for TPA, probably because (a) rice is a staple and people become very sensitive to small differences in textural properties of foods that are consumed frequently and in large quantities; (b) rice has a bland flavor and bland flavors usually increase the attention given to textural properties.

The examples listed above show how the basic texture profile technique can be extended to cover all commodities by suitable adaptation.

Variations on Sensory Texture Profile Analysis

For certain purposes it may not be necessary to use the entire texture profile. The parameter of interest might be simply chewiness, in which case only the chewiness part of the texture profile would be performed. For example, Harrington and Pearson (1962) used a panel to measure chew count for

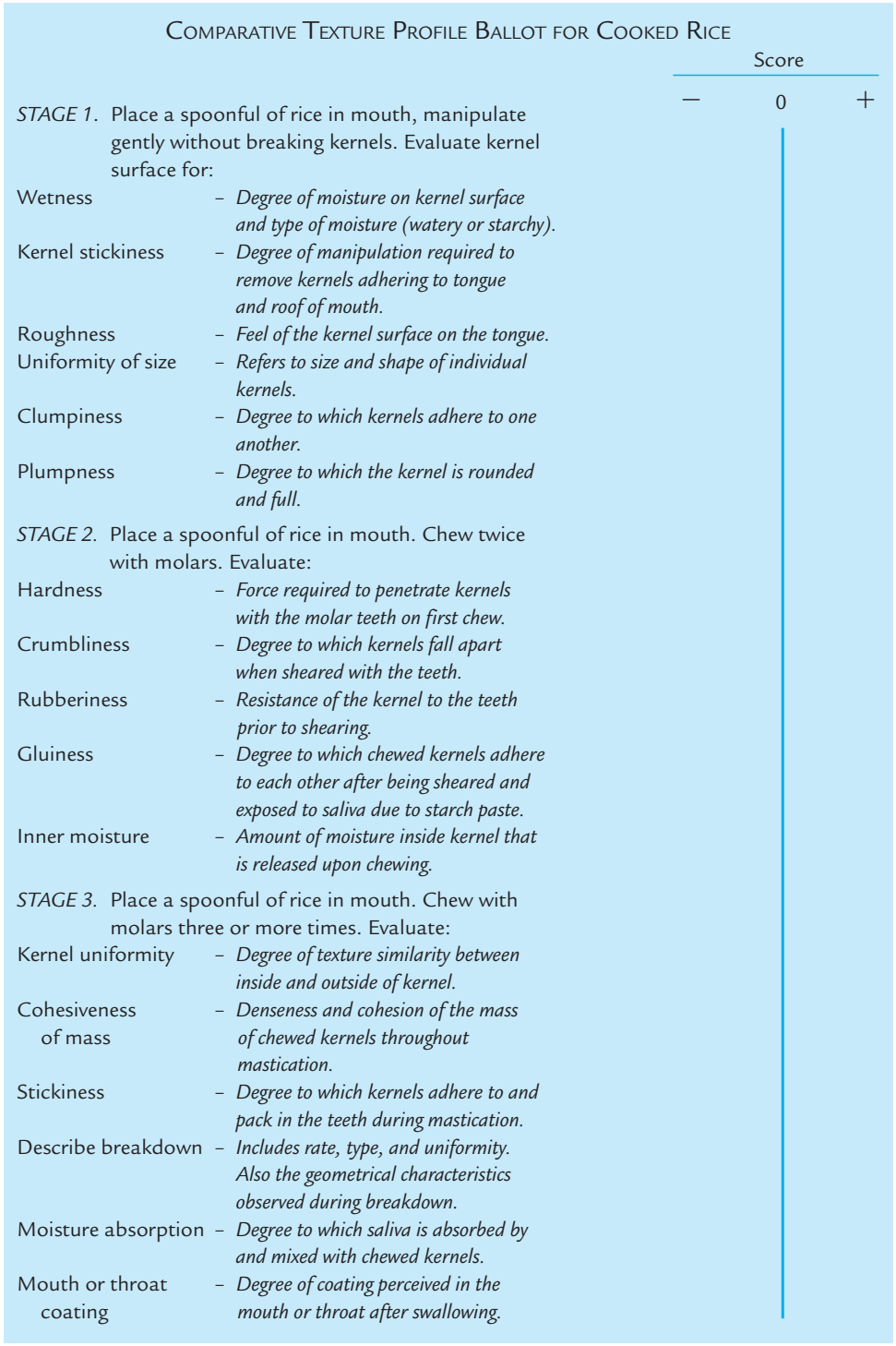


Figure 7.7 Comparative texture profile score sheet for cooked rice. (Courtesy of Dr A. S. Szczesniak.)

measuring the tenderness of pork loins with various degrees of marbling and found a good correlation between chew count and Warner–Bratzler shear readings. In contrast, Cover *et al*. (1962) used a panel to evaluate the juiciness of beef and six components of tenderness: softness to the tongue and cheek, softness to tooth pressure, ease of fragmentation across the grain, mealiness, apparent adhesions between fibers, and connective tissue.

Szczesniak (1979) reported that for fluid foods such as beverages a deeper analysis is required than that obtained by the single parameter of viscosity that appears in the standard texture profile analysis. Table 7.10 lists the classification of sensory mouthfeel terms, typical descriptive words, and examples, as developed by Szczesniak (1979).

Table 7.10 Classification of Sensory Mouthfeel Terms of Beverages

Category	Responses (% total)	Typical words	Beverages that have this property	Beverages that do not have this property
Viscosity-related terms	30.7	Thin	Water, iced tea, hot tea	Apricot nectar, milk shake, buttermilk
		Thick	Milk shake, eggnog, tomato juice	Club soda, champagne, drink made from dry mix
Feel on soft tissue surfaces	17.6	Smooth	Milk, liqueur, hot chocolate	—
		Pulpy	Orange juice, lemonade, pineapple juice	Water, milk, champagne
		Creamy	Hot chocolate, eggnog, ice cream soda	Water, lemonade, cranberry juice
Carbonation-related terms	11.2	Bubbly	Champagne, ginger ale, club soda	Prune juice, iced tea, lemonade
		Tingly	Ginger ale, champagne, club soda	Instant orange, hot tea, coffee
		Foamy	Beer, root beer, ice cream soda	Cranberry juice, lemonade, water
Body-related terms	10.2	Heavy	Milk shake, eggnog, liqueur	Water, lemonade, ginger ale
		Watery	Bouillon, iced tea, hot tea, drink made from dry mix	Milk, V-8 juice, apricot nectar
		Light	Water, iced tea, canned fruit drink	Buttermilk, hot chocolate, V-8 juice
Chemical effect	7.3	Astringent	Hot tea, iced tea, lemonade	Water, milk, milk shake
		Burning	Whiskey, liqueur	Milk, tea, drink made from dry mix
		Sharp	Prune juice, pineapple juice	Water, hot chocolate, canned fruit drink
Coating of oral cavity	4.5	Mouth coating	Milk, eggnog, hot chocolate	Water, apple cider, whiskey
		Clinging	Milk, milk shake, ice cream soda, liqueur	Water, ginger ale, bouillon
Resistance to tongue movement	3.6	Slimy	Prune juice, milk, light cream	Water, ginger ale, champagne
		Syrupy	Liqueur, apricot nectar, root beer	Water, milk, club soda
Afterfeel–mouth	2.2	Clean	Water, iced tea, wine	Buttermilk, beer, canned fruit drink
		Drying	Hot chocolate, cranberry juice	Water
		Lingering	Hot chocolate, light cream, milk	Water, iced tea, club soda
		Cleansing	Water, hot tea	Milk, pineapple juice, V-8 juice
Afterfeel–physiological	3.7	Refreshing	Water, iced tea, lemonade	Buttermilk, prune juice, hot chocolate
		Warming	Whiskey, liqueur, coffee	Lemonade, champagne, iced tea
		Thirst quenching	Coca-Cola, water, drink made from dry mix	Milk, coffee, cranberry juice
Temperature-related	4.4	Cold	Ice cream soda, milk shake, iced tea	Liqueur, hot tea
		Cool	Iced tea, water, milk	Eggnog
		Hot	Hot tea, bouillon, whiskey	Ginger ale, lemonade, iced tea
Wetness-related	1.3	Wet	Water	Milk, coffee, apple cider
		Dry	Lemonade, coffee	Water

Source: Szczesniak (1979); reprinted with permission of Academic Press Inc. (London) Ltd.

In a similar vein, Civille and Liska (1975) developed a sensory texture profiling technique for semisolid foods (see Table 7.11). They expanded the order of appearance from three stages into five stages:

Stage 1. Manipulate the semisolid food without compressing and evaluate heaviness, wetness, wetting and slipperiness.
Stage 2. Compress partially against the palate two times and evaluate firmness, bounciness, gumminess and spread.
Stage 3. Compress completely between the tongue and hard palate and evaluate spread, firmness, airiness and cooling.
Stage 4. Manipulate with the tongue back and forth at one manipulation per second and evaluate adhesiveness, smoothness, rate of disappearance,

Table 7.11 Sensory Texture Profiling Technique and Definition of Terms for Semisolid Foods

Stage I	Place a rounded teaspoonful of product in the mouth; manipulate without compressing or breaking *Evaluate for*: – *Heaviness*: weight of product as perceived when the product is first placed on the tongue – *Wetness*: degree of moisture on the surface (moisture) – *Wetting*: degree of which the product wets down with saliva (moisture absorption) – *Slipperiness*: degree to which the tongue can slide under the product (oil/fat, adhesiveness)
Stage II	Place a fresh spoonful of product in the mouth; compress partially against the palate, release, and repeat *Evaluate for*: – *Firmness*: force to compress partially (hardness) – *Bounciness*: resilience; degree to which the sample returns to the original shape (elasticity) – *Gumminess*: degree of cohesiveness (cohesiveness) – *Spread*: degree to which the product spreads over the tongue (viscosity/gumminess, adhesiveness)
Stage III	Place a spoonful of product in the mouth; compress completely between tongue and palate *Evaluate for*: – *Spread*: degree to which the product spreads over tongue (viscosity/gumminess, adhesiveness) – *Firmness*: amount of force required to compress fully (hardness) – *Airiness*: amount of air in the product perceived as very small bubbles (geometrical-aerated) – *Cooling*: thermal effect on the tongue (thermal mouthfeeling)
Stage IV	Place a spoonful in the mouth; move tongue back and forth at one manipulation per second *Evaluate for*: – *Adhesiveness*: force required to remove the material that adheres to the mouth (adhesiveness) – *Smoothness*: absence of any particles in the product (geometrical) – *Rate of disappearance*: time required for breakdown (gumminess, moisture absorption, thermal reaction) – *Abruptness of disappearance*: manner in which the change from semisolid to liquid occurs; range is from gradual to abrupt (thermal reaction, moisture absorption, gumminess) – *Uniformity of disappearance*: degree to which the product remains uniform throughout the breakdown (geometrical) – *Type of disappearance*: description of changes occurring during the breakdown (description of breakdown) – *Mouthcoating*: type and degree of coating in the mouth after manipulation (geometrical, fat/oil)
Stage V	After manipulation and breakdown; swallow the product *Evaluate for*: – *Ease of swallow*: degree to which the broken-down product can be readily swallowed (geometrical, gumminess) – *Fluidity*: degree to which the product is a thin liquid (gumminess/viscosity)

Source: Civille and Liska (1975). Reprinted from *J. Texture Studies* **6**, page 26. Copyright by Food and Nutrition Press Inc.

abruptness of disappearance, uniformity of disappearance, type of disappearance and mouth coating.

Stage 5. Swallow the product and evaluate ease of swallow and fluidity.

Sensory TPA by Consumer Panels

The previous discussion dealt with the operation of an expert trained panel for texture profile analysis. Szczesniak *et al*. (1975) simplified this procedure to the point where it can be used by untrained consumer panels. The procedure is based on the original sensory texture profiling technique (Brandt *et al*., 1963; Szczesniak *et al*., 1963) and on popular texture terminology as determined in surveys (Szczesniak and Skinner, 1973).

A list of descriptive texture terms for the commodity of interest is compiled by a trained texture profile panel and used to prepare a ballot. A typical ballot is shown in Fig. 7.8. Texture terms are listed in random order in the left-hand column. The consumers check one of six boxes alongside each word to indicate the degree to which they feel this sample has the texture characteristic described by that term, ranging from 'not at all' to 'very much so.' Some antonyms are included in the list of words as an internal check that the respondents understand the meaning of the words. For example, since 'soft' and 'hard' convey bipolarity, a sample that is rated high on softness should rate low on hardness, and vice versa. A few comparative terms such as 'good' and 'bad'

Instructions: Here is a list of terms commonly used to describe texture, that is, how foods feel in the mouth. Using these terms, we would like you to describe the texture of this sample. To do this, please check one of the six boxes along the side of each term to indicate the degree to which you feel this sample has the texture characteristic described by that term. It is very important to our test that you make a choice for each term.

	Not at all					Very much so
Crisp	■	□	□	□	□	■
Soft	□	□	□	□	□	□
Airy	□	■	□	□	□	□
Brittle	□	□	□	□	□	□
Chunky	□	□	■	■	■	□
Flaky	■	□	□	□	□	□
Soggy	□	□	□	□	□	□
Dry	□	□	□	□	□	□
Bad	□	□	□	□	□	□
Chewy	□	□	□	□	□	□
Crunchy	□	□	□	□	□	□
Hard	□	□	□	□	□	□
Slippery	□	□	□	□	□	□
Doughy	□	□	□	□	□	□
Good	□	■	□	□	□	□
Gritty	■	□	□	□	□	■

Figure 7.8 Typical consumer texture profile score sheet for cold cereals. (From Szczesniak *et al.*, 1975. Reprinted from *J. Food Sci*. **40**, 1253, 1975. Copyright by Institute of Food Technologists.)

are included in order to obtain an overall measure of textural quality. This technique has proved successful for a variety of foodstuffs in both central location and home use situations (Szczesniak *et al*., 1975).

Repeatability

With a properly trained panel, the sensory texture profile analysis method produces data than can be reproduced in the same location at different times and in different locations with different panels. Figure 7.9 shows the texture profile for whipped toppings developed by a panel in Scarsdale, New York and the profile for the same product developed by a different panel in Indianapolis, Indiana (Szczesniak *et al*., 1975). The close match between the two

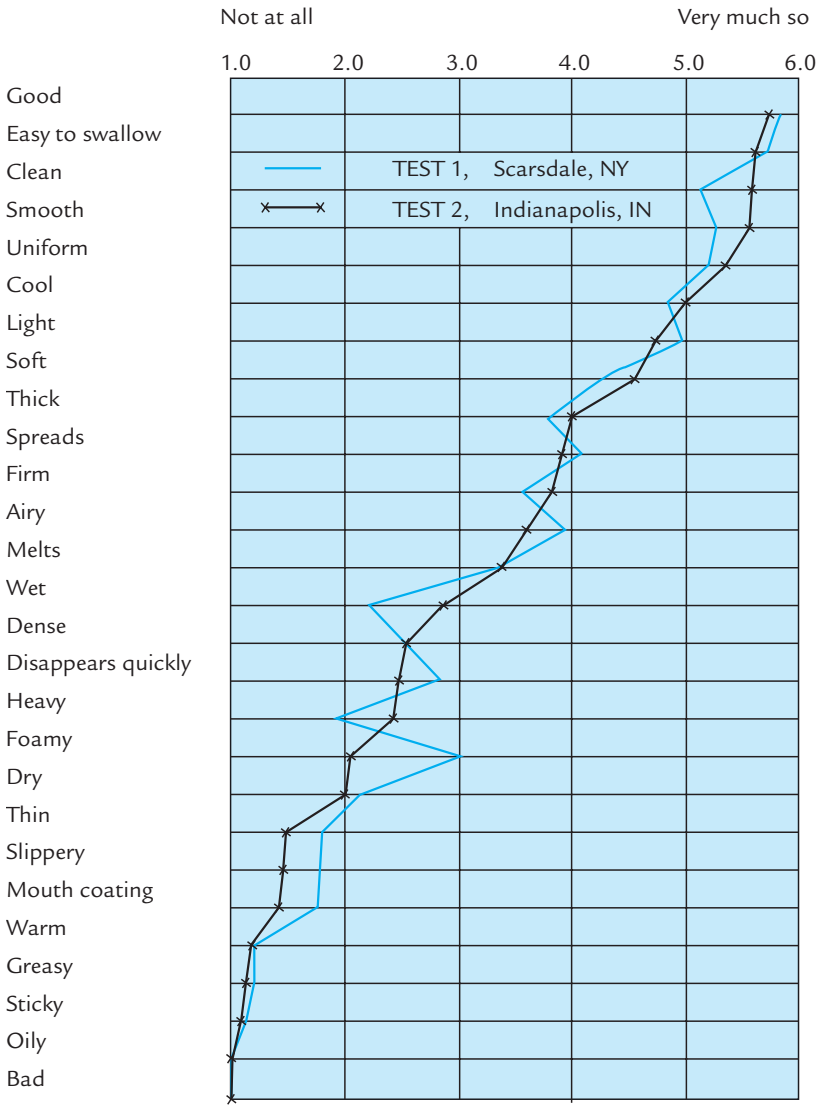


Figure 7.9 Consumer texture profile of whipped toppings done by two separate panels in two locations. Note the high degree of reproducibility of the test. (From Szczesniak *et al*., 1975. Reprinted from *J. Food Sci*. **40**, 1256, 1975. Copyright by Institute of Food Technologists.)

panels clearly demonstrates the reproducibility of the procedure. Szczesniak *et al*. (1975) also showed that a group can reproduce their score on the same product even when the second test was conducted 16 months after the first test.

The Texture Profile as an Objective Method

Texture profiling is, without question, a sensory method, but this does not necessarily mean that it is a subjective method. The word 'subjective' has the connotation that the personal feelings, biases, and previous experiences of the judge play a major role in the results that are obtained. A subjective method measures an individual's response to the test material; that is, the data are some complex combination of the properties of the test material and the personal characteristics of the judge, and both factors carry considerable weight in the results.

In contrast, an objective method is usually thought of as an instrumental or chemical method. This concept of an objective method may not be always correct. The true characteristics of an objective method are (1) that the data obtained are independent of the individual observer; that is, the result is fair, impartial, factual, and unprejudiced by the personal characteristics of the observer; (2) that the results are repeatable and verifiable by others; that is, other laboratories can obtain the same results within the limits of experimental error.

The author believes that a properly trained texture profile panel is objective, not subjective, because the texture profile method complies with the two criteria of objectivity enunciated above.

(1) Freedom from personal bias. The data obtained are partly quantitative and partly descriptive, but always objective because the panel is trained to take an analytical approach and use intensity scaling, not acceptability scaling. The members of the panel are trained to observe and record data, not allowing their personal likes and dislikes to influence their results.

(2) Repeatability. Results from different panels are reproducible to a high degree as discussed under the previous heading. The author has seen a panel produce a texture profile on a product one week and then reproduce that profile a week later in the absence of the previous data, on a product they were led to believe was different but was not. He has personal experience with a panel in Ithaca, New York, and another panel in Bogota, Colombia, who gave substantially identical texture profiles for the same food.

The texture profile technique passes the tests of impartiality and reproducibility and should, therefore, be considered as an objective method. It trains a small group of people to use their mouth as a scientific instrument, similar to a balance or a pH meter. The advantages of the texture profile technique over other objective methods are that this particular scientific instrument (the trained mouth) can measure a number of textural parameters that

can be measured by no instrument at the present time, and, in many instances, it can measure a given textural parameter with greater sensitivity than an instrument.

Modifications to Sensory Texture Profile Analysis

Many are under the impression that the original sensory texture profile analysis developed by Dr Szczesniak's group in the early 1960s is a rigid and unchangeable procedure. This is not correct. It is a flexible method that can be adapted to accommodate different geographical areas, different foods, and different cultures. It can also be expanded to encompass textural sensations not described in the original procedure.

In reviewing texture profile analysis ten years after it was first announced, Szczesniak (1975c) noted that some people assume the originally published examples must be adhered to very strictly. She pointed out that although much work went into the selection of foods representing various points on the scales it was realized from the beginning that:

(1) these foods may not be available in other parts of the world;
(2) some of them would become unavailable in the future;
(3) the intensity of their textural properties may change because of changes in raw materials or changes in manufacturing processes.

Table 7.8 is an example of how the standard rating scales established in New York were modified for Bogota, Colombia. Mogen David frankfurters were assigned a hardness scale of 3 in New York, but Suiza frankfurters were assigned a score of 4 because no frankfurters could be found with similar hardness to Mogen David frankfurters in Bogota. However, a local cream cheese, Ubaté, was assigned a hardness score of 3 in Bogota because it was found to be intermediate between cooked egg white and Suiza frankfurters.

For the viscosity scale, sucrose syrups were used in Bogota because the creams and evaporated milk used in New York were not available. The standard viscosity scale in Bogota was shortened to seven points instead of the eight points used in New York. Mayonnaise was not used in Bogota because this is a non-Newtonian fluid with a yield stress and it was thought that the standard scale would be easier to grasp by the panel if all the standards were Newtonian fluids.

The standard gumminess scale in New York is a six-point scale that uses mixtures of Gold Medal flour and water ranging from 40% flour + 60% water to 60% flour + 40% water. When a sample of Gold Medal flour from New York was taken to Bogota and compared with local flour it was found that the local flour was not quite the same. Therefore, the standard gumminess scale in Bogota used the local flour with concentrations ranging from 41% flour

+ 59% water to 57% flour + 43% water in increments of 4% instead of the 5% increments used in New York (see Table 7.8, page 265).

Muñoz (1986) gives examples of changes in the foods used in standard scales in New Jersey because some of the items used more than 20 years earlier in New York were not available or the textural quality had changed over the years.

Some standards are likely to be constant from one geographical area to another. For example, cooked egg whites, peanuts, and carrots that appear in the original hardness scale are not manufactured products and are unlikely to change to any great degree over time or place. These make useful international reference standards that can help anchor the hardness scale.

Muñoz (1986) added scales for denseness, wetness, adhesiveness to lips, roughness, self-adhesiveness and springiness which are shown in Tables 7.12–7.17. Szczesniak and Ilker (1988) formulated a tentative scale for sensory juiciness which is shown in Table 7.18.

It should be noted that the size of the samples presented to a panel is part of the standard scale and must be kept constant because sample size can affect the panel's judgment (Cardello and Segars, 1989).

The sensory texture profiling technique developed by Dr Szczesniak's group at the General Food Corporation was the first all-encompassing method applied to texture. It followed the principles developed by the Arthur D. Little Corp. for flavor profiling. Other programs have since been developed that include texture profiling including Spectrum™ Descriptive Analysis, Quantitative Descriptive Analysis (QDA) which relies heavily on statistical analysis, and Free Choice Profiling (Marshall and Kirby, 1988). These methods include evaluation of all attributes including general appearance, color, texture, flavor and aroma.

Sensory texture profiles for a number of other foods are given in the tables in Appendix IV. These tables demonstrate both the power of the sensory texture profile method and its adaptability to any food or beverage.

Table 7.12 Denseness Reference Scale

Scale value	Product	Type/brand	Manufacturer/ distributor	Sample size	Temperature
0.5	Whipped topping	Cool Whip, nondairy	General Foods Corp.	1 tsp	40–45°F
2.5	Marshmallow topping	Fluff	Durkee Mower	1 tsp	Room
4.0	Nougat	Three Musketeers, chocolate cover removed	M&M Mars	½-in. cube	Room
6.0	Malted milk balls	Whoppers	Leaf Confectionery, Inc.	One piece	Room
9.0	Frankfurter[a]	Beef Franks, cooked 5 min in boiling water	Oscar Mayer Foods Corp.	½-in. slice	Room
13.0	Fruit jellies	Chuckles	Nabisco Brands	Half a piece	Room

Source: Muñoz (1986). Reprinted from *J. Sensory Studies* **1**, page 67. Copyright by Food and Nutrition Press Inc.
[a]Area compressed with molars is parallel to cut.

Table 7.13 Wetness Reference Scale

Scale value	Product	Type/brand	Manufacturer/ distributor	Sample size	Temperature
0	Cracker	Premium, unsalted tops, low sodium	Nabisco Brands	One piece	Room
3.5	Carrot[a]	Uncooked, fresh, unpeeled	—	½-in. slice	Room
7.5	Apple[a]	Red Delicious, fresh, unpeeled	—	½-in. slice	Room
10.0	Ham	Smoked, cooked	Oscar Mayer Foods Corp.	½-in. square	40–45°F
12.0	Tomato[a]	Uncooked, fresh, unpeeled	—	½-in. slice	Room
15.0	Water	Filtered	—	1 tsp.	Room

Source: Muñoz (1986). Reprinted from *J. Sensory Studies* **1**, page 69. Copyright by Food and Nutrition Press Inc.
[a]Area contacting lip is parallel to cut.

Table 7.14 Adhesiveness to Lips Reference Scale

Scale value	Product	Type/brand	Manufacturer/ distributor	Sample size	Temperature
0	Tomato	Cherry type, uncooked, fresh, unpeeled	—	One piece	Room
4.0	Nougat	Three Musketeers, chocolate cover removed	M&M Mars	½-in. cube	Room
7.5	Breadstick	—	Stella D'Oro Biscuit Co.	Half a stick	Room
10.0	Pretzel stick	Stix	Bachman Co.	Half a stick	Room
15.0	Rice cereal	Rice Krispies	Kellogg Co.	1 tsp.	Room

Source: Muñoz (1986). Reprinted from *J. Sensory Studies* **1**, page 70. Copyright by Food and Nutrition Press Inc.

Table 7.15 Roughness Reference Scale

Scale value	Product	Type/brand	Manufacturer/ distributor	Sample size	Temperature
0	Gelatin dessert	Jell-O, prepared according to package directions	General Foods Corp.	1 tsp.	40–45°F
5.0	Orange peel[a]	From fresh fruit	—	½-in. square	Room
8.0	Potato chip	Pringle's regular	Procter & Gamble	Half a piece	Room
12.0	Granola bar[b]	Chewy bar	The Quaker Oats Co.	¼-in. square	Room
15.0	Thin bread[b] wafer	Finn Crisp, light, inside part	Schaffer, Clarke & Co.	½-in. square	Room

Source: Muñoz (1986). Reprinted from *J. Sensory Studies* **1**, page 71. Copyright by Food and Nutrition Press Inc.
[a]Use outside surface for evaluation.
[b]Use back of product for evaluation.

Table 7.16 Self-adhesiveness Reference Scale

Scale value	Product	Type/brand	Manufacturer/ distributor	Sample size[a]	Temperature
0	Gummi-bear	Haribo Gold bears	Haribo GMBH & Co.	Two pieces	Room
2.0	Licorice	Shoestring, red laces	E. J. Brach & Sons, Inc.	Two ½-in. pieces	Room
7.5	American cheese	Velveeta, yellow	Kraft	Two ¼-in. cubes	40–45°F
9.0	Rice[b]	Enriched long grain	Pathmark (any local brand)	1 tsp.	Room
15.0	Caramel	Homemade, light	Robinson's Candies	Two ¼-in. cubes	Room

Source: Muñoz (1986). Reprinted from *J. Sensory Studies* **1**, page 72. Copyright by Food and Nutrition Press Inc.
[a]Sample size refers to amount placed in mouth. For sample serving, cover bottom of container with individual pieces, assuring that each one is in contact with the other. Repeat procedure with a second layer. Hold product for three hours before evaluation.
[b]Bring 3¼ cups of water and one cup of rice to a boil. Lower heat, cover and simmer for 40 min.

Table 7.17 Springiness Reference Scale

Scale value	Product	Type/brand	Manufacturer/ distributor	Sample size	Temperature
0	Cream cheese	Philadelphia	Kraft	½-in. cube	40–45°F
5.0	Frankfurter[a]	Beef Franks, cooked 5 min in boiling water	Hebrew National Kosher Foods	½-in. slice	Room
9.0	Marshmallow	Miniature	Kraft	One piece	Room
15.0	Gelatin dessert[b]	Jell-O and Knox gelatin	General Foods Corp. Knox Gelatine Inc.	½-in. cube	40–45°F

Source: Muñoz (1986). Reprinted from *J. Sensory Studies* **1**, page 73. Copyright by Food and Nutrition Press Inc.
[a]Area compressed betwen tongue and palate is parallel to cut.
[b]One package of Jell-O and one package of Knox gelatin, dissolved in 1½ cups of hot water. Cover and refrigerate (40–45°F) for 24 h.

Table 7.18 Scale of Sensory Juiciness (10 = most juicy; all raw)

Product	Ranking
Watermelon/Persian melon	10
Orange	9
Honeydew melon	8
Strawberry	7
Apple	6
Cucumber	5
Tomato wedge	4
Snap bean	3
Mushrooms	2
Carrot	1
Banana	0

Source: Szczesniak and Ilker (1988). Reprinted from *J. Sensory Studies* **1**, page 70. Copyright by Food and Nutrition Press Inc.

Nonoral Methods of Tactile Texture Measurement

Although most of the sensing of texture occurs in the mouth and with the lips, it is possible to measure textural properties outside the mouth, most commonly with the fingers and the hand. It is a common practice to hold foods in the hand or squeeze them or bend them. The food may be squeezed between the forefinger and the opposed thumb or between two, three, or four fingers and the opposed thumb. It may be squeezed by pressing with the whole palm on top of the food, which is resting on a firm surface such as a table, or the two palms may be placed at opposite ends of the food and squeezed. The size of the object frequently determines the method that is used. The forefinger and opposed thumb are generally used for small objects while the entire hand or two hands are used on large objects such as a loaf of bread.

In the squeeze test the fingers sense the distance they move as they apply a force to that food. The fingers are well suited to perform the squeeze test because they are able to sense small distances quite accurately. When the fingers move a greater distance, the food is considered to be soft, and vice versa. Whether firmness is a desirable or undesirable characteristic depends on the food being squeezed. The simple hand squeeze tells a potential customer that there are more leaves in a firm head of lettuce than in a soft head of equal size, that the soft marshmallow is fresh whereas the firm marshmallow is older and probably stale. The squeeze test also enables one to determine the ripeness of many fruits and some vegetables. For elongated products such as licorice sticks and green beans the product is grasped at both ends using two hands and the ease of bending or the distance before snapping occurs is sensed. For fruits such as apples the thumb is pressed onto the fruit until it 'gives' which senses the force required to reach the yield point.

Bourne (1967b) measured how firmly people squeeze foods by hand. Some of his results are shown in Fig. 7.10, which plots the force exerted in successive squeezes on two foods by three individuals. The group of lines marked A were obtained by a young lady squeezing a large fresh cucumber. Notice how uniformly she squeezes each time. This degree of uniformity is unusual. This lady squeezes quite hard: a little over 4 kg at each squeeze. The group of curves marked B shows how hard another person squeezes the same cucumber. There is some change in force exerted from one squeeze to the next. This amount of variation in force exerted from one squeeze to the next is about normal for most people. Operator B squeezed the cucumber at an average force of about 2.5 kg. Operator C squeezed the same cucumber but the force exerted in successive squeezes fluctuated widely. The C type of squeezing pattern is less common than the B pattern.

The series of lines marked D were obtained from operator B squeezing a fresh loaf of bread. There is still about the same amount of variation from one squeeze to the next but the average squeezing force drops from about 2.5 kg

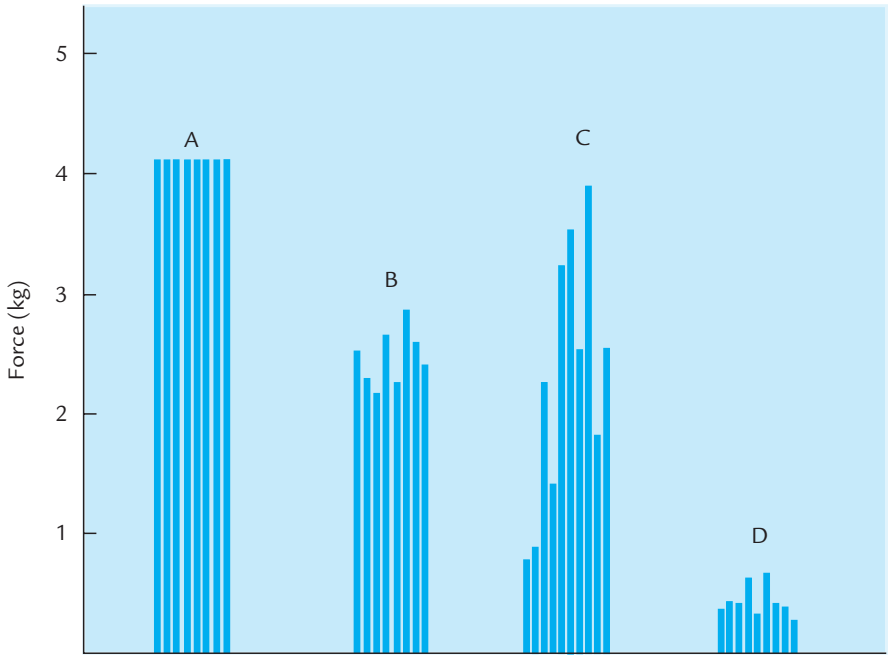


Figure 7.10 Firmness of successive hand squeezes of foods: A, B, C, from three individuals squeezing a whole cucumber; D, individual B squeezing a loaf of fresh bread. (From Bourne, 1967b; reprinted with permission from New York State Agricultural Experiment Station.)

for the cucumber to about 0.5 kg for the fresh bread. The fresh bread is much softer than the fresh cucumber. People generally squeeze soft and spongy foods more gently than harder foods. The force exerted by the hand in the squeeze test is, therefore, partly dependent on the person making the test and partly dependent on the nature of the food.

The measurement of firmness by an objective deformation test was discussed on page 152 where it was shown that a small deforming force gives a better resolution between similar samples than a high deforming force. This principle should apply to the sensory deformation test: a gentle squeeze should discriminate better between the firmness of two samples of food than a hard squeeze. Squeezing gently has another point in its favor – there is less damage to the food. All the advantages lie with the gentle squeeze.

Peleg (1980) studied the sensitivity of the human tissue in squeeze tests and pointed out that in these types of tests there can be significant deformation of the human tissues (e.g. the balls of the fingers) in addition to the deformation of the specimen. He pointed out that the combined mechanical resistance in a squeezing test is given by the equation

$$M_c = M_1 M_x / (M_1 + M_x) \tag{7.1}$$

where M_c is the combined mechanical resistance of the sample and the fingers; M_1, the resistance of the human tissue; and M_x, the resistance to deformation of the test specimen. This equation provides a simple explanation as to why there are differences in the sensing range between the fingers and the jaws and why the human senses are practically insensitive to hardness beyond certain levels.

There are three different types of responses that can be drawn from this equation:

Case No. 1: $M_1 >> M_x$. This case occurs when a soft material is deformed between hard contact surfaces (e.g. a soft food is deformed between the teeth). Under these conditions Eq. (7.1) becomes $M_c = M_x$ (since $M_1 + M_x \simeq M_1$). In this situation the sensory response is primarily determined by the properties of the test specimen.

Case No. 2: M_x and M_1 are of comparable magnitude. In this case the response is regulated by both the properties of the test material and the tissue applying the stress, as given in Eq. (7.1).

Case No. 3: $M_x >> M_1$. This case occurs when a very firm product is compressed between soft tissues. For example, pressing a nut in the shell between the fingers. Under these conditions the equation becomes $M_c = M_1$ (because $M_1 + M_x \simeq M_x$). In this situation the response is due to the deformation of the tissue and is insensitive to the hardness of the specimen. This appears to be interpreted as 'too hard to detect' or 'out of range.'

Swyngedau and Peleg (1992) give a pictorial example of these three cases (Fig. 7.11). Practically all the deformation is in the finger in Fig. 7.11a because the object is so much more rigid than the finger. Figure 7.11b shows both the object and the finger being deformed. Practically all the deformation is in the object in Fig. 7.11c because it is so much less rigid than the finger.

Swyngedau and Peleg (1992) also showed that the deformability constant of the ball of the finger is approximately $2\,N\,mm^{-1}$ and for the ball of the thumb $0.8\,N\,mm^{-1}$.

Voisey and Crête (1973) measured the amount of force and the rate at which force is applied to fruits and vegetables by the hands of consumers who were judging firmness. They found that males generally squeeze harder than females and applied the force more quickly. In squeezing an onion the mean force for females was 3910 g and for males 5670 g, and for tomatoes the mean force was 1522 g for females and 1705 g for males. The rate of force application on onions for females was $11{,}900\,g\,s^{-1}$ and for the males $17{,}560\,g\,s^{-1}$ whereas for tomatoes the rate of force application for females was $14{,}040\,g\,s^{-1}$ and for males $5470\,g\,s^{-1}$.

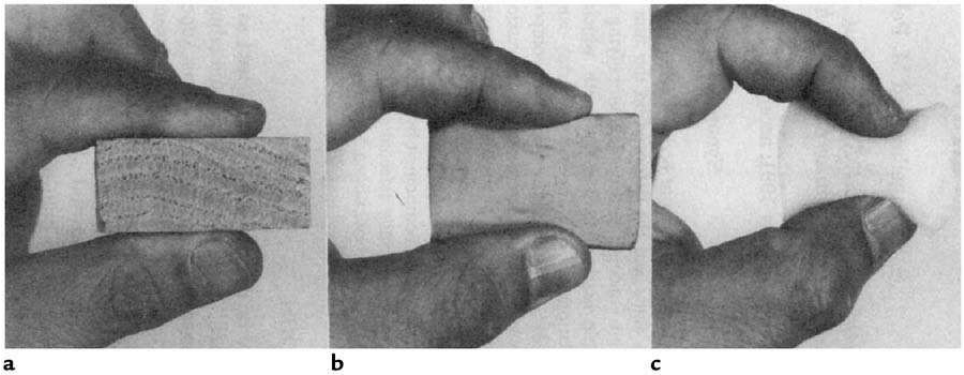


Figure 7.11 Three situations in 'hardness' assessment by compression with the fingers. (a), practically all the deformation is in the finger. (b), both object and finger are substantially deformed. (c), practically all the deformation is in the soft object. (From Swyngedau and Peleg, 1992. Reprinted from *J. Rheology* **36**, page 46. Copyright by Society of Rheology.)

Stirring a fluid or semifluid food with a spoon or a finger is frequently used to measure viscosity or consistency. It is possible to use other parts of the anatomy such as cheeks, elbows, and feet to obtain some index of the textural qualities of foods.

Shama *et al*. (1973) showed that nonoral assessment of viscosity was performed by two different methods that used different shear stress–shear rate conditions.

Method 1. Tilting or shaking the container and observing the rate of flow. The shear rate is the stimulus observed. It ranges from 0.1 to 40 s^{-1} while the shear stress is in the range of 6–60 Pa.

Method 2. Stirring the contents with a spoon. The shear stress is the observed stimulus. It ranges from 10 to 1000 Pa while the shear rate is maintained over the narrow range of 90–100 s^{-1}.

Table 7.19 Texture Profile as Modified for Use in Skin-care Product Evaluation

Stage of evaluation	Skin-care product attribute and definition	Texture profile parameters
PICK-UP, product removed from container, product poured or squeezed from bottle onto fingertips, or product lifted from jar with forefinger.	Thickness – Perceived denseness of product. Evaluated as force required to squeeze between thumb and forefinger. Rated as thin–medium–thick. or Consistency – Perceived structure of product. Evaluated as resistance to deformation and difficulty of lifting from container. Rated as light–medium–heavy.	Viscosity (for lotions) or Hardness, Cohesiveness (also Springiness, Adhesiveness) for creams
RUB-OUT (application), spread of product over and into skin with fingertips using gentle circular motion at a rate of two rubs per second for a specified period of time, depending on the product.	Spreadability – Ease of moving product from point of application over rest of face. Evaluated as resistance to pressure. Rated, or described, as: 'slips' – very easy to spread 'glides' – moderately easy 'drags' – difficult to spread Absorbency – Rate at which product is perceived to be absorbed into skin. Evaluated by noting changes in character of product and in amount of product remaining (tactile and visual) and by changes in skin surface. Rated as slow–moderate–fast.	Viscosity, Cohesiveness, Springiness, Gumminess, Adhesiveness Other characteristics – (oil and water content of product)
AFTER-FEEL (and appearance), evaluation of skin surface with fingertips, visually and kinesthetically immediately after product application and possibly at varying intervals thereafter.	After-feel – Type and intensity of product residue left on skin; changes in skin feel. Product residue is described by type, i.e. film (oily or greasy), coating (waxy or dry), flaky or powdery particles; the amount of such residue is identified as slight–moderate–large. Skin feel is described as dry (taut, pulled, tight); moist (supple, pliant), oily (dirty, clogged). Other sensations are also noted and identified where applicable, i.e. clean, stimulated, irritated, etc.	Other characteristics – (oil and water content) Geometrical characteristics – (gritty, powdery, etc.)

Source: Schwartz (1975). Reprinted from *J. Texture Studies* **6**, page 36. Copyright by Food and Nutrition Press Inc.

Use of Sensory Texture Profile Analysis for Nonfood Consumer Products

The principles of the sensory texture profile technique can be applied to nonfood consumer items such as creams, lotions, cosmetics, paper tissues, and any other product that is contacted by the skin. In these cases the sensory profile is adapted to mimic the manner in which the item is treated by the hand or applied to the skin. For example, Schwartz (1975) lists the texture profile for skin-care products (Table 7.19).

This Page Intentionally Left Blank

CHAPTER 8

Correlation Between Physical Measurements and Sensory Assessments of Texture and Viscosity

Introduction

It is now generally accepted that texture is a sensory attribute (see the definitions on pages 12 to 15). Therefore, only people can measure the textural properties of foods. Instruments measure physical properties not sensory properties. There are several good reasons for measuring physical (mechanical and rheological) properties of foods.

(1) *Engineering process design*. The flow properties and deformation properties of foods need to be understood in order to design equipment for handling foods. This can be conveyor belts, storage bins, pumps, pipelines, spray devices, heat exchangers and the like. The rate of heat transfer in pasteurizers, and in cans and jars of foods being sterilized is partly dependent on their rheological properties.

(2) *Determination of structure*. Some physical measurements provide information on the structure of the food or on the conformation, chain length, degree of branching and intertangling of the macromolecular constituents in foods.

(3) *Texture*. The third is to make the measurements that will predict the sensory assessment of some of the textural attributes of the product. Based on these measurements the process or the formula for a given product may be changed in order to produce a finished product that falls within the range of textural parameters that experience has shown to be acceptable to the consumer. Sometimes these measurements are employed to establish a quality grade used to set a price for the product.

This chapter will discuss only item (3) above. The quality of the correlation between sensory and objective measurements of texture is of paramount

importance. To be of value, instrument readings need to have a high level of predictability of sensory assessments of textural quality. The human assessment of texture has to be the standard against which instrument readings are calibrated. This concept was clearly enunciated by Brennan (1980) in the following words:

> Texture is a sensory attribute, perceived by the senses of touch, sight and hearing. Thus the only direct method of measuring texture is by means of one or more of the senses. Nonsensory techniques can never be more accurate than sensory methods. The accuracy of the former can only be judged by their ability to predict the sensory quality being studied.

Consumers have a rich vocabulary of words relating to quality. Terms such as thin, thick, sticky, smooth, creamy, slimy, slippery, gummy, tough, crisp, and firm have specific meanings which are very clear in the consumer's mind (Szczesniak and Kleyn, 1963; Yoshikawa *et al*., 1970a–c). As scientists we have the task of translating these descriptors into scientific principles that can be measured by instruments. This task is sometimes straightforward and sometimes difficult.

There are a number of solid reasons for using instruments.

(1) Instrument readings cost less than sensory assessments.
(2) Most instrument readings are obtained more quickly than sensory evaluations.
(3) Instruments give numbers, which on the surface appear to be more 'scientific' than sensory results. Some consider sensory assessments to be 'opinions' rather than 'facts,' a view not held by the author (see page 282).
(4) Instruments give reproducible results, whereas each human is different and even the same person can change from one day to the next.
(5) When correctly calibrated and operated, instruments in different locations should give the same result which offers the potential for setting national and international standards for textural quality. However, as discussed under the heading, 'Calibration' in Chapter 9, considerable work will be needed to make this a reality.

It must also be remembered that the number of instruments being used to measure food texture or viscosity is much smaller than the number of human beings measuring texture. A rough order of magnitude estimate of the number of mechanical instruments in use worldwide would be about 20,000. In contrast, the number of human instruments measuring texture exceeds six billion. If there is poor agreement between instrument tests and human assessments of texture it will be relatively easier to change 20,000 instruments than to attempt to change the opinion of 6,000,000,000 humans.

Two Types of Sensory Assessment

Sensory testing may be divided into two broad classes.

Class 1. Intensity scaling is how much of a property is present in the food. There should be a unidirectional relationship between the sensory score

and the physical measurement within the limits of human sensitivity. This class of test is amenable to correlation with instrumental tests.

Class 2. Acceptability scaling, also called 'hedonic scaling,' measures the degree to which people like the food. This class of sensory tests cannot be directly measured by instruments because no instrument can express an opinion on how well it likes the texture of the sample it is testing. An acceptability versus intensity graph usually takes the form of an inverted U and is known as the Wundt curve after Wilhem Max Wundt (1832–1920), a German psychologist who was a professor at the University of Leipzig, where in 1878 he founded the first laboratory for experimental psychology (Fig. 8.1). The level of acceptance increases at first as the attribute increases, reaches a maximum, and then decreases. One can have too much of even a good thing.

The difference between intensity scaling and acceptability scaling is shown for a real system in Fig. 8.2 where the scores for hardness and ease of spreadability of bentonite–water mixtures are displayed. The sensory panel used monotonically increasing scores for hardness across the whole range of increasing bentonite concentration because this is an intensity scale (Fig. 8.2b). In contrast, the score for spreadability by the same panel rose to a maximum and then declined because this is an acceptability scale (Fig. 8.2a). At low bentonite concentrations the paste is too sloppy to control, at intermediate concentrations it is 'just right' and at high concentrations it is too stiff to spread easily (Lucisano *et al*., 1989).

Trant *et al*. (1981) pointed out the fallacy of trying to correlate physical and chemical measurements with hedonic responses. Acceptability scaling is best

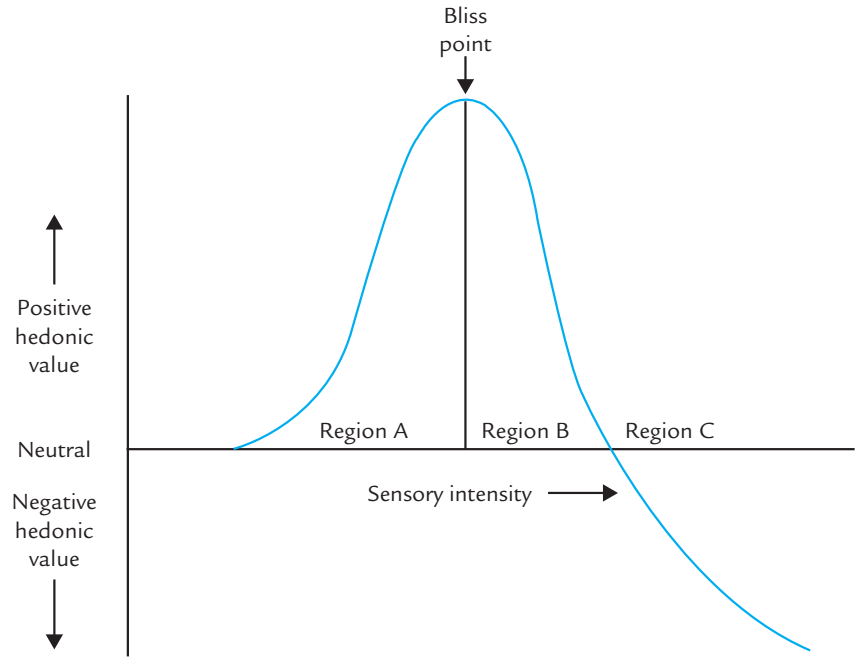


Figure 8.1 Basic relationship between sensory intensity and hedonic response (Wundt curve). (From Cardello, 1996. Reprinted from Food Choice Acceptance and Consumption, Fig. 1.2, page 9. eds Meiselman and Mactie. Copyright by Blackwell Science Ltd.)

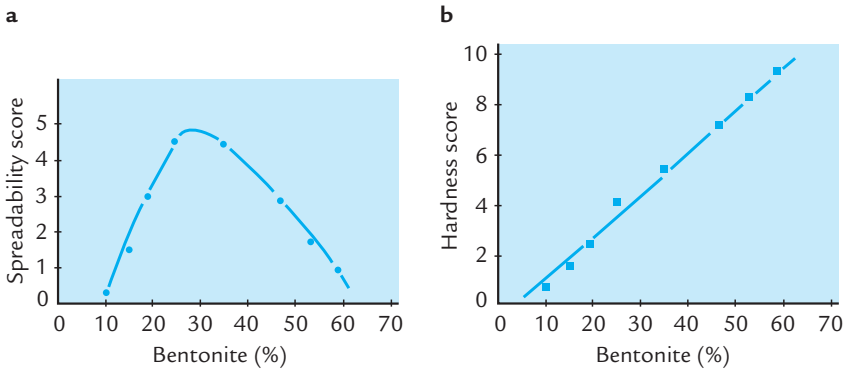


Figure 8.2 Bentonite concentration vs (a) spreadability (hedonic score) and (b) hardness (intensity score). (From Lucisano *et al.*, 1989. Reprinted from *J. Texture Studies* 20, pages 306, 307. Copyright by Food and Nutrition Press Inc.)

performed by consumer panels and will not be discussed any further. The rest of this chapter refers to correlations between instrument readings and sensory intensity scaling. However, it is worth noting that once the peak of the Wundt curve has been identified for a specific textural property for a particular population, instrument readings can be used to monitor whether the product is being kept within the targeted range if an objective method is available that correlates highly with an intensity scale.

Psychophysical Models

The correlation between an intensity scale and a physical measurement usually follows one of three psychophysical models.

(1) The linear model. There is a direct linear relationship between the stimulus (measured by some objective method) and the response which is the sensory measurement. It can be described by the equation

$$R = AS + B$$

where R is the response to stimulus S, and A and B are constants.

(2) The Weber–Fechner (semilog) relationship. The sensory response makes a linear relationship when plotted against the logarithm of the stimulus. It is described by the equation

$$R = A \log S + B$$

(3) The Power model (log–log relationship). This model is described by the equation

$$R = CS^n$$

which may be rearranged into the form

$$\log R = n \log S + \log C$$

where n and C are constants.

Each of these psychophysical models has been successfully applied to certain systems. There has been a long debate by psychologists as to which is the most suitable model. The present consensus seems to be that the power model is the correct one because it satisfactorily describes most situations that arise. In other words, a plot of the logarithm of the objective measurement versus the logarithm of the subjective measurement will be linear in most circumstances.

The numerical value of the exponent n in the power model is an index of the degree of compression or expansion of the physical scale by the senses.

(1) When $n < 1.0$, there is compression of the physical scale; that is, a tenfold increase in the stimulus will give less than a tenfold increase in the sensory response. This allows a wide stimulus range to be compressed into a smaller and more manageable one for the senses and brain to process.
(2) When $n = 1.0$, there is no compression or expansion of the scale; a tenfold increase in stimulus gives a tenfold increase in response.
(3) When $n > 1.0$, there is expansion of the scale; that is, a tenfold increase in stimulus gives a more than tenfold increase in response.

Some experimentally measured values for the exponent n for human subjects are given in Table 8.1. Note that pressure on the palm has a value of 1.1 for the exponent n, indicating slight expansion, while tactual roughness has

Table 8.1 Measured Exponents and Their Possible Fractional Values for Power Functions Relating to Subjective Magnitude to Stimulus Magnitude

Continuum	Measured exponent	Stimulus condition
Loudness	0.67	3000-Hz tone
Brightness	0.33	5° target in dark
Brightness	0.5	Very brief flash
Smell	0.6	Heptane
Taste	1.3	Sucrose
Taste	1.4	Salt
Temperature	1.0	Cold on arm
Temperature	1.5	Warmth on arm
Vibration	0.95	60 Hz on finger
Vibration	0.6	250 Hz on finger
Duration	1.1	White-noise stimuli
Finger span	1.3	Thickness of blocks
Pressure on palm	1.1	Static force on skin
Heaviness	1.45	Lifted weights
Force of handgrip	1.7	Hand dynamometer
Vocal effort	1.1	Vocal sound pressure
Electric shock	3.5	Current through fingers
Tactual roughness	1.5	Rubbing emery cloths
Tactual hardness	0.8	Squeezing rubber
Visual length	1.0	Projected line
Visual area	0.7	Projected square
Angular acceleration	1.41	5-sec stimulus

Source: Stevens (1970); reprinted with permission from *Science*. Copyright 1970 by the American Association for the Advancement of Science.

a value of 1.5 (great expansion) and tactual hardness has a value of 0.8 (moderate compression).

Peleg and Campanella (1988) point out that although the power model appears to be linear over a wide range of intensities, it does not take into account the existence of a threshold stimulus below which there is no sensory response, nor a saturation stimulus above which the sensory response no longer increases. That is, there is a low threshold and a high threshold beyond which there is no change in sensory response, with changing stimulus. Peleg and Campanella (1988) derived an equation that takes these thresholds into account

$$R = 1 - \exp[-C(S - S_o)^m]$$

where R is the sensory response; S is the stimulus; S_o is the threshold stimulus below which there is no response, and C and m are constants.

Example of a Successful Correlation

Cutler *et al*. (1983) studied the oral perception of thickness in fluid foods over a range of almost five orders of magnitude. For Newtonian fluids the logarithm of the perceived thickness (sensory assessment) versus the logarithm of the viscosity (instrument) was rectilinear with a correlation coefficient $r = 0.995$ (Fig. 8.3a). For non-Newtonian fluids made from aqueous solutions of alginate, pectin, guar and xanthan gums the correlation coefficient between log apparent viscosity measured at $50\,s^{-1}$ and perceived thickness was $r = 0.933$ (Fig. 8.3b). These high correlations mean that a viscosity measurement can be confidently accepted as a reliable indicator of perceived thickness.

Example of a Variable Correlation

The instrument most widely used for measuring the tenderness of meat is the Warner–Bratzler Shear (see page 209). In an extensive review of tenderness of

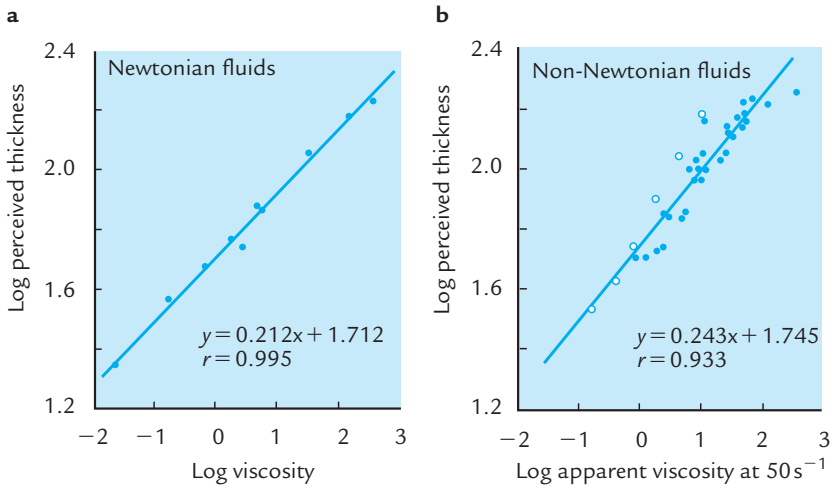


Figure 8.3 Sensory thickness vs (a) viscosity for Newtonian fluids, and (b) apparent viscosity measured at $50\,s^{-1}$ for non-Newtonian fluids. Solid circles, aqueous solutions of alginate, pectin and guar gums; open circles, solutions of xanthan gum. (From Bourne 1992. Reprinted from *J. Food Engineering* **16**, page 160. Copyright 1992 with permission of Elsevier Science. Plotted from data of Cutter *et al*. 1983.)

meat, Szczesniak and Torgeson (1965) summarized 38 studies on beef, four on pork, and nine on poultry where researchers had listed correlation coefficients between the Warner–Bratzler Shear and some method of sensory testing and found correlations ranging from $r = -0.001$ to $r = -0.942$. Most of the correlation coefficients were fairly evenly distributed between about $r = -0.2$ and $r = -0.9$. Reports published subsequent to this early review article continue to show very wide correlation coefficients between the Warner–Bratzler Shear and sensory measurements of meat texture.

This wide variation in correlation coefficients which ranges from worthless to very satisfactory (see Table 8.8) raises the question why this happens using the same machine on the same type of product (muscle meats). Three types of error may have occurred in these reports summarized by Szczesniak and Torgeson (1965).

Type 1. Instrument problems

- Is the instrument working properly?
- Are the working parts bent, blunt or dented?
- Has the force-measuring system been calibrated recently?
- Was the right information extracted from the force–time curve?
- Did the operator use the instrument correctly?
- Are the working parts within specifications? Some instruments that claim to perform the Warner–Bratzler Shear test use a different shape or thickness of the blade or the clearance between the blade and the anvil is different. The correct dimensions for the Warner–Bratzler Shear are given on page 135.

Type 2. Sensory panel problems

- Was the panel trained and maintained properly?
- Did the panel use the correct procedure?
- Was the definition of the measured textural property clear to the panel?
- Did the panel have standard samples to serve as anchor points?
- Is the parameter of interest a combination of characteristics that is not amenable to description by a single sensory score?
- Did other parameters (such as juiciness, appearance, or odor) sway the panel's judgment?
- Was the panel located in surroundings free from distractions such as strange odors, bad lighting and distracting noises?

Type 3. Commodity problems

- Was the sample representative of the lot from which it was taken?
- Was the sample size large enough and were a sufficient number of replicates used?
- Was the sample uniform? Was it free from tough connective tissue and soft fatty tissue? Meat is notorious for lack of uniformity. Since most texture tests are destructive, a sensory test and an instrumental test cannot be performed on the same sample.

- Was the sample prepared correctly? Degree of cooking affects Warner–Bratzler Shear readings.
- Were all samples tested at the same temperature?
- Was the sample presented to the Warner–Bratzler blade in the correct orientation? Samples should be so positioned that the blade cuts through the longitudinal fibers in the meat.

Had every researcher whose work was summarized in the review by Szczesniak and Torgeson (1965) paid careful attention to all the above problems it is likely that the range of correlation coefficients would be much narrower, and also higher than reported.

Matching Sensory Descriptors to Scientific Principles

The meaning of words people use to describe texture is generally not the same as used by scientists. Hence, the scientist must take the descriptors commonly used by people and translate them into words with precise scientific meaning. Even then problems arise because people may use the same term for different scientific principles. For example, Szczesniak and Bourne (1969) studied how people measure firmness of foods by nonoral techniques. In this study 128 people were presented with pairs of each of nine different foods, and asked to identify the firmer sample of the pair. For soft foods such as puddings and whipped toppings people used some kind of viscosity measurement. For products such as bread, lettuce, marshmallow and tomatoes, they used the principle of deformation which is the distance the food is compressed when gently squeezed in the hand. For firmer foods, such as apples and pears, people measured the force required to push their thumb into the fruit which is the puncture principle. Finally, for elongated foods such as a carrot they used the flexing principle as the index of firmness (see Fig. 8.4).

In this study the panelists used four entirely different test principles: viscosity, deformation, puncture, and flexure to describe 'firmness.' Thus the type of sensory test used to judge firmness of a food depends on the level of firmness in the test sample. When one test failed to differentiate between samples, the subject changed to another principle until a suitable method was found. A deformation test should correlate well with the sensory evaluation of firmness of bread or tomato, but can be expected to correlate poorly with firmness scores for apple or carrot, whereas a puncture test should show a high correlation with sensory firmness of apple and a poor correlation with firmness of bread, and so on. The test principle used in the instrument should always match the test principle that people use for that food.

In a study on nonoral assessment of viscosity of fluid foods Shama *et al*. (1973) showed that people use two different techniques. The first is to observe the rate of flow when the container is tilted or shaken which uses the sense of

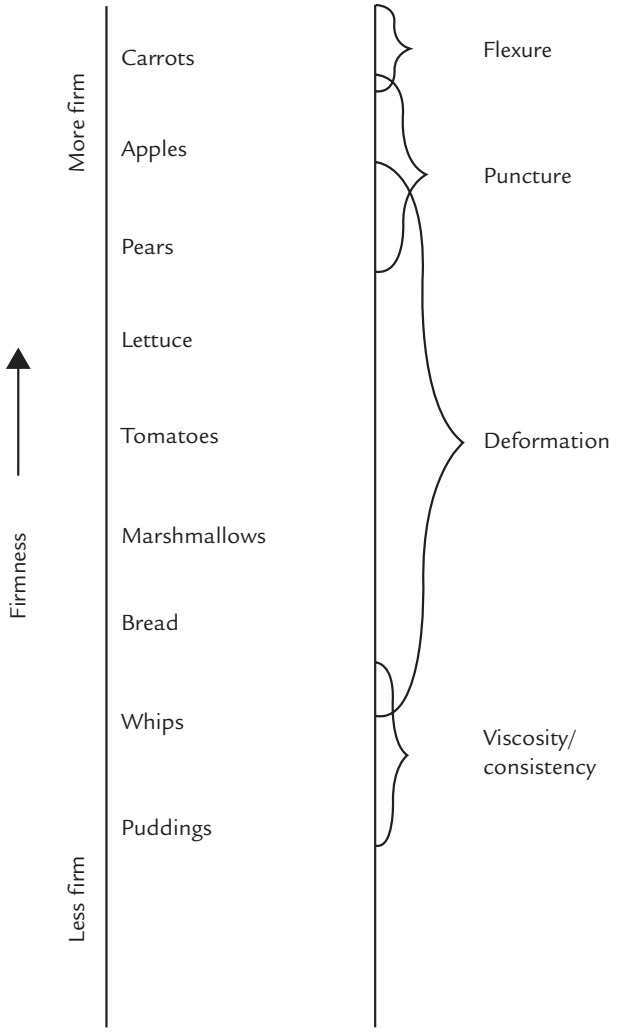


Figure 8.4 Sensory tests to measure firmness. (From Szczesniak and Bourne, 1969. Reprinted from *J. Texture Studies* **1**, page 59. Copyright by Food and Nutrition Press Inc.)

sight. The second is to feel the force required to stir the product with a spoon which uses the tactile sense.

Some Physical Properties Are Not Textural Properties

A well-equipped food laboratory has the capability of measuring numerous physical properties of foods. However, one cannot assume that a physical property is also a textural property. Figure 8.5 shows schematically that whereas most textural properties are physical properties, not all physical properties are textural properties. Unless the physical property is detected by the human senses it can be dismissed for use as a textural property.

An analogous situation is found in the electromagnetic spectrum. The visible range of wavelengths of light is 0.4–0.7 μm whereas the invisible range extends from ultraviolet to x-rays at shorter wavelengths (0.4 μm to 10^{-14} m) and from infrared to radio waves (0.7 μm to 10^{4} m) at longer wavelengths than the visible

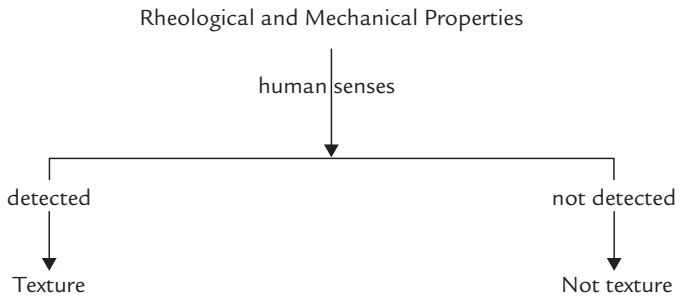


Figure 8.5 Rheological properties may or may not be textural properties.

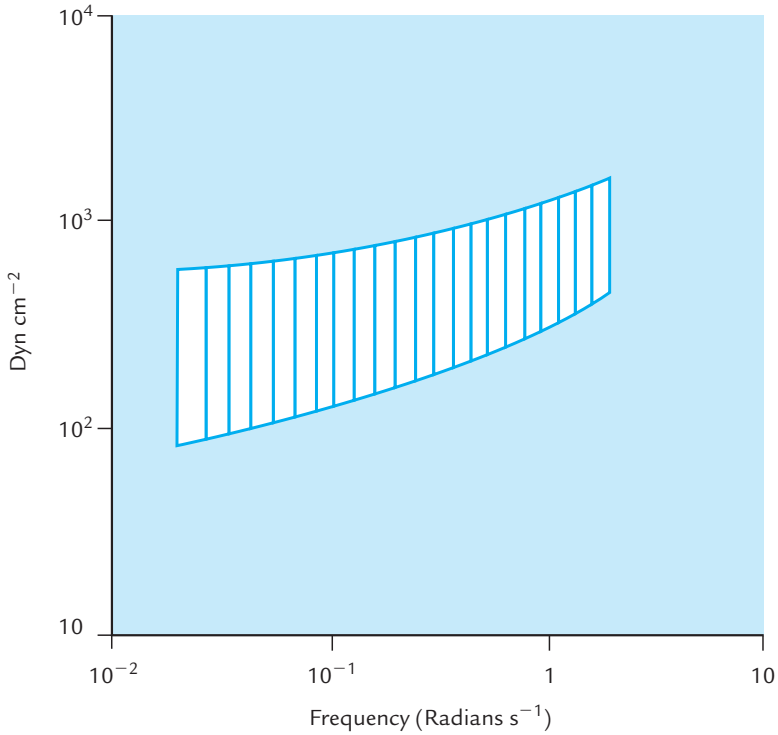


Figure 8.6 Range of dynamic yield stress (shaded area) of commercial mayonnaise and salad dressings. (From Elliott and Ganz, 1977. Reprinted from *J. Texture Studies* 8, page 368. Copyright by Food and Nutrition Press Inc.)

region. Food laboratories that use infrared and ultraviolet spectrophotometers would not even consider using these instruments to measure the color of foods although they have useful purposes. A similar analogy can be found in acoustical vibrations that generate notes too low or too high to be heard by the ear. The audible range for people with good hearing is about 16–16,000 Hz. The human ear cannot hear sound above about 16,000 Hz (ultrasonic region) or below about 16 Hz (subsonic region). As people age they tend to lose the higher frequencies and their upper audible range may fall well below 10,000 Hz.

In a similar manner, we need to understand that humans are 'blind' and 'deaf' to some physical properties and hence, it is a waste of time to measure them for textural purposes. For example, Elliott and Ganz (1977) showed that commercial mayonnaises and salad dressings exhibit as much as an order of magnitude range in some of their rheological properties and concluded that consumers have a high tolerance to variation in these properties (Fig. 8.6).

It is likely that consumers are 'blind' to such rheological properties, just as they are insensitive to changes in the UV spectrum or ultrasound.

Effect of Compression Speed

Chapter 3 explained the difference between elastic and viscoelastic behavior. For elastic or near-elastic behavior the speed at which a test is performed should have little effect on the result, whereas for viscoelastic foods the speed may have a profound effect. Figure 8.7 shows the puncture force of three apple cultivars ('Stark,' 'Conrad,' and 'Missouri') with the punch tip mounted in an Instron and operated at speeds ranging from 0.5 to 50 cm min^{-1}. Over a hundred-fold range of speed there is little change in the puncture force. Therefore, it does not matter how fast this test is performed. This is called a 'strain rate insensitive' food.

Another example of a strain rate insensitive food is given by Thybo *et al*. (2000) who performed uniaxial compression tests on ten potato cultivars at speeds ranging from 20 to 1000 mm min^{-1} and found no relevant effect of the deformation rate on the correlation between instrumental measurements and sensory textural profile parameters. Van Hecke *et al*. (1995) reported that crosshead speed from 10 to 50 mm min^{-1} did not affect the flexural modulus in bending tests on crispy puffed foods. Mancini *et al*. (1999) found that compression speed from 60 to 480 mm min^{-1} had little effect on the compression behavior and relaxation of 1.25% alginate gels. Wium *et al*. (1997) compressed cylinders of UF-Feta cheese in an Instron at twelve crosshead speeds of

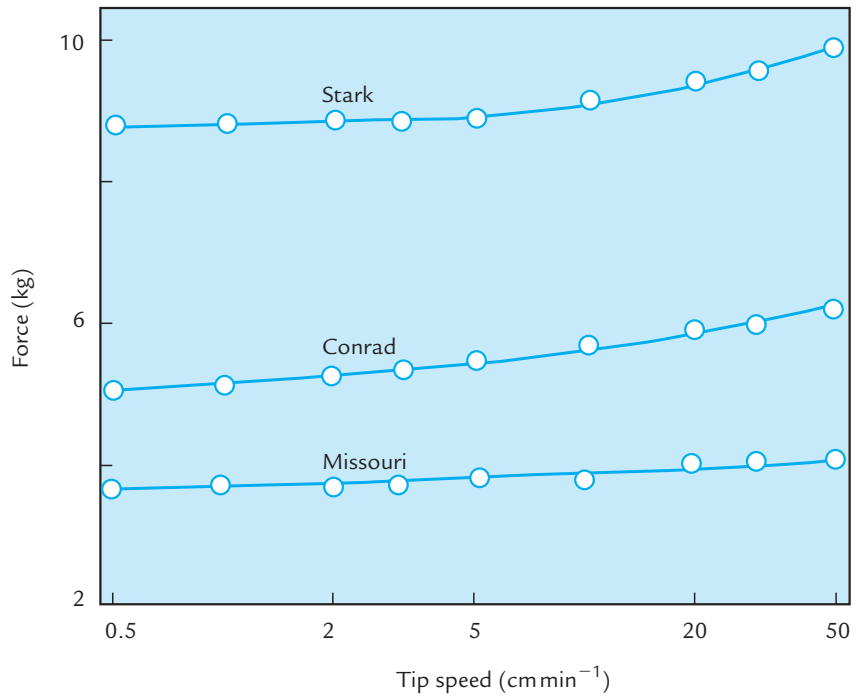


Figure 8.7 Effect of punch speed on puncture force of three apple cultivars. (From Bourne, 1965a. Reprinted from *Food Technology* **19**, page 117, 1965. Copyright by Institute of Food Technologists.)

50–2500 mm min^{-1} and found the deformation rate had almost no effect on the correlation between stress at fracture and sensory oral firmness even though the maximum stress increased from 45,300 Pa at 50 mm min^{-1} to 80,100 Pa at 2500 mm min^{-1} compression speed.

In contrast, control of compression speed is critical for some foods. An excellent example of the need to select the correct compression speed is given by Shama and Sherman (1973a) who compressed two cheeses in an Instron Universal Testing Machine at various compression speeds. The results are shown in Fig. 8.8. The solid line depicts the force–compression curve for Gouda cheese and the dashed line for White Stilton cheese. When compressed at 5 cm min^{-1}, the compression curve for White Stilton cheese always lies above that of Gouda cheese. This would be interpreted to mean that White Stilton cheese is firmer than Gouda cheese. At a compression speed of 20 cm min^{-1} the curve for White Stilton cheese lies above that for Gouda cheese from 0 to 30% compression and beyond 60% compression. Between 30% and 60% compression the line for White Stilton cheese lies below that of Gouda cheese. At compression speeds of 50 and 100 cm min^{-1} a similar effect occurs; the compression curve of White Stilton cheese is above that for Gouda at the beginning then drops below it and then crosses over and lies above it

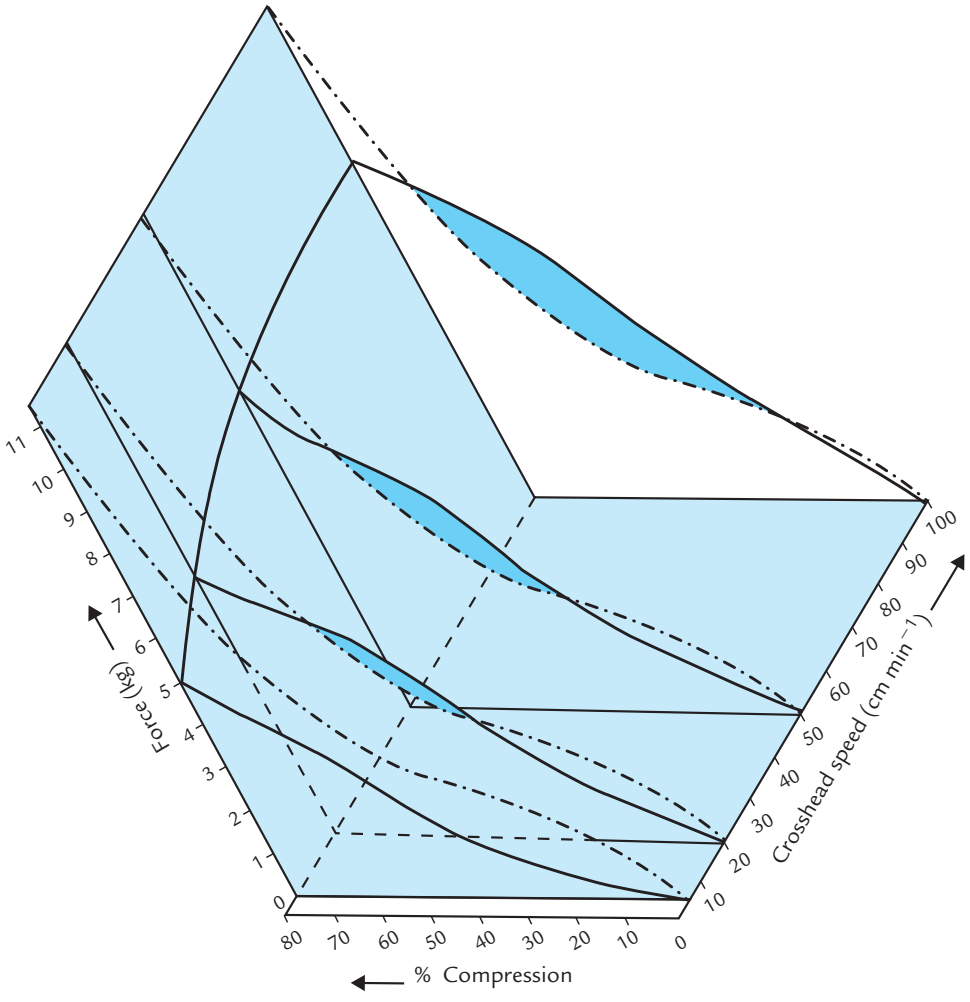


Figure 8.8 Three-dimensional plot of force–degree of compression–speed of compression for White Stilton and Gouda cheeses. A sensory panel always rated Gouda as harder than White Stilton. The compression test shows that the Gouda cheese is the harder sample only in the dark area. (From Shama and Sherman, 1973a. Reprinted from *J. Texture Studies* **4**, page 351, 1973. Copyright by Food and Nutrition Press Inc.)

again at high compressions. This graph demonstrates that White Stilton cheese will be considered to be firmer than Gouda cheese under some test conditions and softer under other conditions. The dark blue areas in this three-dimensional plot define the conditions under which Gouda cheese would be considered to be firmer than White Stilton cheese. A sensory panel always rated Gouda cheese as being harder than White Stilton cheese. Therefore, the rheological test will correlate with the sensory test only when the instrument test conditions fall within the dark blue areas shown in Fig. 8.8. This example demonstrates how selection of the degree of compression and the compression speed is critical for certain foods if a rheological test is to correlate with a sensory test.

Chapter 2 points out that the speed of movement of the human jaw is approximately sinusoidal, the compression rate between the third molar (which is closest to the temperomandibular joint) is about one-half the speed of the incisors (which are farthest from the temperomandibular joint). There are wide variations in chewing speed from individual to individual (see Table 2.5 page 47**)**. In contrast, most compression machines use a constant speed. This disparity between the highly variable and usually high speed compression between the teeth, and the constant and relatively slow compression speed of machines probably accounts for some of the low correlations between sensory and objective tests, especially for strain rate sensitive foods.

Uniformity of Sample

Some foods have a highly uniform texture from point to point within the sample (e.g. most gels) whereas other foods show wide variations from point to point. For example, Segars *et al*. (1974) highlighted the inherent variability in beef by taking five whole muscles from the left hindquarter of a US Good grade animal: (1) *biceps femoris*, (2) *gluteus medius*, (3) *longissimus dorsi*, (4) *psoas major*, and (5) *rectus femoris*. Each muscle was cut into 2.5 cm thick slices perpendicular to a line drawn from the origin to the insertion end of that muscle. The odd-numbered slices from each muscle were tested raw and the even-numbered slices cooked in a plastic bag until the internal temperature reached 63°C. As many as possible, 2.5 cm diameter cylinders were cut from each slice and compressed 20% in a universal testing machine and the apparent modulus of elasticity, E_a, determined from the initial slopes of the force–distance curves. There is a wide range of mean values for E_a from muscle to muscle, and from slice to slice in the same muscle (Table 8.2). The high values for the standard deviation of the mean indicate a wide range of E_a value within the slice. This wide inherent variation of textural properties is characteristic of many foods, especially native foods.

In the uncooked *biceps femoris* muscle the mean apparent modulus of elasticity ranged from 64 (slice no. 1) to 338 g cm^{-2} (slice no. 15) and after cooking the same muscle it ranged from 195 (slice no. 6) to 1301 g cm^{-2} (slice no. 16). In the *psoas major* muscle the mean E_a for uncooked muscle ranged

Table 8.2 Mean Value of Apparent Modulus of Elasticity, E_a in g cm^{-2} for Each Slice and Standard Deviation of the Mean for Five Beef Muscles

Slice no.	*Psoas major*	*Longissimus dorsi*	*Gluteus medius*	*Rectus femoris*	*Biceps femoris*
Raw					
1	382.9 ± —	256.2 ± 57.8	125.5 ± 48.4	257.7 ± 248.1	63.92 ± 6.71
3	388.7 ± —	394.6 ± 206.0	280.2 ± 150.9	124.4 ± 40.5	73.52 ± 20.75
5	809.9 ± 92.9	207.5 ± 74.1	186.3 ± 108.6	268.9 ± 119.5	75.91 ± 25.41
7	764.0 ± 455.3	194.0 ± 108.7	77.94 ± 24.33	258.0 ± 169.2	69.38 ± 27.87
9	1289 ± 593	295.4 ± 189.8			243.3 ± 261.9[a]
11	1179 ± 336	235.7 ± 368.6[a]			134.2 ± 73.8
13	653 ± 131	618.1 ± 1177.9[a]			129.5 ± 76.2
15	293 ± 8				338.1 ± 371.4[a]
17					198.9 ± 160.9
19					209.6 ± 88.9
21					226.0 ± 76.7
Cooked					
2	2433 ± —	1443 ± 396	2293 ± 1018	1845 ± 871	322.5 ± 144.9
4	1900 ± 111	1413 ± 821	2124 ± 822	2152 ± 1033	229.1 ± 84.5
6	2661 ± 749	1434 ± 295	1391 ± 559	1950 ± 889	195.0 ± 38.9
8	2395 ± 948	1096 ± 432		1561 ± 586	1217.6 ± 776.8
10	2344 ± 270	1045 ± 667			814.4 ± 582.8
12	2267 ± 453	1158 ± 609			585.2 ± 260.3
14	1950 ± 149				580.1 ± 110.5
16					1301.4 ± 1336.2
18					724.5 ± 1124.1
20					890.3 ± 974.1

Source: Segars *et al*. (1974). Reprinted from *J. Texture Studies* **5**, page 288. Copyright by Food and Nutrition Press Inc.
[a]Contain one extreme sample.

from 293 (slice no. 15) to 1289 g cm^{-1} (slice no. 9) but was somewhat more uniform after cooking when the E_a ranged from 1900 (slice no. 4) to 2661 g cm^{-1} (slice no. 6). Even within each slice of meat the variation was sometimes high. The coefficients of variation (100 × standard deviation/mean)% ranged from a low of 2.7% for slice no. 15 of the uncooked *psoas major* muscle up to 155.2% for slice no. 18 of the cooked *biceps femoris* muscle. Eight of these slices had a coefficient of variation less than 20%, 43 were between 20% and 70% and ten slices were above 70%.

Spanier *et al*. (2000) also showed major differences in Warner–Bratzler Shear force of four beef steaks broiled to 71°C (Table 8.3).

Another example of variation in texture is given by Sigurgisladottir *et al*. (1999) who performed a cutting–shear test on raw salmon fillets and found large changes in the shear force from head to tail (Fig. 8.9). The lowest shear force was found in the center of the salmon fillet. It became a little higher towards the head and much higher towards the tail. There was a threefold change in shear force within a salmon from head to tail.

Culioli and Sherman (1976) compressed 2 cm high × 2 cm diameter cylinders of Gouda cheese in an Instron after the rind had been removed. Cylinders were taken from the center of the cheese block, at an intermediate location,

Table 8.3 Average High and Low Shear Force Values of Individual Steaks Obtained from Along the Length of Four Beef Strip Loins

	Shear force (kg ± SD)[a]	
Strip loin	**High**	**Low**
1	6.74 ± 2.34	4.86 ± 1.75
2	5.43 ± 3.61	2.71 ± 2.74
3	5.81 ± 2.59	4.33 ± 3.19
4	6.45 ± 4.21	1.51 ± 2.93
Column mean ± SD	6.11 ± 0.52	3.35 ± 1.33

Source: Spanier *et al*. (2000). Reprinted from *J. Muscle Foods* **11**, page 187, 2000. Copyright by Food and Nutrition Press Inc.

[a] High and low shear force refer to the steak along the strip loin with the highest and lowest mean shear force. Shear force determined from a minimum of six cores in each steak along the length of a strip loin.

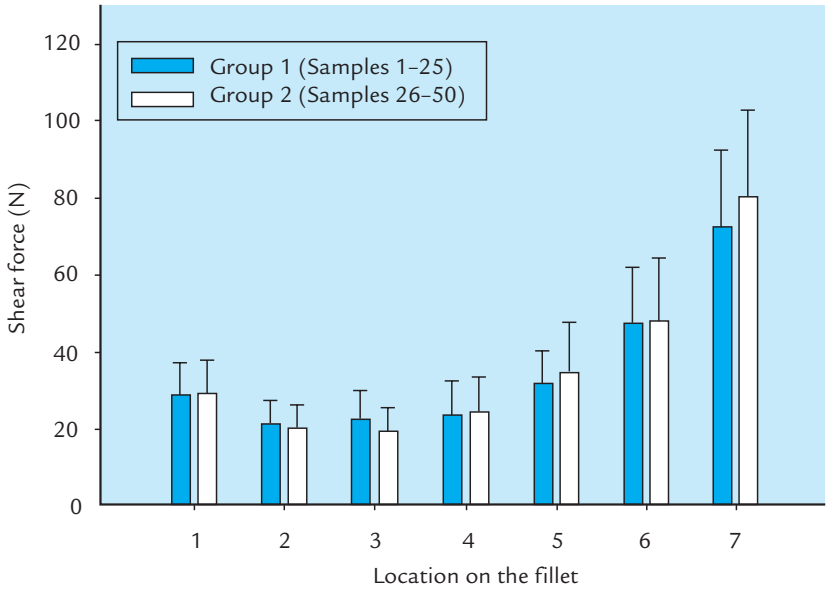


Figure 8.9 Shear force of salmon fillets measured by cutting with blade at seven locations from the head to the tail. Data are mean and standard deviation of 25 fish from the first sampling (1–25) and the second sampling (26–50). Locations 6 and 7 are significantly different from locations 1, 2, 3, 4 and 5. Location 1 is near the head and location 7 near the tail. (From Sigurgisladottir *et al.*, 1999. Reprinted from *J. Food Science* **64**, page 102. Copyright by Institute of Food Technologists.)

and near the surface. The force required to achieve a given percentage compression increased from the center to the edge of the block (Fig. 8.10).

Ponte *et al*. (1962) showed that the force required to deform slices of bread was lowest at the ends and highest at the center of the loaf, the center slices requiring about 20% more force than the end slices to achieve the same level of deformation.

This wide range of textures naturally inherent in foods is a common problem. The first step in handling it is to determine the degree of variability within the product. The examples given above show that the inherent variation can be very high. For carrots the author found the puncture force of the core tissue (xylem) to be significantly higher than the outside cortex tissue (phloem). However, within the core and cortex tissues of a single carrot the puncture force was very uniform along its length after the 2 cm nearest the

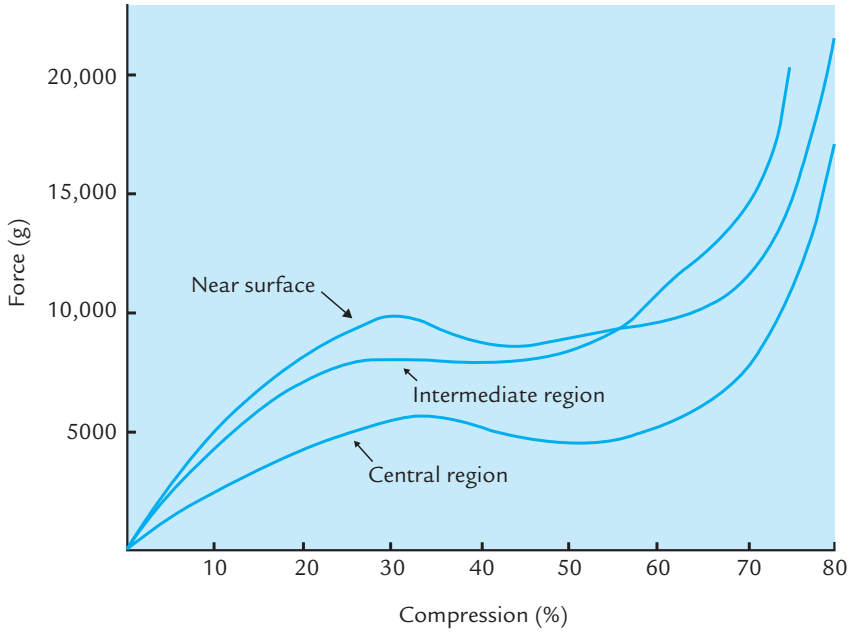


Figure 8.10 Force–compression data of cylinders of mature Gouda cheese. (From Culioli and Sherman, 1976. Reprinted from *J. Texture Studies* **7**, page 356. Copyright by Food and Nutrition Press Inc.)

crown and 3 cm nearest the tip had been discarded. The difference between puncture force of xylem and phloem tissue in carrots varies widely from cultivar to cultivar. Bourne (1989) found that the ratio of xylem/phloem puncture force in 17 different carrot varieties ranged from 0.71 to 2.29 depending on the cultivar and the blanch temperature.

The distribution of textures within particulate foods need to be taken into account. For example, Bourne (1972b) punctured cooked bean seeds and found an approximately normal distribution of puncture forces. However, in some samples there were a few hard beans whose puncture force was about five times greater than the mean puncture force. These hard beans would not be detected in a texture test that used a large, mixed sample, such as the extrusion test, but they would be prominent in a sensory test.

Szczesniak (1968) also gives a good example of distribution problems when crushing individual corn flakes. The average force for sample 1 was 3.2 lb (1.45 kg) and for sample 2, 2.8 lb (1.27 kg). However, sample 1 exhibited a relatively narrow distribution whereas sample 2 had a number of very soft and very hard flakes. Although the average values were within about 10% of each other, the distributions were very different. The less homogeneous sample would probably show a poorer correlation with sensory assessment than would the homogeneous sample.

As noted above, most gels are uniform in texture because they are formed from a uniform liquid. Nevertheless it is possible to have a uniform-texture gel displaying a tough skin because evaporation of moisture from the surface increases the concentration of the gelling agent in the part exposed to the air.

Every effort should be made to obtain a sample that is as uniform as possible. Some techniques that can help are as follows.

(1) For products with a noticeably different texture, separate the product into its two components, e.g. remove the surface skin of a gel. If necessary, test the skin separately from the rest of the gel.
(2) For products with a known variation in texture, always take the sample from the same location, e.g. take the center slice of a loaf of bread (Ponte *et al*., 1962); with blocks of cheese take the sample either from the center or near the edge, but do not mix edge samples with center samples (Culioli and Sherman, 1976).
(3) Mincing the product followed by mixing will yield a more uniform material for products such as meat and fish. For example, Borderias *et al*. (1983) reported that correlations between sensory texture profile and instrumental analysis on fish changed from nonsignificant to significant when minced fish was used in place of fillets. However, the process of size reduction may impair the integrity of some of the textural properties that need to be measured.
(4) For products with inclusions with a different texture, each type of inclusion should be considered as a separate product and tested separately. For example, a chocolate bar containing nuts, raisins and puffed rice should be treated as four different products and each component tested separately from the other three.

Even after selecting a sample that is as uniform as can be obtained without biasing the sample, the problem of a high inherent variability still remains for many foods. In these cases it is necessary to replicate the test a number of times. The number of replications needed depends on the degree of variability in the product, and the degree of certainty needed in the mean value. A statistician can help decide how many replicates are needed. This is a case where a compromise must be made between the statistical reliability of the mean and the amount of material and time that can be afforded to perform the test.

Isotropic Versus Anisotropic Foods

Isotropy and anisotropy were described in Chapter 3, page 103. When a food is known to be isotropic the direction in which the sample is presented to the machine is immaterial, but anisotropic foods must always be oriented in the same direction. Some examples of anisotropic foods were given in Chapter 3. Another example is given by Weinrichter *et al*. (2000) who showed that Tilsit cheese contains lentil-shaped holes because the method of manufacture makes it highly anisotropic. Test specimens cut perpendicular to the flat side of the cheese wheels showed significantly higher stresses and lower Poisson numbers than specimens taken parallel to the flat side.

Anisotropy can also affect sensory evaluations of texture. On one occasion the author trained a panel to develop the sensory texture profile of surimi. The panel gave a bimodal distribution of hardness scores with one group

consistently giving a score about twice as high as the other group on the nine-point hardness scale. After some discussion it was realized that surimi is anisotropic because of its flaky structure. Panelists who bit into surimi cubes with the flakes in a vertical direction gave a hardness score around 3 whereas those who oriented the cubes with the flakes in a horizontal direction gave a hardness score around 6. This problem was resolved by asking the panel to give two hardness scores: (1) with flakes vertical, (2) with flakes horizontal between the molars.

Effect of Temperature

It is well known that temperature affects the viscosity of liquid foods. Most viscometers maintain sample temperature within ±0.1°C in the sample to eliminate this variable from the measurement.

Figure 3.10 (page 78) shows the effect of temperature on the viscosity of sucrose solutions. Figure 8.11 shows how strongly the viscosity of depectinized apple juice and concentrates is affected by temperature. Rao (1977)

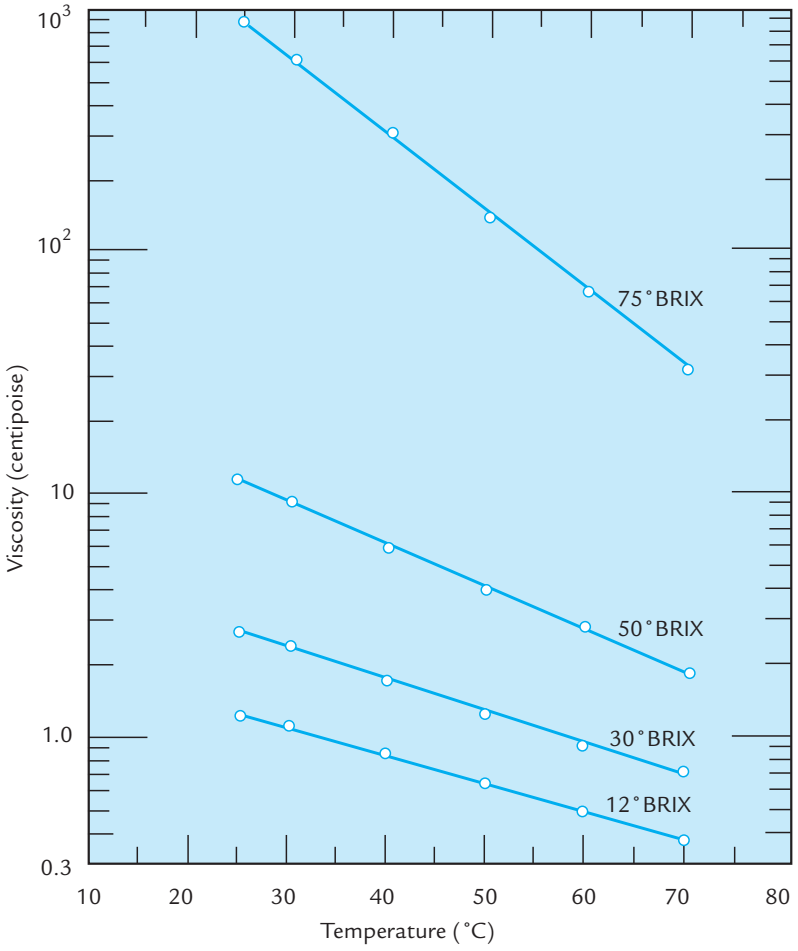


Figure 8.11 Effect of temperature on viscosity of depectinized apple juice and three apple juice concentrates. (From Saravacos, 1970. Reprinted from *J. Food Science* **35**, page 123. Copyright by Institute of Food Technologists.)

pointed out that, with few exceptions, the effect of temperature on viscosity can be expressed by the equation:

$$\eta = Be^{E/RT}$$

where η is viscosity, E is the activation energy in kcal gmol^{-1}, R is the gas constant, T is the absolute temperature in °K, and B is a constant.

Temperature may also affect the nature of flow of non-Newtonian fluids. For example, Fig. 8.12 shows that the power law exponent of butter, semisoft butter and margarine is about $n = 0.4$ at 31°C but increases to 1.0 or higher as the temperature increases to 40°C. These spreads change from a shear thinning fluid ($\eta < 1$) to a shear thickening fluid ($\eta > 1$) as the temperature rises about 10°C.

Many researchers are not aware that temperature also affects the measurements on solid food. Bourne (1982) defined a Texture–Temperature Coefficient (TTC) as:

$$\text{TTC} = \frac{\text{texture at temperature } T_2 - \text{texture at temperature } T_1}{\text{Texture at } T_1 \times (T_2 - T_1)} \times 100$$

percent texture change per degree temperature change where T_1 is the lowest temperature and T_2 the highest temperature over which the texture was measured. This definition assumes linearity between the texture parameter and temperature. For foods in which this relationship is not linear, this definition can still be used if the temperature range is narrowed to an approximately linear segment and the temperature range over which the TTC applies is specified (see the curve for Morepark apricot in Fig. 8.13).

Bourne (1982) published a lengthy list of TTC values for a number of raw fruits and vegetables. Figure 8.13 shows that over the temperature range 0–45°C the firmness of raw fruits and vegetables usually decreases linearly with temperature. Bourne and Comstock (1986) published a similar list of

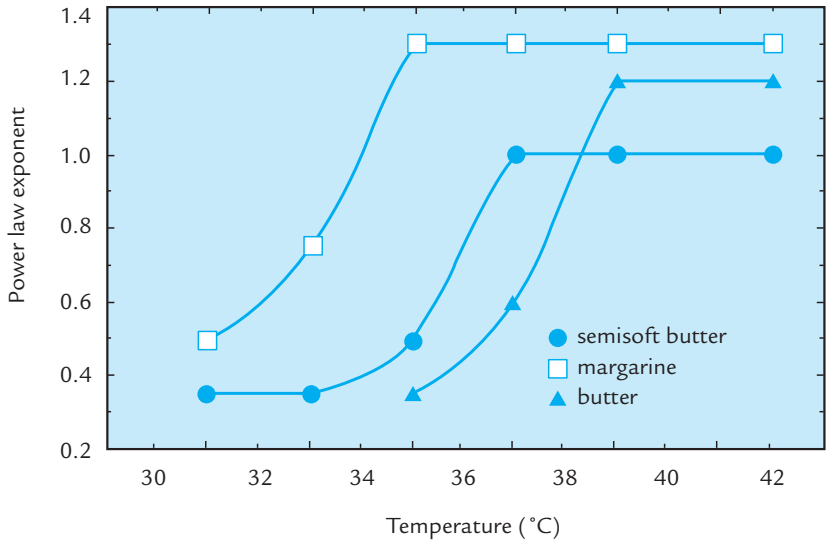


Figure 8.12 Temperature dependence of power law exponents for butter (▲), semisoft butter (●) and margarine (□). (From Britton and Callaghan, 2000. Reprinted from *J. Texture Studies* **31**, page 253. Copyright by Food and Nutrition Press Inc.)

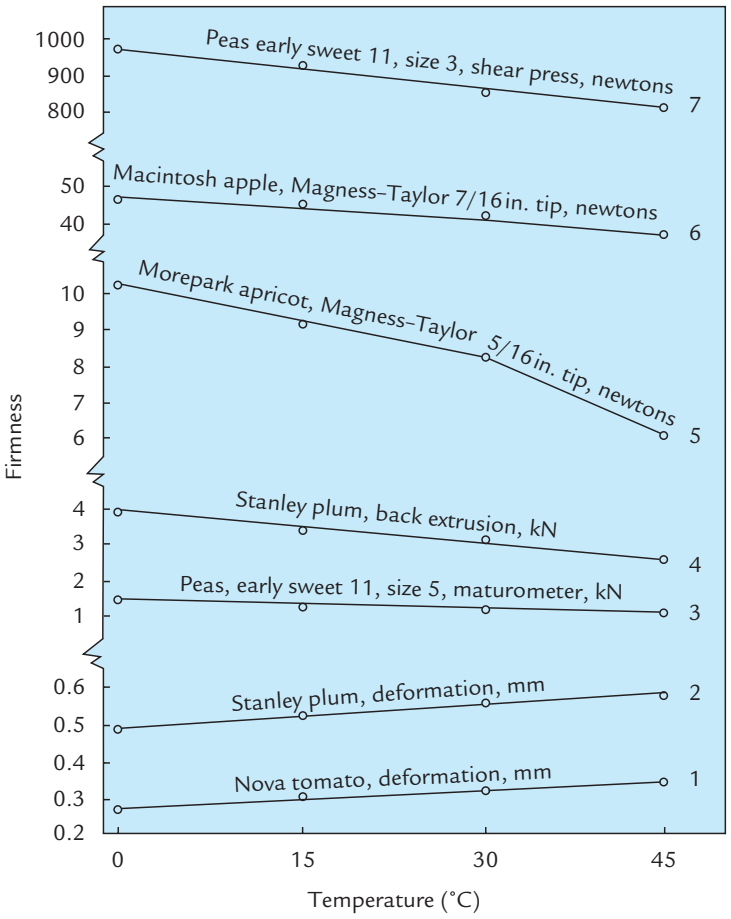


Figure 8.13 Effect of temperature on firmness of some raw fruits and vegetables. (From Bourne, 1982. Reprinted from *J. Food Science* **47**, page 444. Copyright by Institute of Food Technologists.)

TTC values for a number of canned fruits and vegetables and again found a linear relationship between firmness and temperature for most of the products tested. These TTC values for a large number of fruits and vegetables are given in Appendix II.

Table 8.4 lists texture–temperature coefficients that were calculated from published data for a wide variety of foods. Note that in almost every case, the magnitude of the texture measurement decreases as the temperature increases. The minus sign indicates that the TTC is inversely related to the temperature at which the measurement was made. The major exception to the inverse rule is the deformation test measuring the degree to which the food deforms under a standard force. In this test, the softer food gives a higher reading and since the product becomes softer with increasing temperature the TTC value is positive (see the curves for deformation of Stanley plum and Nova tomato in Fig. 8.13).

A study of Table 8.4 shows a wide range of TTC values. It becomes very high when the test temperature approaches a temperature-induced phase change, e.g. fats and gels near their melting point. For example, lard has a TTC of −27.7%/°C between 25 and 30°C (Table 8.4). In contrast most fruits and vegetables show a TTC between −0.2 and −1.0%/°C although Canoga strawberries show a TTC value of 7.7%/°C (see Appendix II). For water at

Table 8.4 Effect of Temperature on Texture of Various Foods

Food	Test	Temp range (°C)	T–T Coefficient (%/°C)	Reference
Water	Viscosity	20–21	−2.5	
Apple	Extrusion	0–45	−0.55	Bourne (1982)
Apple	Shear press	0–45	−0.43	Bourne (1982)
Apple	Puncture	0–45	−0.73	Bourne (1982)
Beans, green canned	Puncture	3–48	−0.02	Bourne and Comstock (1986)
Beans, green canned	Texture Press	3–48	−0.51	Bourne and Comstock (1986)
Beans, green fresh	Puncture	0–45	−0.10	Bourne (1982)
Beef, cooked	Warner–Bratzler Shear	22–50	−0.45	Caparaso *et al*. (1978)
Butter	Casson yield	5–15	−7.36	Kawanari *et al*. (1981)
Butter	Shear failure	5–15	−5.25	Kawanari *et al*. (1981)
Carrageen gel 1%	Puncture	4–24	−4.80	Oakenfull and Scott (1985)
Carrageen gel 1%	Puncture	24–44	−11.75	Oakenfull and Scott (1985)
Carragenan gel	Strength	10–20	−1.4	Szczesniak (1975a)
Cheese, Cheddar	Sliding pin Consistometer	1–20	−3.3	Davey (1986)
Cheese, Cheddar	Sliding pin Consistometer	20–25	0	Davey (1986)
Cheese, Mozzarella	Sliding pin Consistometer	1–20	−4.2	Davey (1986)
Cheese, Philadelphia cream	Sliding pin Consistometer	1–25	−2.5	Davey (1986)
Cheese, Cream				
Kraft Philly Regular	Yield stress	5–22	−3.36	Breidinger and Steffe (2001)
Kraft Philly Neufchatel	Yield stress	5–22	−3.19	Breidinger and Steffe (2001)
Kraft Philly Light	Yield stress	5–22	−4.15	Breidinger and Steffe (2001)
Kraft Philly Fat Free	Yield stress	5–22	−1.29	Breidinger and Steffe (2001)
Kraft Philly Whipped	Yield stress	5–22	−3.79	Breidinger and Steffe (2001)
Store Brand Regular	Yield stress	5–22	−3.46	Breidinger and Steffe (2001)
Store Brand Neufchatel	Yield stress	5–22	−3.27	Breidinger and Steffe (2001)
Store Brand Fat Free	Yield stress	5–22	−1.91	Breidinger and Steffe (2001)
Bruegger's Regular	Yield stress	5–22	−4.46	Breidinger and Steffe (2001)
Bruegger's Light	Yield stress	5–22	−4.00	Breidinger and Steffe (2001)
Chocolate	Viscosity	38–42	−1.2 to −3.8	Aeschliman and Beckett (2000)
Cottonseed oil, hydrogenated	Ball penetrometer	10–57	−2.04	Feuge and Guice (1959)
Cream, whipped	Extrusion	7–24	−3.9	Szczesniak (1975a)
Frankfurters	Puncture	0–21	−2.6	Simon *et al*. (1965)
Frankfurters	Puncture	21–49	0	Simon *et al*. (1965)
Gellan gels	Failure stress	2–62	−0.59 to −1.35	Mao *et al*. (1999)
Gellan gels	Failure strain	2–62	−0.36 to −0.79	Mao *et al*. (1999)
Gelatin gel	Strength	10–20	−6	Szczesniak (1975a)
Lard	Penetrometer	10–25	16.2	Bailey (1934)
Lard	Penetrometer	25–30	27.7	Bailey (1934)
Mango pulp	Yield stress	5–55	−0.51	Bhattacharya *et al*. (1999)
Mango pulp	Yield stress	55–80	−2.69	Bhattacharya *et al*. (1999)
Margarine	Shear failure stress	3–21	−4.21	Hamann (1983)
Peach, canned	Extrusion	3–48	−0.66	Bourne and Comstock (1986)
Peach, fresh	Puncture	0–45	−0.74	Bourne (1982)
Pectin (HM) gel	Puncture	4–48	−4.40	Oakenfull and Scott (1985)
Surimi gel, preset	Torsion shear stress	5–65	−0.83	Hamann and MacDonald (1992)
Whey protein gel 0% fat	Compressive strength	4–40	−0.25	Mor *et al*. (1999)
Whey protein gel 30% fat	Compressive strength	4–40	−0.75	Mor *et al*. (1999)

20°C the TTC value is −2.5%/°C which means that the viscosity at 21°C is 2.5% less than at 20°C.

Table 8.4 demonstrates that control of temperature at the time the texture of food is measured is essential if reproducible data are to be obtained. For foods with a low TTC value the temperature should be controlled to within ±2° to ±4°C of the target temperature, whereas for foods with a high TTC value it should be controlled within tighter limits. For many fats the previous temperature history can affect the texture. Thus, for this type of food the temperature needs to be controlled all the time, not only at the time of testing.

As stated above, for fruits and vegetables that have a low TTC value it is adequate to control the temperature at the time of testing to within ±2° to ±4°C because the temperature-induced change of texture will not be detected within the wide variation of textures normally encountered from one unit to the next. For example, if the TTC value is −0.4%/°C a change of 3°C will change the texture reading by $3 \times -0.4 = 1.2\%$, a difference unlikely to be detected given the high inherent variability from unit to unit. However, a change of 10°C will likely cause a measurable change in reading. For this reason, fruits and vegetables should not be tested at room temperature one day and at refrigerator temperature another day. It is also poor practice to compare texture measurements made in summertime with those made in wintertime in locations that have no climate control.

The temperature–texture effect can have commercial implications. If the texture reading for a food is close to a borderline standard of quality, the reading can be made to cross that border by raising or lowering the temperature at which the test is performed. For this reason, any food standard that includes a texture test as part of that standard should specify the temperature range at which the test should be performed.

Effect of Sample Size

The size of the test sample has little effect for some texture tests and a profound effect for others.

- Puncture test. The sample size is immaterial so long as semi-infinite geometry is maintained (see page 123).
- Warner–Bratzler Shear. The sample size affects the force reading but the exact relationship is unclear (see page 137).
- Back extrusion. The sample size has little effect on the force to begin extrusion but it should be large enough to ensure that true extrusion has begun (see page 128).
- Kramer Shear press. For some foods the force is directly proportional to sample weight, for other foods the force increases in a nonlinear manner with increasing weight, and for a third class of foods the force is constant after a certain minimum weight has been exceeded (see Fig. 5.6, page 205).

- Deformation. The specimen size and shape has a definite effect on the deformation reading. The degree of this effect depends both on the shape, size and deformability of the specimen (see pages 156–158).
- Texture profile analysis. The shape and size of the test piece is critical for obtaining reproducible results.

The texture technologist needs to know which test principles are sensitive to sample size and which ones are not. For those tests in which the sample size is immaterial, it is not necessary to take the time to standardize the amount, size and shape before executing the test.

Integrated Texture Notes

Some texture notes appear to be an integration of more than one physical property. For example, Twigg (1963) showed that two different measurements were needed to specify quality of both fresh and canned sweet corn: (1) the force to extrude the corn kernels through the slits of the Food Technology Corporation Texture Press ('Kramer Shear Press'); and (2) the volume of free juice expelled when compressed in a succulometer (Fig. 8.14).

In a similar vein, Daubert *et al*. (1998) showed that spreadability of products such as grape jelly, mayonnaise, and peanut butter was a function of both yield stress and yield strain. They constructed a 'spreadability map' with yield stress up the ordinate and yield strain along the abscissa and divided the map into three regions: (1) easy to spread; (2) mild to spread; (3) hard to spread (Fig. 8.15).

'Creaminess' is one of the most highly relished textural attributes in foods but has been very difficult to define completely. The consumer has a clear idea of the property of creaminess and considers it easy to assess whereas the scientist finds it very difficult to describe and measure. Wood (1974) showed that creaminess is found in soups when the viscosity exceeds 50 mPa·s and the

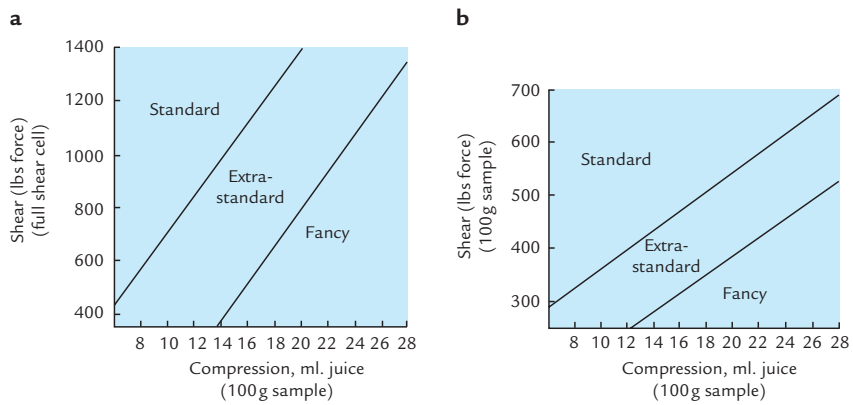


Figure 8.14 Shear Press force and Succulometer juice volume are needed to specify textural quality of (a) raw and (b) canned sweet corn. (From Twigg, 1963 with permission.)

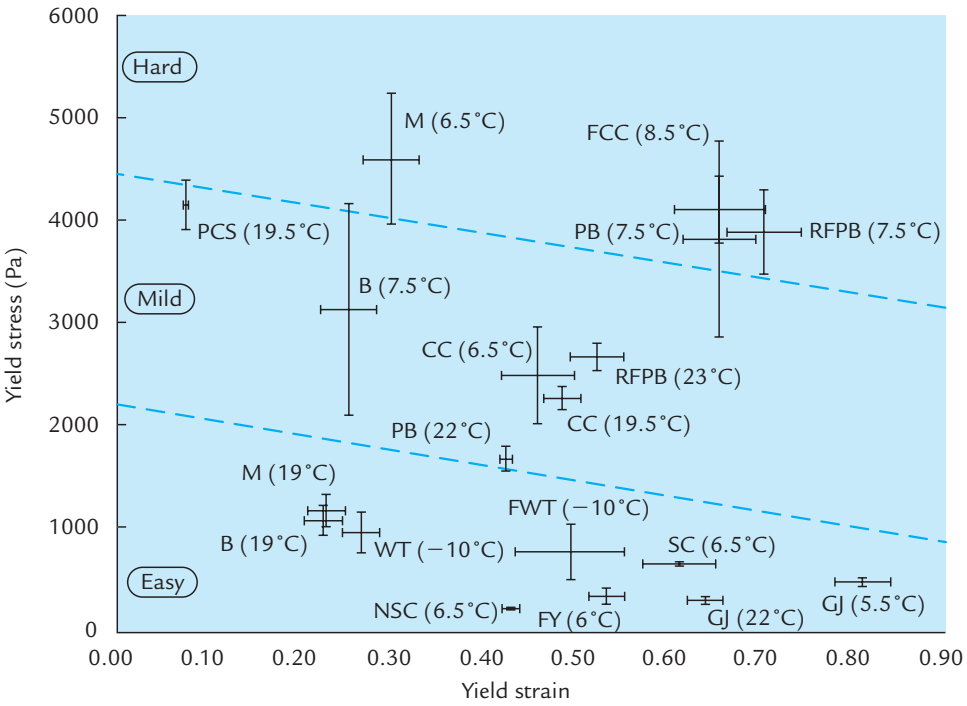


Figure 8.15 Spreadability map for elastoplastic foods (bars represent standard error; experimental temperatures are in parentheses). PCS, processed cheese spread; PB, peanut butter; RFPB, reduced fat peanut butter; GJ, grape jelly; CC, cream cheese; FCC, free cream cheese; M, margarine; B, touch of butter; FY, fat-free plain yogurt; SC, sour cream; NSC, nonfat sour cream; WT, whipped topping; FWT, fat-free whipped topping. (From Daubert *et al*., 1998. Reprinted from *J. Texture Studies* **29**, page 433. Copyright by Food and Nutrition Press Inc.)

Table 8.5 Sensory Creaminess of Thickened Dairy Creams[a]

% Fat	Optimum viscosity (mPa·s)	Optimum flow behavior index (*n*)	Sensory creamy score
3.5	880	0.15	17.5
10	1064	0.14	20.5
20	1808	0.11	22.6
30	7480	0.04	26.9

Source: Data from Daget *et al*. (1987). Reprinted from *J. Texture Studies* **18**, page 379. Copyright by Food and Nutrition Press Inc.
[a]Milk and creams were thickened with xanthan gum.

flow behavior index (n) is about 0.5 mPa·s. Kokini *et al*. (1984) showed that the regression equation:

$$\log \text{creamy} = 0.52 \log \text{thick} + 1.56 \log \text{soft} - 0.32 \log \text{slippery}$$

gave a correlation coefficient $r = 0.91$ with sensory evaluation of creaminess. Moskowitz and Kapsalis (1974) gave two equations for creaminess:

(1) $\text{creaminess} = 0.63 \times \text{cohesiveness} + 0.67 \times \text{mushiness} - 1.54 \; (r = 0.71)$

(2) $\text{creaminess} = 0.10 \; (\text{mushiness})^{0.86} \times (\text{cohesiveness})^{0.99} \; (r = 0.71)$

Daget *et al*. (1987) working with model dairy creams found maximum creaminess at viscosities ranging from 880 to 7480 mPa·s depending on the fat content (Table 8.5). However, Daget and Joerg (1991) found maximum

creaminess in soups at viscosities ranging from 90 to 430 mPa·s depending on the thickener used (Table 8.6). Richardson *et al*. (1993) showed that homogenized full fat milk was significantly lower in creaminess than nonhomogenized milk, but when the milks were thickened with sodium carboxymethylcellulose to the same viscosity as high fat cream the homogenized product was more creamy than the nonhomogenized (Table 8.7). However, even when thickened to the same viscosity as 47% fat cream the thickened milk was perceived as being less creamy than real cream, which suggests that the fat content is a factor in the creamy sensation.

So, how does a scientist precisely specify what is 'creamy'? It appears to be a combination of (1) moderate to high viscosity, (2) non-Newtonian flow (shear thinning), (3) presence of some fat, and (4) other factors whose function is not yet clear. The absence of geometrical properties is probably another component in the assessment of creaminess. Creamy foods are very smooth, and have to be free from gritty, lumpy, grainy or abrasive particles. The property of creaminess cannot be described by a single instrumental measurement.

Barreiro *et al*. (1998) gives another example of an integrated texture note. After an extensive study of apple quality they concluded that 'mealiness' of apples is a negative texture quality factor that cannot be described by a single

Table 8.6 Conditions for Optimum Creaminess of Soups

Soup flavor	Thickener	Optimum viscosity (mPa·s)	Optimum flow behavior index (n)
Mushroom	Galactomannan	352	0.42
Leek	Galactomannan	273	0.37
Leek	Xanthan	144	0.32
Leek	Carboxymethylcellulose	90	0.66–0.81
Leek	Starch	⩾140	0.38

Source: Data from Daget and Joerg (1991). Reprinted from *J. Texture Studies* **22**, page 172. Copyright by Food and Nutrition Press Inc.

Table 8.7 Creaminess of Milks

Sample	Viscosity (mPa·s)	Sensory creaminess	
		3.5% fat	4.5% fat
Not homogenized	12	75	77
Homogenized	13	65	63
Thickened, not homogenized	1860	80	82
Thickened, homogenized	1860	82	98
Double cream 47% fat	1850	140	

Source: Data from Richardson *et al*. (1993).
Milks were thickened with carboxymethylcellulose (CMC) to the same viscosity as double cream.

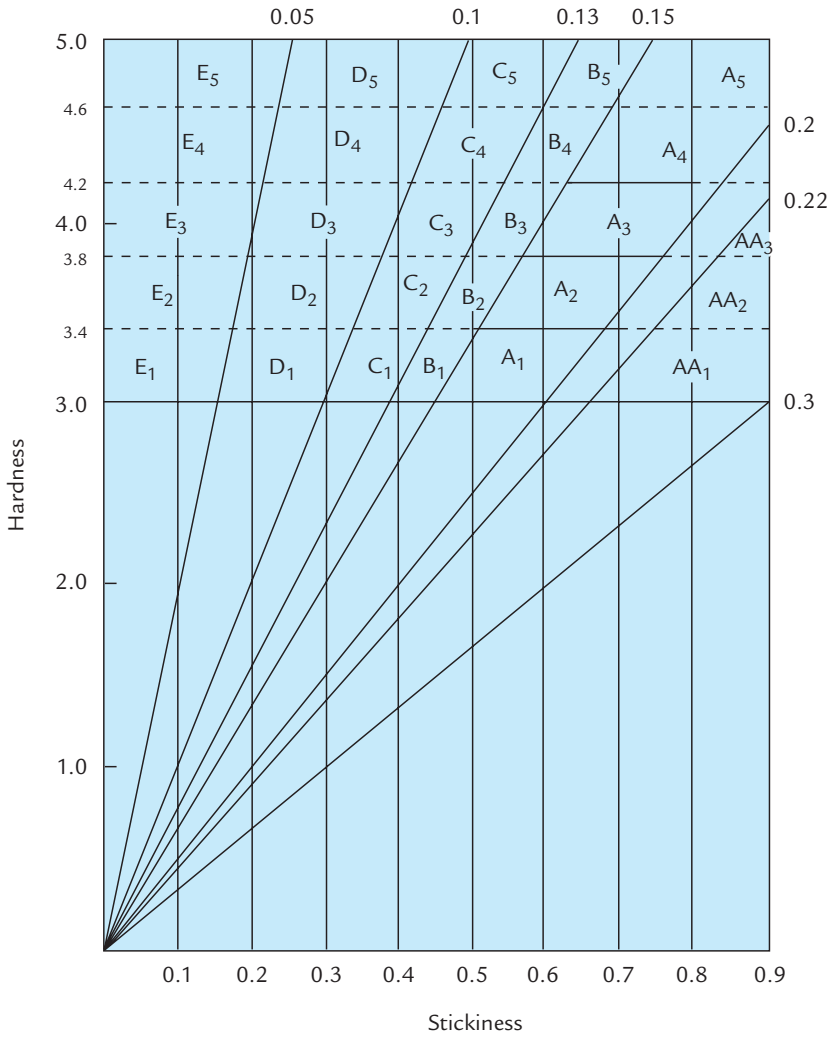


Figure 8.16 Texturogram for cooked rice using the GF Texturometer (from Okabe, 1979). Zones of acceptability are based on hardness (vertical scale 0–5), stickiness (horizontal scale 0–0.9), and stickiness/hardness ratio (sloping lines, scale 0.05–0.3): A, excellent; B, good; C, acceptable; D, poor; and E, unacceptable. Each acceptability zone is also ranked in terms of hardness: for example, A_1 is low hardness, A_3 moderate hardness, and A_5 high hardness for excellent quality rice, while E_1–E_5 covers the hardness range for unacceptable quality rice. The AA zone comprises glutinous rice and some special new rice varieties. (Reprinted from *J. Texture Studies* **10**, page 137, 1979; with permission of Food and Nutrition Press.)

sensory descriptor. It has to be described by four sensory attributes: (1) crispness, (2) floury, (3) first bite juiciness, and (4) juiciness during chewing.

The last example of integrated texture notes is with rice. The palatability of cooked rice for the Japanese was found to be governed primarily by hardness, stickiness, and the ratio of stickiness to hardness (Okabe, 1979). Rice of high hardness can be palatable if stickiness is also high.

Figure 8.16 indicates zones of acceptability of rice as a function of hardness, stickiness, and the hardness/stickiness ratio. This diagram has been used in Japan to characterize factors affecting the palatability of different varieties, and also storage and processing factors that affect rice quality.

Some Foods Easily Give High Correlations

The textural properties of some foods change in unison and in the same direction during processing or storage. In these cases several types of texture

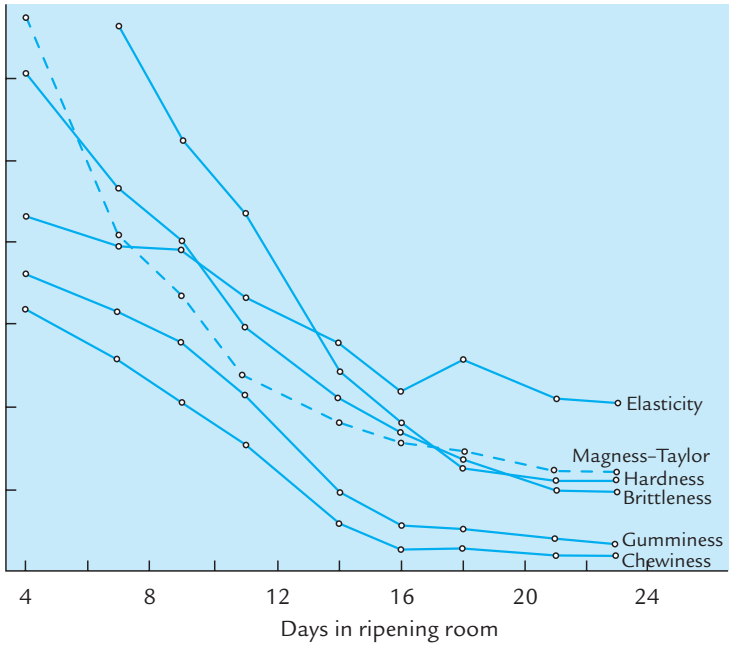


Figure 8.17 Changes in texture profile parameters and Magness–Taylor puncture test on pears as they ripen. Notice how all parameters change in the same direction at approximately the same rate. (From Bourne, 1968. Reprinted from *J. Food Sci.* **33**, 225, 1968. Copyright by Institute of Food Technologists.)

measurement will correlate well with other texture test principles and with a panel. An example of this is fruit that softens greatly as it ripens (pears, peaches, bananas). Measuring the changes in firmness of these commodities is fairly straightforward. Each of several different tests will give satisfactory results (Fig. 8.17). One can measure the wrong parameter and still get the right answer because of the nature of the interrelationships between the different parameters. In these cases the most convenient instrument and easiest to perform test principle should be selected. These foods are easy to measure by means of a simple parameter ('one-point' measurement) because each textural property correlates highly with all the other textural properties.

The textural properties of other foods change in different directions; it may be necessary to make several different kinds of tests to adequately describe the changes in textural properties of these foods. Under these conditions one can select several test principles or use texture profile analysis or an abbreviated version of texture profile analysis.

Correlation Graphs

It is useful to make a scatter diagram of the preliminary subjective and objective measurements before calculating the correlation coefficient because this enables one to see certain aspects of the correlation that may otherwise be overlooked. Some of the possibilities are shown schematically in Fig. 8.18, which shows nine potential relationships between instrumental tests (I) and sensory scores (S).

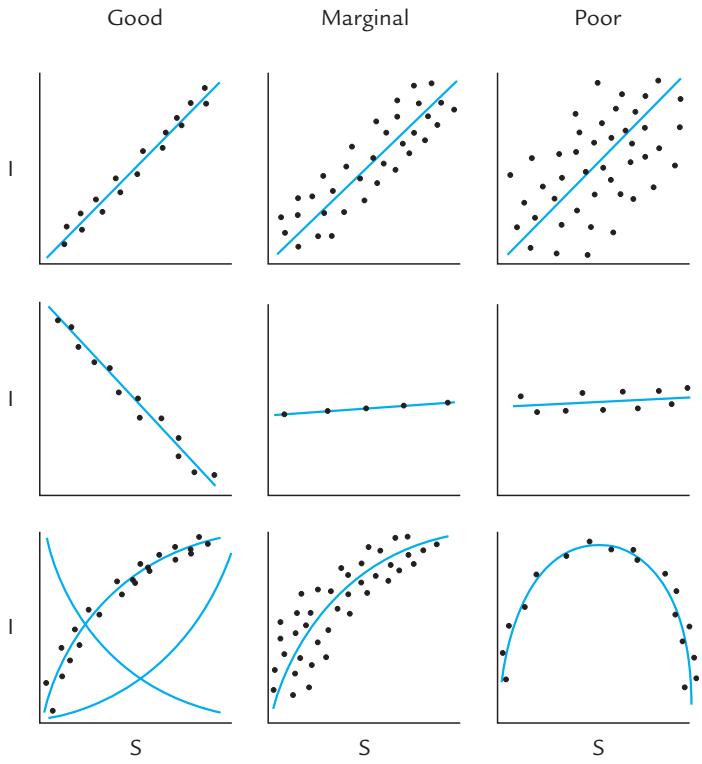


Figure 8.18 Correlation between instrumental tests (I) and sensory tests (S).

The first column on the left-hand side of Fig. 8.18 shows good correlations. The top graph shows a rectilinear relationship with the two desirable factors of a steep slope over the range of interest and a small degree of scatter. It is a very satisfactory relationship. The middle graph is just as satisfactory as the one above it, the only difference being that it has a negative slope. Three curvilinear relationships are shown in the bottom graph, each having the desirable features of low degree of scatter, and a steep slope. (For the sake of clarity, the scatter points are shown for only one line in this graph.) The curve may be concave or convex and may have a positive or negative slope, but it is very satisfactory. The simple correlation coefficient for any one of these three curves does not adequately reflect the goodness of fit of the experimental points to the line because it measures the goodness of fit to a straight line, not to a curve. Under these conditions it is advisable to transform the data in some way to straighten the curve (e.g. by taking logarithms on one or both axes) before calculating the correlation coefficient.

The three graphs in the center column of Fig. 8.18 show a marginal predictive relationship. They can be used to correlate instrumental tests with sensory judgments but not with the degree of certainty that is desirable. It is worth some effort to improve these relationships before using them. The top graph in the center column of Fig. 8.18 has the desirable steep slope, but the degree of scatter of the points is greater than the top curve in the left-hand column. The center graph in the center column has a good fit of the points to the line, but the line has a shallow slope which limits the usefulness of the correlation. The

bottom graph in the center column of Fig. 8.18 has a desirable steep slope, even with its curvature, but an undesirably wide degree of scatter.

The right-hand column in Fig. 8.18 shows relationships between instrument tests and sensory scores that are so poor that they should not be used for predictive purposes. In the top curve the degree of scatter from the line is too great, even though the slope of the line is steep. In the center curve the low slope of the line coupled with a moderate degree of scatter makes this relationship unsatisfactory for predictive purposes. The bottom right-hand graph in Fig. 8.18 is unsatisfactory because the relationship changes slope. It does not matter whether the slope changes from positive to negative or from negative to positive; any relationship in which the direction of the slope changes is unsatisfactory, even when there is a good fit of the data points to the curve.

The use of scatter diagrams as recommended above should not replace adequate statistical analysis of the data. Statistical analysis is definitely needed. Since it is outside the scope of this book to cover the analysis of the data, the reader should refer to a good book on statistical analysis or consult with a qualified statistician. The function of the scatter diagrams shown in Fig. 8.18 is to enable one to have a better understanding of the relationship before embarking on statistical analysis. They can also save unnecessary effort in computation. For example, if any of the relationships shown in the right-hand column of Fig. 8.18 are obtained, it would be better to continue to look for a better test procedure than to put a lot of effort into sophisticated statistical analysis of data that are obviously unsatisfactory.

A useful guide of the suitability of a correlation for quality control purposes, provided that representative samples and adequate sample size have been used, was given by Kramer (1951). When the simple correlation coefficient between the instrument test and sensory score is ± 0.9 to ± 1.0, the instrument test is a good one and it can be used with confidence as a predictor of sensory score. When the correlation coefficient lies between ± 0.8 and ± 0.9, the test can be used as a predictor but with less confidence; it is worth some effort to improve the test to bring the correlation coefficient above ± 0.9. Extending this concept further, when the correlation coefficient lies between ± 0.7 and ± 0.8, the test is of marginal use as a predictor; when it is less than ± 0.7, it is practically worthless for predictive purposes (Table 8.8).

Table 8.8 Instrument–Sensory Correlations

	r	r^2
Excellent	± 0.9–± 1.0	0.81–1.00
Good	± 0.8–± 0.9	0.64–0.81
Marginal	± 0.7–± 0.8	0.49–0.64
Poor	$< \pm 0.7$	<0.49

Source: After Kramer (1951).

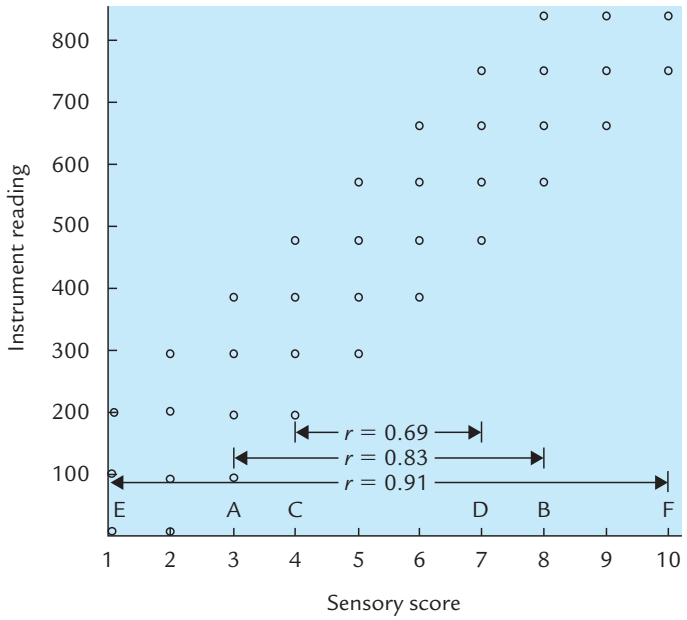


Figure 8.19 A hypothetical case of instrumental vs sensory measurement of firmness showing how the range of firmness examined affects the correlation coefficient *r*. A–B, normal range, $r = 0.83$; C–D, narrow range, $r = 0.69$; E–F, excessively wide range, $r = 0.91$.

A statistically significant relationship between an instrument test and sensory score may be found even with a low correlation coefficient if the sample size is large enough. For example, a correlation coefficient of 0.3 may be statistically significant, but it is far from adequate for predictive purposes. One needs to distinguish between statistical significance and predictive reliability.

The full textural range that will be encountered under reasonable circumstances should be used when setting up the preliminary tests. When a restricted range is used, the correlation coefficient will be lower than when the full range is used. Conversely, the correlation coefficient will be spuriously high when an excessively wide range is used.

The effect of too narrow or too broad a range on the numerical value of the correlation coefficient is demonstrated in Fig. 8.19, which is a hypothetical example of comparisons between instrumental and sensory testing of firmness of a food. The normal range of variability in this commodity is A–B and the correlation coefficient *r* over this range is 0.828. When a narrower range C–D is covered, the correlation coefficient drops to 0.695. This is a spuriously low figure because an unnecessarily narrow range was studied. On the other hand, when an extremely wide range E–F is covered, the correlation coefficient increases to 0.910. But this is a spuriously high figure because an abnormally wide range was taken.

Texture technologists work hard to obtain high correlation coefficients between physical tests and sensory assessments because a high value of *r* indicates that the physical test will be a good predictor of sensory assessment of textural quality. Such tests are useful for quality control purposes in the food factory. However, a high correlation coefficient does not prove there is a cause-and-effect relationship. It only means that the variables are changing in unison. Szczesniak (1968) points out that as fruits ripen they generally become softer and sweeter. A high negative correlation is often found between

firmness and sweetness in fruit. This does not mean that the loss of firmness causes the increase in sweetness. The depolymerization of the pectin material and the increase in sugar content are two independent processes that happen to occur simultaneously.

Figure 8.17 is another example of high correlations that do not mean cause-and-effect. All the textural properties of pears decrease at about the same rate as the pear ripens. However, there is no reason to expect that any of these properties are causing changes in any of the other properties.

Commonsense Helps

Because there are so many different textural properties occurring in foods with vastly different structures and different chemical compositions that are measured by a complex instrument (human body), the reader is cautioned against blindly using some test procedure and hoping it will work. It is worth stepping back and reviewing the whole problem including all the points raised in this chapter. A commonsense overview of the whole procedure is recommended. Are there any artifacts? Have unwarranted assumptions been made? Can some modification improve the reliability of the procedure? For example, Szczesniak (1968) measured in a calorimeter the heat absorbed by whipped cream-like products, and related this to the degree of sensory coolness reported by a sensory panel. Calorimeters express results in calories per gram of product. The correlation between calories per gram and sensory coolness was $r = 0.62$. However, whipped toppings contain entrapped air, and the panel was given a standard volume of 5 ml, not a constant weight of product. When the correlation was calculated between calories per 5 ml and sensory coolness the r was 0.94. Commonsense brought out the fact that sensory coolness is related to both heat capacity and density of these products.

Summing Up

Obtaining a high correlation between physical tests and sensory assessments of textural quality has been the goal of scientists from many disciplines including food scientists, physicists, sensory scientists, psychologists and dentists. This chapter explains the complexities involved in this search. Much has been accomplished, but much more needs to be known. The reader should be aware of the broad ramifications of this subject area, and look for further advances. The final chapter is yet to be written on this subject.

This Page Intentionally Left Blank

Selection of a Suitable Test Procedure

CHAPTER 9

Introduction

The previous chapters have described a large number of methods for measuring texture or viscosity of foods. A food technologist can easily become bewildered when first faced with the problem of developing a suitable procedure for measuring the textural properties of a particular food. Where does one begin? The following discussion is intended as a guide for selecting and establishing a texture measurement, particularly for those who are just entering the field.

A number of factors should be considered before setting up a new test procedure, otherwise a good deal of money and time can be wasted. The following recommended steps are based on the author's experience on a wide range of problems associated with many different kinds of foods.

The procedure described below can be used to select a suitable instrument. If one already has a universal testing machine the same procedure can be used to select which test principle is most appropriate for that particular food and which attachments are needed to perform the test.

Factors to be Considered

Instrument or Sensory

The first decision is whether to use an instrument or a sensory test. Instruments are generally preferred because they are believed to be more reproducible, use less time, and utilize a minimum of labor. On the other hand, there are times when sensory methods are the only way in which adequate information can be obtained. If the decision is made to use sensory methods, the reader is referred back to Chapter 7 because the remainder of this chapter is directed to the selection and use of instrumental methods.

Nature of Product

The kind of material (liquid, solid, brittle, plastic, homogeneous, heterogeneous) affects which type of instruments will be selected. Most tests on solid or near-solid foods use some form of uniaxial compression whereas sophisticated tests for viscosity generally use some form of rotational motion.

Purpose of Test

Is the test to be used for quality control, for setting legally binding official standards, for product development, or for basic research? These questions should be answered because they are an essential feature of the selection process. The previous chapters discussed a wide range of instruments ranging from simple and inexpensive to highly sophisticated. Each of them has its place. In some cases a single-point measurement is adequate; in other cases a multipoint measurement is needed. One is usually prepared to sacrifice sophistication for the sake of rapidity for routine quality control purposes where a rapid test is essential. On the other hand, difficult problems that are handled in the research laboratory or in new product development may need more sophisticated instrumentation.

The difference between simple and sophisticated instruments might be likened to the difference between a $20 and a $500 camera. A $20 camera usually has a fixed focus, is simple to operate, and almost foolproof. The quality of the picture is not as good as that obtained with an expensive camera that has been properly operated, and it is restricted in the conditions of lighting and movement of the subject under which satisfactory pictures can be taken. Nevertheless, a great number of low-cost cameras are sold because the simplicity of operation and low cost are of paramount consideration. In contrast, the $500 camera has a better lens, it provides better-quality pictures, and it can be used under a wide range of conditions. However, the person operating the $500 camera needs to know something about its operation because of the complexity of the adjustments that need to be made. Novices frequently take poorer pictures with an expensive camera than with a cheap camera because they do not know how to set the adjustments on the expensive camera. A similar situation occurs with texture-measuring instruments. Sophisticated instrumentation has its place, but there is also room for the simple low-cost instruments.

Accuracy Required

Another question that should be resolved is the required accuracy of the results. Greater accuracy is obtained as the number of replications is increased. Generally, a larger sample size gives a result closer to the true mean than a small sample size, and hence fewer replicate tests are needed to obtain a given degree of accuracy. But a larger sample size usually means that higher forces are needed, and the force capacity of the instrument may be exceeded. When

the 'spread' of values between individual units is needed, it is preferable to use a small sample size and run a large number of replicates in order to increase the probability of obtaining the full spread of values.

It comes as a surprise to some researchers to find a large inherent variability from unit to unit in the same sample lot. This is especially noticeable on most native foods where coefficients of variation of 10%, 20%, or higher are common. This variation is inherent in the commodity and is to be expected. It is not a defect of the instrument, provided the instrument is correctly operated. When working with a new commodity, it is advisable to run a preliminary test to ascertain the degree of inherent variability in the product and to establish how large a sample size and number of replicates are necessary to give the desired degree of confidence in the data. An example of this type of exercise is shown in Table 9.1. Fairly large numbers of apples are required for reliable reproducible results at harvest time because of the large variation in firmness readings within the same lot of apples. A smaller number suffices after 4 months storage because of the reduced fruit-to-fruit variation.

Since this inherent wide variability is the norm for most foods (see pages 305–309), the primary consideration in most texture work is to look for an instrument that can perform tests rapidly, thus allowing a number of replicate tests to be made. A high degree of precision is a secondary consideration because there is little point in attempting to measure some textural parameter to a precision of 1% when the replicate samples may vary by 20% or more, especially when considerable extra time is required to obtain the high degree of precision. It is usually preferable to replicate a 1-min test five times than to run a more precise 5-min test only once.

Table 9.1 Differences in Magness–Taylor Measurements (lb) on Fresh Apples Required for Evaluating Significance Between Treatment Means for Various Sample Sizes

	95% Confidence level[a]				99% Confidence level[a]			
	10	20	100	200	10	20	100	200
At harvest								
Red Delicious	1.9	1.3	0.6	0.4	2.6	1.8	0.8	0.6
Golden Delicious	1.1	0.8	0.4	0.3	1.5	1.1	0.5	0.3
Rome	1.1	0.8	0.3	0.2	1.4	1.0	0.5	0.3
York	2.0	1.4	0.7	0.5	2.8	1.9	0.9	0.6
Stored 4 months at 31°F								
Red Delicious	0.8	0.5	0.2	0.2	1.0	0.7	0.3	0.2
Golden Delicious	0.8	0.6	0.3	0.2	1.1	0.8	0.3	0.2
Rome	0.9	0.6	0.3	0.2	1.2	0.8	0.4	0.3
York	1.7	1.2	0.5	0.4	2.3	1.6	0.7	0.5

Source: Worthington and Yeatman (1968); reprinted with permission from the *Proc. Am. Soc. Hort. Sci.* See also Schultz and Schneider (1955).

[a]Columns are set up according to number of apples.

Destructive or Nondestructive

Destructive tests ruin the structure and organization of the sample, rendering it unsuitable for repeating the test. Nondestructive tests should leave the food in a condition so close to its original state that the test can be repeated and give the same result as the first time. Both destructive and nondestructive tests have had their successes and failures (Bourne, 1979a). Because the majority of the textural parameters of foods are sensed in the mouth and mastication is a destructive process, it seems logical that destructive tests should be the predominant type to be used on foods. Nevertheless, nondestructive tests are sometimes effective, and they offer the advantage that the same piece of food can be repeatedly tested, thus eliminating variations in geometry from piece to piece. The deformation test in which a food is gently compressed in a manner that imitates the squeezing of the food in the hand is the most widely used nondestructive test. It is a test principle that is likely to be more widely used in the future.

Costs

How much money can be spent on this test? This includes the initial cost of the instrument, and maintenance and operating costs. An instrument that uses chart paper has an operating cost not found with an instrument in which a dial reading is taken. The maintenance cost should be considered. Does the instrument need spare parts and what is their availability and cost? Is the instrument used occasionally or frequently? Another element is the labor cost. A simple instrument can be operated by unskilled or semiskilled personnel whereas sophisticated instruments need to be operated by a person with higher qualifications. An automatic instrument costs more than a simple instrument but may cost less per test because of reduced labor requirement and less chance of making errors.

Time

How much time can be spent on the test? Routine quality control tests need an instrument that gives results rapidly. In contrast, some tests in the research laboratory may be so sophisticated that the amount of time required to obtain reliable data is not of great consequence. Research needs may require measuring a number of textural parameters, which will take more time than a one-point measurement.

Location

Where will the instrument be operated? Any instrument can be used in a clean, dry laboratory. Instruments used in the plant may need to withstand steam, water, dust, vibration, and other hazards that render some instruments unsuitable. Instruments using a chart, complex electronic systems or computers are

likely to suffer damage in the steamy atmosphere of a processing plant unless specially designed to withstand the poor environment.

Eliminate Unsuitable Tests

Some test principles are obviously unsuitable for the commodity that needs to be tested and should be eliminated from consideration. For example, an extrusion test is unsuited for crackers and bread because these products do not flow; the puncture test works poorly on most brittle foods because they crumble or fracture before penetration: a cone penetrometer test is unsuitable for fibrous materials such as meat or raw vegetables; a snapping test will not be effective for flexible or fluid materials. Sometimes the geometry of the sample (size and shape) may impose limitations. For example, a large item cannot be tested in an instrument that has a small compartment for holding the sample.

Preliminary Selection

The steps described above will reduce the number of instruments or test principles under consideration. The next step is to narrow the field to the most promising two or three test principles. It is advisable to observe what kind of test principle people use in the sensory evaluation of textural quality because one can usually get good clues for the type of objective test to select by observing how people test the commodity. For example, if people judge textural quality by gently squeezing in the hand, consideration should be given to a test that works on the deformation principle. If people use a bending or snapping test, then this test principle should be given a high priority. If people bite the product between the incisors, the cutting–shear principle should be included among the preliminary tests.

The test principles that should be considered are

Puncture	Viscosity–consistency
Deformation	Crushing
Extrusion	Indirect methods (e.g. chemical or sound analysis)
Penetration	Tensile
Cutting–shear	Texture profile analysis
Snapping–bending	Distance measurement
Torsion	Volume measurement
	Miscellaneous methods

All researchers should be warned about persevering with an instrument just ‘because it is there.’ By all means, try out an instrument if it is available and

continue to use it if it gives satisfactory results. However, if it fails to give satisfaction after adequate testing, its use should be abandoned and one should look for another instrument that uses a different principle. One can easily spend far more than the cost of another instrument in labor costs by persevering with a test that uses the wrong principle for that particular application.

If you are getting unsatisfactory results with a universal testing machine, consider using another configuration and test principle. Some instrument suppliers have built up a library of successful test procedures for a wide range of food types and are willing to share their accumulated experience with their customers.

Sometimes none of the established procedures give satisfactory results. In these cases the researcher should have the confidence to develop a new test procedure or apparatus that is suitable for the purpose.

Final Selection

By this time, the number of principles should have been reduced to a small number. It is now time to test each of the remaining principles over the full range of textures that will normally be encountered with the food (i.e. excellent to poor) and identify the most suitable one. If any principle proves to be ineffective after being given a fair try, do not persevere with it; abandon it and try some other principle. For example, if the Magness–Taylor puncture test fails to give satisfactory results after a fair trial, then other instruments that work on the puncture principle will probably be unsatisfactory also. Therefore, abandon the puncture test principle and look at instruments that use another principle such as deformation or extrusion. The author has seen instances where a laboratory has persevered with a single test principle for a long time hoping it will eventually give satisfactory results when in fact an unsuitable test principle was being used that would never be satisfactory for the commodity under study. In these cases, refining the test is not going to help because an inappropriate test principle is being used.

The selection among several principles to identify one that gives the best results can be done rather quickly. For example, the author was once faced with the problem of measuring the firmness of whole potatoes. Having gone through the preliminary selection it was agreed that the most suitable test would be either a puncture test or a deformation test. Three groups of potatoes (soft, medium, hard) were selected by hand with about 10 potatoes in each group. Each of these potatoes was then tested in the Instron using first a deformation test and then a puncture test. The mean values were calculated and are plotted in Fig. 9.1. It is obvious from this simple test, which only needed a few hours to perform, that the puncture principle is unsuitable for measuring the kind of firmness that was being sensed in the hand, but the deformation test showed promise. Therefore, we concentrated on refining the deformation test

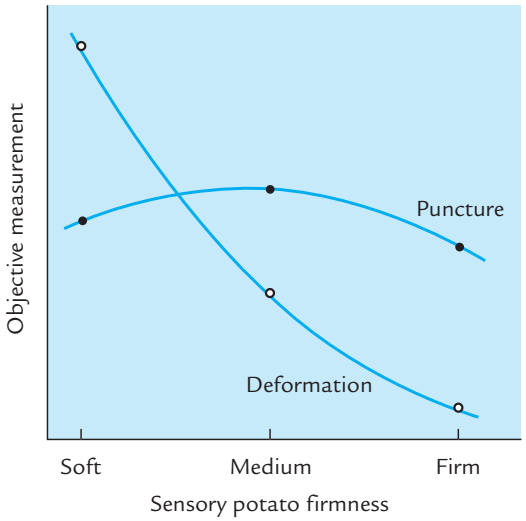


Figure 9.1 Two objective methods for measuring firmness of whole potatoes versus sensory evaluation of firmness of the same potatoes.

and wasted no more time trying to perfect the puncture test principle for this particular application (Bourne and Mondy, 1967).

The needed result from such an exploratory plot of instrument texture reading versus sensory texture assessment is a line with a steep slope and a close fit of the data points to that line. The differences between good, marginal and poor scatter plots are shown in Fig. 8.18 (page 320). If the exploratory plot resembles those shown under the marginal or poor columns in Fig. 8.18 it is best to abandon that test principle and try a different one. 'Tweaking' the conditions of the test is unlikely to change a marginal test into a good test.

Even when a plot of instrument texture reading versus sensory texture assessment falls in the 'good' column shown in Fig. 8.18, it is possible that trying several different instruments or test principles will identify one as being superior to the others. For example, Fig. 9.2 shows how the consistency of chapati dough is affected by the amount of water added to the wheat flour. Three instruments were used to measure the consistency: the farinograph, the General Foods Texturometer and the research water absorption meter (RWAM). Each instrument gave a rectilinear plot when log (instrument reading) was plotted against percent (added water). Each instrument gave an excellent fit of the data points to a straight line. Therefore, it was concluded that any of these instruments would be satisfactory. However, as explained below they differed in their resolving power.

The resolving power of any measurement is the ability to distinguish between two items that are close together. For example, a telescope with a large lens has greater resolving power than one with a small lens because it will show a distant point of light as two stars whereas the small telescope will show only one point of light. Figure 9.2 shows that the RWAM gave a slope more than twice as steep as those for the other two instruments (0.0565 for RWAM versus 0.0200 for the farinograph and 0.0235 for the GF Texturometer). Therefore, the RWAM will give the strongest separation between the samples because it has the strongest resolving power.

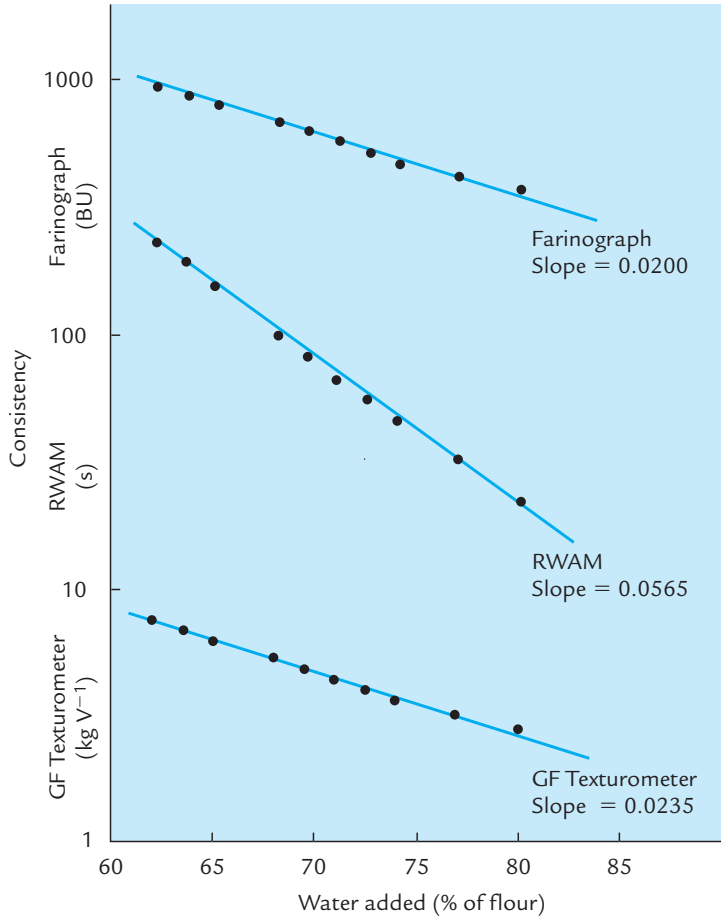


Figure 9.2 Consistency of chapati dough as a function of added water measured by three instruments: Farinograph, Research Water Absorption Meter (RWAM) and General Foods Texturometer. (From Bourne, 1990. Plotted from data of Rao *et al.*, 1986. Reprinted from Dough Rheology and Baked Products Texture, eds Faridi and Faubion, Fig. 6.3, page 339. This material used by permission of John Wiley and Sons, Inc.)

Refine Test Conditions

The final step is to standardize the test conditions such as sample size, test cell dimensions, force range, speed of travel of moving parts, chart speed, temperature, and perhaps other factors. Several variations of the test conditions should be studied to find which gives the best resolution between different samples. For example, a small deforming force generally gives a better resolution in deformation tests than a high force (see pages 154, 155). The test conditions finally selected should then be recorded for future use.

Some of the questions that should be addressed at this time are:

(1) Does sample size affect the test result? (see page 314).
(2) Does the textural property change slightly or greatly as the temperature changes? (see page 314).
(3) Does the rate of compression affect the result, i.e. is the product strain rate sensitive? (see pages 303–305).
(4) Is the product anisotropic? (see pages 103 and 309). When the product is isotropic it can be presented to the instrument in any direction, but if it is anisotropic it must always be presented in the same direction.

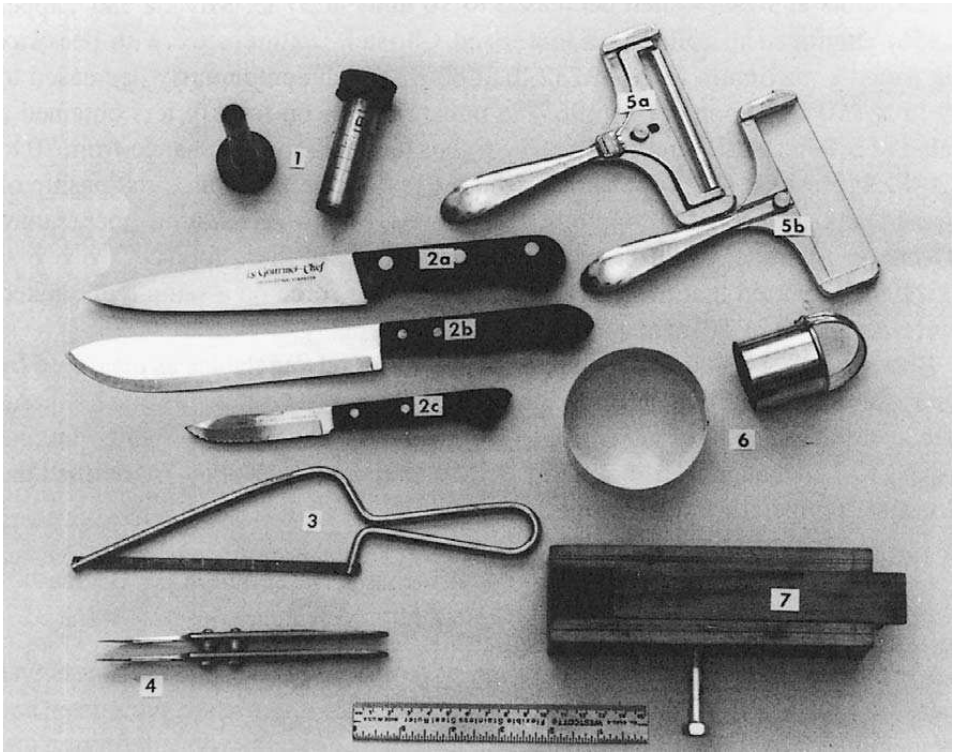


Figure 9.3 Some useful tools for shaping foods: 1, cork borers; 2, knives; 2a is the preferred type; 2b is undesirable because it is hollow ground and has a thick blade; 2c is undesirable because it is too small, is hollow ground and has a serrated edge; 3, small fine-tooth saw; 4, a pair of scalpels bolted together; 5a, household cheese cutter as purchased; 5b, cheese cutter with roller removed leaving space to cut samples up to 25 mm thick; 6, a large and a small cookie cutter; 7, a miter box with an adjustable slide.

(5) How uniform is the product? A larger sample size or more replicate tests are needed if the product is not uniform (see page 305). Does the texture vary consistently across the length of the product? If so, always take the sample from the same location (see page 309).

Preparation of the Sample

Adequate sample preparation is an important element in performing food texture measurements. Problems with sample preparation sometimes impel the researcher to use a particular test principle or instrument. The sample selected for testing should be representative of the lot from which it was drawn. This point is so well known and so important that it should not require an extended discussion.

The shaping of foods to standard measurements is a practical problem that is often frustrating and time consuming. Some practical tips that the author has found useful are the following (see Fig. 9.3):

(1) A cork borer is useful for cutting out cylinders. A motorized borer is preferred to a hand-operated borer. Make sure the borer is kept sharp. Apply a light uniform pressure when cutting because an uneven diameter is obtained if the pressure is not held steady. Continuous heavy pressure will give an hourglass shape instead of a uniform cylinder especially on highly deformable foods such as meat.

(2) A sharp knife is useful for cutting many foods. A fairly long thin blade that is not hollow ground and not serrated gives the best results. A back-and-forth sawing motion under gentle pressure gives better control of dimensions than applying a heavy downward cutting action. It is difficult to get surfaces flat and parallel when using a thick-bladed or hollow ground knife.
(3) A small saw with very fine teeth is useful for cutting hard fracturable materials to size. We use a saw blade 6 in. long with 32 teeth per inch.
(4) Two scalpels bolted together with spacers between them make an implement that is useful for some applications.
(5) A wire cutter is good for shaping adhesive foods such as soft cheese. An easy way to get one is to buy a household cheese cutter and remove the roller bar.
(6) A circular cookie cutter is helpful for cutting dumbbell shapes suitable for a tensile test.
(7) A miter box used in conjunction with a sharp knife, a small saw, or a wire cutter helps in cutting samples to a standard length and cutting uniform cubes for texture profile analysis.

Food technologists have to face the fact that some foods cannot be shaped. It is impossible to cut a head of lettuce, a peanut, or a potato chip to a standard geometry without destroying the integrity of the sample as a whole. In these cases the best one can do is to select units of as uniform shape and size as possible and be realistic about the fact that the data points will show more scatter than if pieces of standard size and shape had been available. If possible a nondestructive test should be used for these foods because the same unit can be repeatedly tested as it undergoes the experimental treatments while the geometry factor remains constant.

An example of careful selection for size is given by Garruti and Bourne (1985) who performed instrumental texture profile analysis on cooked red kidney beans. The bean seeds were sized on bean sieves the base of which comprised a metal sheet containing 3/4 in. long slits with parallel sides and semicircular ends. In each succeeding member in the set of sieves the slit was 1/64 in. wider than the previous member. Ninety-five percent of the beans passed through the 7/16 in. wide slits and were retained in the 12/64 in. wide slits. However, only those seeds that passed through the 16/64 in. wide slits and were retained on the 15/64 in. wide slits were used for instrumental texture profile analysis. This meant that the maximum size variation from seed to seed was 1/64 in. ($\equiv$0.4 mm).

Calibration

In the past, a texture measurement was often considered to be satisfactory so long as it gave consistent results at one location but this attitude is no longer

adequate. Several forces are now building pressure for internationally accepted standards of textural quality.

(1) Food corporations became larger and established factories in a number of different locations and countries, each of which is required to manufacture a product to consistent standards.
(2) The strength of huge buyers such as supermarket chains and fast food restaurant chains who must obtain their foods from various sources yet need to deliver a consistent quality to their customers.
(3) The need for agreement on textural quality between buyers and sellers of foods and food ingredients.
(4) Great increase in food trade around the world.

Therefore, the calibration and operation of instruments to ensure that the same quality product receives exactly the same measurement no matter where it is tested is becoming a matter of increasing importance.

Most of the problems associated with getting high correlations between an instrument reading and sensory assessment of texture discussed in the previous chapter can also be applied to calibration of instruments and procedures for measuring texture and viscosity. (See Instrument Problems, page 299, and Commodity Problems, page 299.) A strong effort should be made to standardize every aspect of a test to ensure that results are comparable between laboratories. A written protocol should be developed giving every detail.

Unfortunately, the record to date is not an encouraging one. Major differences are sometimes found when the same product is tested in different laboratories. For example, in a collaborative study involving eight laboratories in seven countries the reported viscosity of a sucrose solution ranged from 5.5 to 8.4 mPa·s and 5% of the data points lay outside ±31% of the mean value (Prentice and Huber, 1983). For a vegetable oil (assumed to be a medium viscosity Newtonian fluid) the power equation was used and the reported flow behavior index (n) values ranged from 0.950 to 1.037 and the consistency index (K) values from 0.0639 to 0.399.

Prentice and Huber (1983) also reported power equation n and K values for other products tested in the same eight laboratories. For an aqueous karaya gum solution, n ranged from 0.41 to 0.67 and K from 0.12 to 2.45; for an aqueous carrageenan gum solution, n ranged from 0.43 to 0.81 and K from 0.91 to 2.54; and for applesauce, n ranged from 0.25 to 0.58 and K from 16.8 to 36.1. The Casson viscosity for one sample of chocolate ranged from 1.67 to 4.40 in these laboratories.

Wheeler *et al*. (1997) compared Warner–Bratzler shear force readings on cooked beef *longissimus dorum* muscles from 27 steers within and among five meat research laboratories in the United States. In the first study each institution cooked and tested the beef using procedures they normally used. In the second study they used a standardized protocol. The results, summarized in Table 9.2, show substantial differences between these five laboratories. The authors concluded there was clearly a need for greater control of thawing

Table 9.2 Comparison of Warner–Bratzler Shear Force on Beef Longissimus Muscle among Five Institutions

	Normal institution procedure				Standardized protocol			
Institution	*n*	Mean	Standard deviation	Range	*n*	Mean	Standard deviation	Range
A	53	4.7	1.1	2.6–7.6	89	5.1	1.7	2.6–10.7
B	52	2.9	0.5	1.7–4.0	90	4.3	1.2	2.1–7.1
C	52	3.2	0.8	2.0–5.4	90	4.6	1.5	2.2–10.7
D	52	3.4	0.9	2.1–6.6	90	4.2	1.3	2.0–7.7
E	52	3.4	0.7	2.5–5.4	89	3.7	1.5	1.7–8.3

Source: Data from Wheeler *et al*. (1997). Reprinted from *J. Animal Science* **75**, page 2427. Copyright by Journal of Animal Science.
n, number of samples tested; Warner–Bratzler shear force expressed in kg force.

conditions before cooking commences. They also noted that proper execution of a standardized protocol is imperative for obtaining accurate and repeatable shear force measurement. Their final comment, 'until a standardized protocol is uniformly adopted, it is not valid to compare Warner–Bratzler shear force values among institutions or use shear force thresholds developed at other institutions.'

Aeschlimann and Beckett (2000) coordinated a study among 32 laboratories in eight countries of factors affecting chocolate viscosity with the goal of improving the standard method for measuring viscosity of chocolate published by the International Office of Cocoa, Chocolate and Sugar Confectionery. The first ring test in this study showed a wide range of values for the Casson plastic viscosity and Casson yield value on three different chocolates (Table 9.3). Factors that were found to affect the viscosity values were:

(1) Traces of moisture thicken the chocolate. The use of a water bath to maintain constant temperature must be avoided. Chocolate must be melted in sealed containers.
(2) The fat in the chocolate must be completely melted because unmelted crystals reduce the liquid phase and increase the viscosity. Any chocolate below 40°C should be placed in an oven at 52°C for a minimum of 75 min before a viscosity measurement is performed.
(3) Changes in the milk protein that occur after storing the chocolate in liquid form for extended periods increase the thickness of milk chocolate. Milk chocolates should be melted for a maximum of 2–3 h before measuring the viscosity.
(4) The viscosity of chocolate decreases 1.2% to 3.8% per 1°C temperature increase. Close temperature control is essential. Large temperature variations were found in one laboratory where the connecting pipes from the circulator had been connected backwards.
(5) The geometry of cup and bob viscometers affects the measurement. One laboratory that used a wider gap gave outlier data as compared to the other laboratories.

Table 9.3 Casson Yield Values and Plastic Viscosities for Three Chocolates Tested on 22 Viscometers in 13 Laboratories

	Milk Chocolate 1	Milk Chocolate 2	Dark Chocolate
Casson plastic viscosity (Pa·s)			
Mean	4.1	3.2	2.6
Range	2.7–5.5	2.2–4.6	2.1–3.9
Casson yield value (Pa)			
Mean	8	12	20
Range	4–16	2–18	4–32

Source: Aeschlimann and Beckett (2000). Reprinted from *J. Texture Studies* **31**, page 543. Copyright by Food and Nutrition Press Inc.

(6) One laboratory whose viscometer was out of calibration also gave outlier data.
(7) When the cylinder and bob were thoroughly defatted using 1,1,1,trichloroethane the Casson plastic viscosity decreased 5.5% and the yield value 6.5%.
(8) A viscometer using cone and plate geometry gave significantly different results from viscometers using concentric cylinder geometry.

The three examples cited above demonstrate that meticulous care must be taken in every aspect of a texture test. Nothing should be taken for granted. Regular calibration of the instrument and a standardized procedure for preparing the sample and presenting it to the instrument are critical for reproducible results. One should regard compilations of texture data with skepticism because much of that data may be wrong and it is difficult to know which data are reliable and which worthless.

From time to time some group attempts to calibrate instruments against a 'standard product.' Bourne (1972a) reviewed attempts to find a standard reference material that could be tested in the instrument in the same manner as food. These have included asbestos sheet, solid rubber, foam rubber, silicone rubber, filter paper, blotting paper, foamed plastics, plastic sheets, paraffin wax, metal foil, a specified brand of cigarettes, resins, 'Play Do,' 'Buz,' gels, putty, and a single batch of dried peas canned with calcium chloride. Every one of these efforts to find a 'standard product' has been a failure. Bourne (1972a) predicted that the search for a standard product to calibrate instruments will continue to be unsuccessful and cited the following reasons:

(1) Textural properties of the standard material generally bear only a faint resemblance to the textural properties of the food for which it is supposed to act as standard. Even when it matches one textural property of the food, it fails to match the other textural properties.
(2) The manufacturer's specifications generally take little account of the physical properties that are of interest to a food rheologist. For example,

paraffin wax and other petroleum fractions are extremely variable materials (Barry and Grace, 1971) and their physical properties change rapidly with temperature.

(3) Suppose some material was found that resembled the textural properties of a food; there is no assurance that the manufacturer would or could maintain those properties precisely from batch to batch or from year to year. Each manufacturer has their own specifications and since the product is usually nonfood it would be sheer coincidence if the physical properties of the product matched those of a food and maintained that match over a long period of time and under a wide range of climate conditions.

(4) The manufacturer is not aware that their product is being used as a standard material by the food industry. Even if they knew, the sales volume for this purpose would be too small to warrant the special effort to give the food market the highly standardized product it wanted.

Bourne (1972a) also pointed out that only functions of force, distance, and time are involved in specifying the textural properties of foods. These functions may be numerous and complex in nature, but it is unlikely that any variable other than force, distance, or time is involved. The logical approach to instrument standardization would be to standardize in units of force, distance, time or some combination of these (e.g. work) because they are fundamental standards that are completely reproducible at all times.

The main problem in standardizing many instruments is the friction between the moving parts of the test cells and slip in rotational viscometers. The frictional error varies from instrument to instrument because of small differences in dimensions or alignment of the working parts. In a single instrument, the friction can vary from test to test for several reasons:

(1) Working parts may be bent, twisted, dented, or otherwise misaligned during a test.
(2) Frictional force is not constant throughout the working stroke.
(3) Particles of food, especially skin and fibers, may jam between the moving parts causing a temporary increase in friction.
(4) Liquid exuding from the food may act as a lubricant, causing a temporary decrease in friction.
(5) Food material can build up on the working parts and increase the friction if these are not thoroughly cleaned after each test.

Hence, the degree of error caused by friction cannot be standardized. This is a compelling reason to give preference to test cell geometries in which there can be no friction between the parts of the test cell.

There is one potential exception to the bleak picture in this search for reference materials – the calibration of viscometers with a Newtonian fluid. The viscosity of a Newtonian fluid is a physical property that is precisely defined in fundamental units and is completely reproducible. Consequently, the

calibration of a viscometer with a Newtonian fluid may be effective, provided the material to be tested is also Newtonian. Unfortunately, there are few liquid foods that exhibit Newtonian behavior and this restricts the applicability of the method. Even then there is no guarantee of success. The report by Prentice and Huber (1983), discussed earlier, showed poor agreement between eight laboratories testing two Newtonian liquids, sugar syrup and vegetable oil. With rotational viscometers one must always be alert to the possibility of slip between the food and the moving surface. Other artifacts often found in rotational viscometers are lack of concentricity and inertial effects of the rotating member. Some of the viscosity data cited in tables in this book may be unreliable because of unnoticed slip, lack of concentricity or inertia of the bob.

Bourne (1972a) expressed the opinion that we cannot have satisfactory reference materials until each of the textural properties of foods is defined as rigorously as the viscosity of a Newtonian fluid, and until products that possess each of these properties in pure form can be supplied. Even then, the problem of friction between moving parts will remain. Food rheologists should give up the wild goose chase of searching for a test material that will overcome deficiencies in test cell design and instrument operation. It would be a better procedure to concentrate on designing the friction out of the test cells and calibrate the instruments in fundamental units of force, distance, or time and to recalibrate the instruments on a regular basis.

There are a number of organizations around the world, such as the American Society for Testing and Materials, that are dedicated to establishing written protocols for calibration and operation of instruments and preparation of the sample to ensure that reproducible results are obtained between and among laboratories. Texture technologists have much to learn from the many years of experience that has been condensed into official test protocols by these standards organizations.

This Page Intentionally Left Blank

APPENDIX

I

Suppliers of Texture and Viscosity Measuring Instruments

The compilation that follows represents the best information available to the author at the time of writing. However, the author takes no responsibility of the accuracy of the information. The reader should contact the manufacturer or distributor directly for the latest information on hardware, software, accessories, availability, delivery and price.

The price ranges are given as a rough guide to cost. Contact the manufacturer for the latest price quotation. The price designations are as follows:

A	less than $1000
B	$1000 to $5000
C	$5000 to $25,000
D	more than $25,000

Since the author resides in the United States it is possible that some instruments used in other countries are not on the following list. The author invites instrument makers to send him information if their instruments are not listed below.

Mail to M. C. Bourne, NYSAS-Cornell University, Geneva, New York 14456-0462, USA.

Table A I.1

Instrument	Supplier	Price range
Albumen Height Gauge	(see Haugh Meter)	
Amylograph	C. W. Brabender Instruments, Inc. 50 E. Wesley St South Hackensack, NJ 07606, USA www.cwbrabender.com	C
Applesauce Consistometer	(see USDA Applesauce Consistometer)	

(*Continued*)

Table A I.1 (*Continued*)

Instrument	Supplier	Price range
Bostwick Consistometer (Many laboratory supply houses carry the Bostwick)	Cole-Parmer Instrument Company 625 East Bunker Court Vernon Hills, IL 60061-1844, USA www.foodtechsource.com	A
Brookfield Viscometers	Brookfield Engineering Laboratories, Inc. 240 Cushing St Stoughton, MA 02072-2398, USA www.brookfieldengineering.com	B–D
Capillary Glass Viscometers (Most laboratory supply houses carry capillary viscometers)	Cannon Instrument Co. PO Box 16 State College, PA 16804-0016, USA www.cannon-ins.com	A
	Cole-Parmer Instrument Company 625 East Bunker Court Vernon Hills, IL 60061-1844, USA www.foodtechsource.com	
Chatillon Testers	Ametek, Inc. 8600 Somerset Drive Largo, FL 33773, USA www.ametek.com	A
	Wagner Instruments PO Box 1217 Greenwich, CT 06836, USA www.wagnerforce.com	A
Consistometer	(see Adams. Bostwick, USDA, FMC Consistometers)	
Effi-Gi Tester	Effi-Gi Fruit Tester via Real 63 48011 Alfonsine RA Italy email: fucchini.itaweb.com	A
The US Distributors:	Wagner Instruments PO Box 1217 Greenwich, CT 06836, USA www.wagnerforce.com	
	Wilson International 1104 E. Mead Yakima, WA 98903, USA www.wilsonirr.com	
Electromyography	BioResearch, Inc. 4113 N. Port Washington Road Milwaukee, WI 53212-1029, USA www.biojva.com	C
Extensigraph	C. W. Brabender Instruments Co. 50 E. Wesley St South Hackensack, NJ 07606, USA www.cwbrabender.com	C

(*Continued*)

Table A I.1 (*Continued*)

Instrument	Supplier	Price range
Farinograph	C. W. Brabender Instruments Co. 50 E. Wesley St South Hackensack, NJ 07606, USA www.cwbrabender.com	C
FMC Consistomer	C. W. Brabender Instruments Co. 50 E. Wesley St South Hackensack, NJ 07606, USA www.cwbrabender.com	B
Food Technology Corporation (FTC) Texture Test System (Kramer Shear Press)	Food Technology Corporation 45921 Maries Road, Suite 120 Sterling, VA 20166, USA www.foodtechcorp.com	C (all models)
Fruit Firmness Tester (Firmtech2)	BioWorks Inc. 1621 W. University Stillwater, OK 74074, USA email: BioworksFT@aol.com	B
Gel Torsion	Gel Consultants 2620 Lizei St Raleigh, NC 27616, USA www.gelconsultants.com	C
Gilmont Viscometer	Barnant Company 28W092 Commercial Avenue Barrington, IL 60010, USA www.barnant.com	A
Haake Viscometers	Haake Instruments Inc. 53 West Century Road Paramus, NJ 07652, USA www.thermohaake.com	B, C
Haugh Meter	B. C. Ames Inc. 78 Stone Place Melrose, MA 02176, USA www.bcamesco.com	A
Instron Universal Testing Machine	Instron Corporation 2500 Washington St Canton, MA 02021, USA www.Instron.com	D (Model 5542) C (Model 4442)
Kramer Shear Press	(see Food Technology Corporation Texture Test System)	
Loaf Volumeter	National Manufacturing, A Division of TMCO Inc. 507 "J" St Lincoln, NE 68508-2935, USA	B
Lloyd Universal Testing	Ametek, Inc. 8600 Somerset Drive Largo, FL 33773, USA www.ametek.com	C
Magness-Taylor Pressure Tester	(see Puncture testers)	

(*Continued*)

Table A I.1 (*Continued*)

Instrument	Supplier	Price range
Mixograph	National Manufacturing, A Division of TMCO Inc. 507 "J" St Lincoln, NE 68508-2935, USA	C
Nametre Viscometer	Nametre Company 55 Wiggins Avenue Bedford, MA 01730, USA www.nametre.com	C
Penetrometer (Many laboratory supply houses carry Penetrometers)	Petrolab Company 874 Albany-Shaker Road Latham, NY 12110, USA www.petrolab.com	B
	Cole-Palmer Instrument Company 625 East Bunker Court Vernon Hills, IL 60061-1844, USA www.foodtechsource.com	
Puncture Testers	(see Ballauf, Chatillon, Effi-Gi, Magness-Taylor, Stevens)	
QTS Texture Analysers	(see Stevens LFRA Texture Analyser)	
Rapid Visco-Analyzer	Newport-Scientific Pty. Ltd. 29 Gondola Road Narrabeen (Sydney) New South Wales 2101 Australia www.newport.com.au	
The North American Distributor:	Foss Food Technology Corp. 10355 W. 70th St Eden Prairie, MN 55344, USA www.fossnorthamerica.com	
Rheometrics Fluids Rheometer	Rheometrics Inc. One Possumtown Road Piscataway, NJ 08854, USA www.rheosci.com	E
Stevens LFRA Texture Analyzer	CNS Farnell 1 Manor Place, Manor Way Borehamwood WD6 7WG, UK www.textureanalysis.com	
The US Distributor:	Michael Brown & Associates, Inc. 14 Locust Lane Newton, PA 18940, USA www.stevenstextureanalyser.com	
Structograph	C. W. Brabender Instruments, Inc. 50 E. Wesley St South Hackensack, NJ 07606, USA www.cwbrabender.com	C
TA.XT2 Texture Analyser	Stable Micro Systems Vienna Court Lammas Road Godalming, Surrey GU7 1YL, UK www.stablemicrosystems.com	C

(*Continued*)

Table A I.1 (*Continued*)

Instrument	Supplier	Price range
The North American Distributors:	Texture Technologies Corp. 18 Fairview Road Scarsdale, NY 10583, USA www.texturetechnologies.com	
Tensipresser	Taketomo Electronic Co. Ltd. 1-55 Wakamatsu-Cho Shinjuku-Ku Tokyo 162, Japan	D
Universal Testing Machine	see Lloyd, Instron, TA.XT2 Tensipresser, Wagner	
USDA Applesauce Consistometer	Head, Standardization Section U.S. Department of Agriculture Agricultural Marketing Service Fruit and Vegetable Programs Processed Products Branch Stop 0247 1400 Independence Ave 5W Washington, DC 20250-0247, USA www.ams.usda.gov/fv/ppbweb/PPBfilecodes/105a15.htm	
Viscometers	Analytical Process Inc. PO Box 131301 Houston, TX 77219-1301, USA www.analyticalprocess.com	A–D
	ATS Rheosystems 52 Georgetown Road Bordentown, NJ 08505, USA www.atsrheosystems.com/~ats	
	Haake Instruments Inc. 53 West Century Road Paramus, NJ 07652, USA www.thermohaake.com	
	Nametre 25 Wiggins Avenue Bedford, MA 01730, USA www.nametre.com	
	Rheometric Inc. One Possumtown Road Piscataway, NJ 08854, USA www.rheosci.com	
	TA Instruments Inc. 109 Lukens Drive New Castle, DE 19720-2795, USA www.tainst.com	
Wagner Universal Testing Machines	Wagner Instruments PO Box 1217 Greenwich, CT 06836-1217, USA www.wagnerforce.com	B
Warner-Bratzler Shear	G-R Electric Mfg. Co. Route 2 Manhattan, KS 66502, USA	B

(*Continued*)

Table A I.1 (*Continued*)

Instrument	Supplier	Price range
Zahn Viscosimeter (Most laboratory supply houses carry Zahn viscometers in stock.)	Cole-Parmer Instrument Company 625 East Bunker Court Vernon Hills, IL 60061-1844, USA www.foodsource.com	A

Effect of Temperature on Texture Measurements

APPENDIX II

Table AII.1 Effect of Temperature on Firmness of Raw Fruits and Vegetables: Literature Values

Commodity	Type of measurement	Temp. range (°C)	Change per 1°C increase	Reference
Apple, Idared	puncture 7/16 in. diam tip	2–21	force −0.42%	Blanpied *et al.* (1978)
Apple, R.I. Greening	puncture 7/16 in. diam tip	2–21	force −0.39%	Blanpied *et al.* (1978)
Apple, Rome	puncture 7/16 in. diam tip	2–21	force −0.61%	Blanpied *et al.* (1978)
Apple, Baldwin	puncture 1/4 in. diam tip	2–33	rupture stress −0.44% rupture strain +0.58% rupture energy −0.27%	Fletcher (1975)
Blackberry, Erie	puncture 0.060 mm diam tip	13–26	force −0.92%	Hawkins and Sando (1920)
Blackberry, Erie	puncture 0.060 mm diam tip	13–27	force −0.83%	Hawkins and Sando (1920)
Blackberry, Lawton	puncture 0.060 mm diam tip	13–28	force −1.07%	Hawkins and Sando (1920)
Blackberry, Lawton	puncture 0.060 mm diam tip	13–25	force −1.52%	Hawkins and Sando (1920)
Blackberry, Wachuset	puncture 0.060 mm diam tip	16–26	force −2.30%	Hawkins and Sando (1920)
Blackberry, unknown variety	puncture 0.060 mm diam tip	13–26	force −2.01%	Hawkins and Sando (1920)
Blackberry, unknown variety	puncture 0.060 mm diam tip	12–27	force −0.90%	Hawkins and Sando (1920)
Cherry, Napoleon	puncture 2 mm diam tip	0–32.2	force −0.93%	Hartman and Bullis (1929)
Cherry, Montmerency	puncture 0.068 mm diam tip	16–27	force −1.95%	Hawkins and Sando (1920)
Cherry, Montmerency	puncture 0.068 mm diam tip	13–29	force −1.12%	Hawkins and Sando (1920)
Pears, Bartlett	puncture 1/2 in. diam tip	0.6–36.1	force −0.38%	Hartman (1924)
Peas, Admiral size 2	FMC Tenderometer	2–49	−0.30 Tenderometer units	Martin *et al.* (1938)
Peas, Admiral size 4	FMC Tenderometer	2–49	−0.31 Tenderometer units	Martin *et al.* (1938)
Peas, Alaska size 2	FMC Tenderometer	2–49	−0.46 Tenderometer units	Martin *et al.* (1938)
Peas, Alaska size 4	FMC Tenderometer	2–49	−0.48 Tenderometer units	Martin *et al.* (1938)
Peas, Tall Alderman	FMC Tenderometer	2–45	−0.48 Tenderometer units, early season	Campbell (1942)
Peas, Tall Alderman	FMC Tenderometer	2–45	−0.40 Tenderometer units, late season	Campbell (1942)

(*Continued*)

Table AII.1 (*Continued*)

Commodity	Type of measurement	Temp. range (°C)	Change per 1°C increase	Reference
Peas, 4 varieties	FMC Tenderometer	not stated	−0.5 Tenderometer units	Makower *et al*. (1953)
Peas, test 1	Ottawa Pea Tenderometer	18–32	−0.27 kg force	Voisey and Nonnecke (1972)
Peas, test 2	Ottawa Pea Tenderometer	18–32	−0.16 kg force	Voisey and Nonnecke (1972)
Raspberry, black	puncture 0.121 mm diam tip	14–25	force −2.60%	Hawkins and Sando (1920)
Raspberry, red	puncture 0.313 mm diam tip	16–27	force −2.20%	Hawkins and Sando (1920)
Raspberry, red	puncture 0.313 mm diam tip	16–28	force −2.16%	Hawkins and Sando (1920)
Strawberry, Cooney	puncture 0.636 mm diam tip	16–29	force −1.08%	Hawkins and Sando (1920)
Strawberry, Cooney	puncture 0.636 mm diam tip	13–24	force −2.54%	Hawkins and Sando (1920)
Strawberry, Cooney	puncture 0.636 mm diam tip	16–26	force −3.21%	Hawkins and Sando (1920)
Strawberry, Cooney	puncture 0.636 mm diam tip	16–23	force −3.14%	Hawkins and Sando (1920)
Strawberry, No. 29-5	puncture 0.636 mm diam tip	16–29	force −2.92%	Hawkins and Sando (1920)
Strawberry, unnamed variety	puncture 0.636 mm diam tip	13–23	force −2.53%	Hawkins and Sando (1920)
Strawberry, unnamed variety	puncture 0.636 mm diam tip	16–30	force −1.93%	Hawkins and Sando (1920)
Strawberry, Fletcher	puncture, Dunkley pitter	2–43.5	force −1.06%	Ourecky and Bourne (1968)
Strawberry, Fortune	puncture, Dunkley pitter	2–43.5	force −1.00%	Ourecky and Bourne (1968)
Strawberry, Frontenac	puncture, Dunkley pitter	2–43.5	force −1.19%	Ourecky and Bourne (1968)
Strawberry, NY 844	puncture, Dunkley pitter	2–43.5	force −0.67%	Ourecky and Bourne (1968)
Strawberry 1928	puncture 1/4 in. diam tip	0–21.1	force −1.36%	Rose *et al*. (1934)
Strawberry 1933	deformation[a]	0–21.1	force −0.29%	Rose *et al*. (1934)
Strawberry 1934	deformation[a]	0–21.1	force −0.32%	Rose *et al*. (1934)

Source: Bourne (1982). Reprinted from *J. Food Science* **47**, page 441. Copyright by Institute of Food Technologists.
[a] This test measured the force in grams to give a combined deformation of 7/8 in. in the fruit and spring scale.

Table AII.2 Effect of Temperature on Firmness of Raw Fruits and Vegetables

Commodity	Description	Type of measurement	Firmness-temp coeffi. (% change in firmness per 1°C increase)
Apple	Golden Delicious, 1972 crop, stored 9 months	Back extrusion	−0.55
Apple	Golden Delicious, 1972 crop, stored 9 months	Shear Press	−0.43
Apple	Golden Delicious, 1972 crop, stored 9 months	Puncture, 1/8 in. tip	−0.73
Apple	Golden Delicious, 1977 crop, stored 7 months	Magness Taylor 7/16 in. tip	−0.45
Apple	Golden Delicious, 1977 crop, stored 7 months	Back extrusion	−0.19
Apple	Golden Delicious, 1977 crop, stored 7 months	Shear Press	−0.04
Apple	Idared, stored 7 months	Magness Taylor 7/16 in. tip	−0.32
Apple	Idared, stored 7 months	Magness Taylor 7/16 in. tip yield point	−0.42
Apple	Idared, stored 7 months	Back extrusion	−0.90
Apple	Idared, stored 7 months	Shear Press	−0.57
Apple	Red Delicious, stored 1 week	Back extrusion	−0.23
Apple	Red Delicious, stored 1 week	Shear Press	−0.33
Apple	Red Delicious, stored 7 months	Magness Taylor 7/16 in. tip	−0.20
Apple	Red Delicious, stored 7 months	Magness Taylor 7/16 in. tip yield point	−0.30

(*Continued*)

Table AII.2 (*Continued*)

Commodity	Description	Type of measurement	Firmness-temp coeffi. (% change in firmness per 1°C increase)
Apple	Red Delicious, stored 7 months	Back extrusion	−0.48
Apple	Red Delicious, stored 7 months	Shear Press	−0.16
Apple	McIntosh, stored 2 weeks	Magness Taylor 7/16 in. tip	−0.39
Apple	McIntosh, stored 2 weeks	Magness Taylor 7/16 in. tip yield point	−0.42
Apple	McIntosh, stored 2 weeks	Back extrusion	−0.58
Apple	McIntosh, stored 2 weeks	Shear Press	−0.61
Apple	Rome, stored 1 week	Magness Taylor 7/16 in. tip	−0.08
Apple	Rome, stored 1 week	Magness Taylor 7/16 in. tip yield point	−0.12
Apple	Rome, stored 1 week	Back extrusion	−0.22
Apple	Rome, stored 1 week	Shear Press	−0.07
Apricot	Morepark, firm ripe 0–30°C	Magness Taylor 5/16 in. tip	−0.66
Apricot	Morepark, firm ripe 30–45°C	Magness Taylor 5/16 in. tip	−1.65
Apricot	Morepark, soft ripe	Magness Taylor 5/16 in. tip	−0.72
Apricot	SHA-47	Deformation to 0.3 Newton	+0.15[a]
Apricot	Vineland 60081	Deformation to 0.3 Newton	−0.29[a]
Apricot	Vineland 60081	Back extrusion	−0.44
Beans, snap	Early Wax, sieve size 3	Puncture, 1/8 in. tip	−0.09
Beans, snap	Early Wax, sieve size 4	Puncture, 1/8 in. tip	−0.10
Beans, snap	Early Wax, sieve size 5	Puncture, 1/8 in. tip	−0.18
Beans, snap	Slim Green, sieve size 4	Puncture, 1/8 in. tip	+0.11
Beans, snap	Slim Green, sieve size 5	Puncture, 1/8 in. tip	+0.06
Beets	Detroit Dark Red 2½–3 in. diam	Deformation to 1 Newton	+0.28[a]
Beets	Detroit Dark Red 2½–3 in. diam	Puncture, 1/8 in. tip	−0.09
Carrot	Chantenary, phloem tissue	Puncture, 3/32 in. tip	+0.12
Cherry	Emperor Francis	Dunkley pitter	−1.11
Corn, sweet	NK199 10–35°C	Shear Press	−1.34
Corn, sweet	NK199 10–35°C	Back extrusion	−0.44
Corn, sweet	Jubilee 10–35°C	Shear Press	−1.31
Corn, sweet	Jubilee 10–35°C	Back extrusion	−0.82
Corn, sweet	Deep Gold 10–35°C	Shear Press	−1.08
Corn, sweet	Deep Gold 10–35°C	Back extrusion	−0.35
Cucumber	Marketor	Deformation to 0.5 Newton	−0.27[a]
Cucumber	Marketor 0–30°C	Puncture, 1/8 in. tip	+0.04
Cucumber	Marketor 30–45°C	Puncture, 1/8 in. tip	−0.65
Onion	Autumn Keeper 1¾–2 in. diam	Deformation to 4 Newtons	−0.58[a]
Onion	Autumn Keeper 1¾–2 in. diam	Puncture, Magness Taylor 5/16 in. tip	−0.18
Peach	Baby Gold (clingstone) 9/5/80	Deformation to 1 Newton	−0.97[a]
Peach	Baby Gold (clingstone) 9/8/80	Deformation to 1 Newton	−0.22[a]
Peach	Hale Haven (freestone)	Deformation to 1 Newton	+3.37[a]
Peach	Sun Cling (clingstone)	Magness Taylor 7/16 in. tip	−0.74
Peach	Bisco (freestone)	Magness Taylor 7/16 in. tip	−0.75
Pear	Bartlett	Magness Taylor 5/16 in. tip	−0.47
Pear	Bartlett	Deformation to 1.5 Newton	+0.12
Peas, green	Early Sweet 11, sieve size 3, AIS 11.6%	Shear Press	−0.32
Peas, green	Early Sweet 11, sieve size 3, AIS 11.6%	Maturometer	−0.52
Peas, green	Early Sweet 11, sieve size 3, AIS 11.6%	Back extrusion	−0.62

(*Continued*)

Table AII.2 (*Continued*)

Commodity	Description	Type of measurement	Firmness-temp coeffi. (% change in firmness per 1°C increase)
Peas, green	Early Sweet 11, sieve size 4, AIS 16.0%	Shear Press	−0.35
Peas, green	Early Sweet 11, sieve size 4, AIS 16.0%	Maturometer	−0.30
Peas, green	Early Sweet 11, sieve size 4, AIS 16.0%	Back extrusion	−0.12
Peas, green	Early Sweet 11, sieve size 5, AIS 18.3%	Shear Press	−0.22
Peas, green	Early Sweet 11, sieve size 5, AIS 18.3%	Maturometer	−0.27
Peas, green	Early Sweet 11, sieve size 5, AIS 18.3%	Back extrusion	−0.20
Peas, green	Target, sieve size 3, AIS 11.0%	Shear Press	−0.37
Peas, green	Target, sieve size 3, AIS 11.0%	Maturometer	−0.28
Peas, green	Target, sieve size 3, AIS 11.0%	Back extrusion	−0.26
Peas, green	Target, sieve size 4, AIS 16.9%	Shear Press	−0.16
Peas, green	Target, sieve size 4, AIS 16.9%	Maturometer	−0.15
Peas, green	Target, sieve size 4, AIS 16.9%	Back extrusion	−0.07
Plums	Stanley, firm ripe	Puncture, 1/8 in. tip	−0.66
Plums	Stanley, firm ripe	Back extrusion	−0.75
Plums	Stanley, firm ripe	Deformation to 1 Newton	+0.42[a]
Plums	Severn Cross	Deformation to 1 Newton	+0.11[a]
Plums	Italian prune	Deformation to 1 Newton	+0.61[a]
Plums	30-4-126	Deformation to 1 Newton	+0.12[a]
Potato	Katahdin, stored 1 month	Magness Taylor 5/16 in. tip	−0.02
Potato	Katahdin, stored 7 months	Magness Taylor 5/16 in. tip	+0.06
Potato	Katahdin, stored 1 month	Deformation to 0.25 Newton	+0.28[a]
Potato	Katahdin, stored 7 months	Deformation to 0.25 Newton	+0.12[a]
Potato	Monona, stored 1 month	Magness Taylor 5/16 in. tip	−0.10
Potato	Monona, stored 7 months	Magness Taylor 5/16 in. tip	+0.06
Potato	Monona, stored 1 month	Deformation to 0.25 Newton	+0.28[a]
Potato	Monona, stored 7 months	Deformation to 0.25 Newton	+0.35[a]
Potato	Russet Burbank, stored 1 month	Magness Taylor 5/16 in. tip	+0.06
Potato	Russet Burbank, stored 7 months	Magness Taylor 5/16 in. tip	+0.04
Potato	Russet Burbank, stored 1 month	Deformation to 0.25 Newton	+0.14[a]
Potato	Russet Burbank, stored 7 months	Deformation to 0.25 Newton	+0.09[a]
Strawberry	Honeoye, mean size 6.0 g 0–30°C	Deformation to 1 Newton	+0.46[a]
Strawberry	Honeoye, mean size 6.0 g 30–45°C	Deformation to 1 Newton	+3.09[a]
Strawberry	Canoga, mean size 6.1 g 0–30°C	Deformation to 1 Newton	0[a]
Strawberry	Canoga, mean size 6.1g 30–45°C	Deformation to 1 Newton	+3.48[a]
Strawberry	Canoga, mean size 12.9 g 0–30°C	Deformation to 1 Newton	+0.09[a]
Strawberry	Canoga, mean size 12.9 g 30–45°C	Deformation to 1 Newton	+7.72[a]
Tomato	New Yorker, stem end down, 1973	Deformation to 1 Newton	+0.87[a]
Tomato	New Yorker, stem end down, 1978	Deformation to 1 Newton	+0.20[a]
Tomato	Nova (plum type), sideways, 1973	Deformation to 1 Newton	+0.58[a]
Tomato	Nova (plum type), sideways, 1978	Deformation to 1 Newton	+0.17[a]

Source: Bourne (1982). Reprinted from *J. Food Science* **47**, pages 442, 443. Copyright by Institute of Food Technologists.
[a]Since deformation is a softness measurement a + sign indicates the product decreases in firmness as the temperature rises.

Table AII.3 Effect of Temperature of Firmness of Canned Fruits and Vegetables

Commodity	Description	Type of measurement	F-T coefficient[a] % per 1°C increase
Apple	Slices	Puncture	−1.09
Apple	Slices	Extrusion	−1.04
Apple	Slices	Texture Press	−0.17
Applesauce	—	USDA Consistometer	+0.59[b]
Apricot	Unpeeled halves, brand A, 3–35°C	Extrusion	−1.32
Apricot	Unpeeled halves, brand A, 35–50°C	Extrusion	+0.07
Apricot	Unpeeled halves, brand A	Texture Press	−0.76
Apricot	Unpeeled halves, brand B, 3–35°C	Extrusion	−1.00
Apricot	Unpeeled halves, brand B, 35–50°C	Extrusion	+0.23
Beans, green	Cut brand A	Puncture	−0.02
Beans, green	Cut brand A	Extrusion	−0.15
Beans, green	Cut brand A	Texture Press	−0.51
Beans, green	Cut brand B	Puncture	−0.64
Beans, green	Cut brand B, 3–18°C	Extrusion	−1.54
Beans, green	Cut brand B, 18–35°C	Extrusion	−0.59
Beans, green	Cut brand B, 35–50°C	Extrusion	−0.30
Beans, green	Cut brand B	Texture Press	−0.38
Beans, green	French cut, brand B	Extrusion	−0.05
Beans, green	French cut, brand B	Texture Press	−0.11
Beans, wax	Cut	Puncture	−0.19
Beans, wax	3–18°C	Extrusion	−0.94
Beans, wax	18–50°C	Extrusion	−0.11
Beans, garbanzo	—	Puncture	−0.88
Beans, garbanzo	—	Extrusion	−0.74
Beans, garbanzo	—	Texture Press	−0.98
Beans, red kidney	Brand A	Puncture	−0.99
Beans, red kidney	Brand A	Extrusion	−0.79
Beans, red kidney	Brand A	Texture Press	−1.01
Beans, red kidney	Brand B	Puncture	−0.84
Beans, red kidney	Brand B	Extrusion	−0.94
Beans, red kidney	Brand B	Texture Press	−0.68
Beans, lima	Baby	Puncture	−0.57
Beans, lima	Baby	Extrusion	−0.87
Beans, lima	Baby	Texture Press	−1.15
Beets	Sliced, brand A	Extrusion	−0.31
Beets	Sliced, brand B	Extrusion	−0.17
Beets	Sliced, brand B	Texture Press	−0.43
Carrots	Sliced, brand A, xylem	Puncture	−1.04
Carrots	Sliced, brand A, phloem	Puncture	−0.61
Carrots	Sliced, brand A	Extrusion	−0.35
Carrots	Sliced, brand A	Texture Press	−0.37
Carrots	Sliced, brand B, xylem	Puncture	−0.47
Carrots	Sliced, brand B, phloem	Puncture	−0.62
Carrots	Sliced, brand B	Extrusion	−0.54
Carrots	Sliced, brand B	Texture Press	−0.40
Cherries	Sweet, whole	Extrusion	−0.13
Cherries	Sweet, whole, 3–19°C	Texture Press	−1.14
Cherries	Sweet, whole, 19–50°C	Texture Press	−0.17

(*Continued*)

Table AII.3 (*Continued*)

Commodity	Description	Type of measurement	F-T coefficient[a] % per 1°C increase
Corn	Whole kernel, brine, 3–18°C	Puncture	−0.55
Corn	Whole kernel, brine, 18–50°C	Puncture	−0.08
Corn	Whole kernel, brine, brand A	Texture Press	−0.48
Corn	Cream style, kernels, brand A	Puncture	+0.15
Corn	Whole Kernel, brand B	Extrusion	−0.42
Corn	Whole Kernel, brand B	Texture Press	−0.49
Corn	Cream style	Extrusion	−1.28
Corn	Cream style	TUC Cream Corn Meter	+0.33[a]
Peach	Clingstone	Extrusion	−0.66
Peach	Clingstone	Texture Press	−0.75
Peach	Freestone	Extrusion	−0.76
Peach	Freestone, 30–36°C	Texture Press	−0.38
Peach	Freestone, 36–50°C	Texture Press	−1.97
Pears	Bartlett	Extrusion	−0.56
Pears	Bartlett	Texture Press	−0.55
Peas	Green, brand A	Puncture	−0.53
Peas	Green, brand A	Extrusion	−0.93
Peas	Green, brand A	Texture Press	−0.62
Peas	Green, brand B	Puncture	−0.65
Peas	Green, brand B	Extrusion	−0.67
Peas	Green, brand B	Texture Press	−0.79
Pineapple	Wedges, brand A	Extrusion	−0.52
Pineapple	Wedges, brand A	Texture Press	+0.06
Pineapple	Wedges, brand B	Texture Press	−0.21
Plums	Whole	Puncture	−0.90
Plums	Whole	Extrusion	−1.03
Plums	Whole	Texture Press	−0.63
Potatoes	Small, whole	Puncture	−0.75
Potatoes	Small, whole	Extrusion	−0.81
Potatoes	Small, whole	Texture Press	−0.86
Spinach	3–18°C	Extrusion	+0.43
Spinach	18–48°C	Extrusion	−1.05
Tomatoes	Whole, pear shape	Extrusion	−0.19
Tomatoes	Whole, pear shape	Texture Press	−0.32

Source: Bourne and Conistock (1986). Reprinted from *J. Food Science* **51**, pages 532, 533. Copyright by Institute of Food Technologists.
[a]The firmness–temperature coefficient is the percent change in firmness per degree temperature increase.
[b]In the Consistometer tests a + sign indicates decreasing firmness with increasing temperature.

Guidelines and Conditions for Testing Foods

APPENDIX III

Table AIII.1 Guidelines for Testing Various Foods in the Food Technology Corporation Texture Test System[a]

Commodity	Type of test cell: Shear–compression	Universal	Single blade	Meat shear	Other	Test principle	Parameters measured
Fruits							
Apples	X	X				Compression–shear	Maximum force
					Penetration	Puncture	Yield point
Applesauce		X				Compression – orifice or back extrusion	Curve peak(s) Frequency and height
Apricots	X	X				Compression–shear	Maximum force
					Penetration	Puncture	Yield point
Cherries	X	X				Compression–shear	Maximum force
					Penetration	Puncture	Yield point
Fruit cocktail	X	X				Compression–shear	Maximum force–curve peaks
Citrus fruit	X	X				Compression–shear	Maximum force
Mangoes	X	X				Compression–shear	Maximum force
					Penetration	Puncture	Yield point
Olives	X					Compression–shear	Maximum force
Peaches	X	X				Compression–shear	Maximum force
					Penetration	Puncture	Yield point
Pears	X	X				Compression–shear	Maximum force
					Penetration	Puncture	Yield point

(*Continued*)

Table AIII.1 (*Continued*)

Commodity	Type of test cell: Shear–compression	Universal	Single blade	Meat shear	Other	Test principle	Parameters measured
Raisins	X					Compression–shear	Maximum force
Strawberries	X	X				Compression–shear	Maximum force
Meat and poultry							
Beef	X					Compression–shear	Maximum force
			X	X		Cutting	Maximum force
Frankfurters	X					Compression–shear	Maximum force
			X	X		Cutting	Maximum force
Lamb	X					Compression–shear	Maximum force
			X	X		Cutting	Maximum force
Pork	X					Compression–shear	Maximum force
			X	X		Cutting	Maximum force
Rabbit	X					Compression–shear	Maximum force
			X	X		Cutting	Maximum force
Luncheon meat	X					Compression–shear	Maximum force
					Tension	Tensile	Maximum force–curve slope
					Thin-slice tensile	Tensile	Maximum force–curve slope
Chicken	X					Compression–shear	Maximum force
			X	X		Cutting	Maximum force
Turkey	X					Compression–shear	Maximum force
			X	X		Cutting	Maximum force
Pheasant	X					Compression–shear	Maximum force
			X	X		Cutting	Maximum force
Poultry bones					Bending	Breaking force	Maximum force
Eggs					Compression	Breaking force	Maximum force

(*Continued*)

Table AIII.1 (*Continued*)

Commodity	Type of test cell: Shear–compression	Universal	Single blade	Meat shear	Other	Test principle	Parameters measured
Miscellaneous							
Gels and semisolids such as fats, jelly, paste, and pharmaceuticals	X					Compression–shear	Maximum force–curve slope
			X			Cutting	Maximum force–curve slope
					Penetration	Yield point	Maximum force
		X				Compression – orifice or back extrusion	Maximum force or curve slope and area
Cottage cheese	X	X				Compression–shear	Maximum force
Mushrooms	X	X				Compression–shear	Maximum force
			X	X		Cutting	Maximum force
Pasta	X	X				Compression–shear	Maximum force
Rice	X				Thin bladed	Compression–shear	Maximum force
Peanuts	X	X				Compression–shear	Maximum force
Seeds	X	X				Compression–shear	Maximum force
Dough	X					Compression–shear tensile	Texture profile
Stems of flowers and plant material	X					Compression–shear	Maximum force
			X	X		Cutting	Maximum force
					Bending	Breaking point	Maximum force
Canned tuna fish	X					Compression–shear	Maximum force
					Succulometer	Compression	Liquid expressed
Dry or moist pet food	X		X	X		Compression–shear	Maximum force
Canned pet food	X	X			Penetration	Puncture	Yield point
Bread and bread products	X					Compression–shear	Maximum force
			X			Cutting	Maximum force
					Thin-slice tensile	Tensile	Maximum force–curve slope

(*Continued*)

Table AIII.1 (*Continued*)

Commodity	Type of test cell: Shear–compression	Universal	Single blade	Meat shear	Other	Test principle	Parameters measured
Cakes and other similar bakery products	X					Compression–shear	Maximum force
			X			Cutting	Maximum force
Vegetables							
Asparagus			X	X		Cutting	Maximum force
Beans, dry-baked	X	X				Compression–shear	Maximum force
Beans, lima	X					Compression–shear	Maximum force
Beans, green	X					Compression–shear	Maximum force
			X			Cutting	Maximum force
Broccoli	X					Compression–shear	Maximum force
			X			Cutting	Maximum force
Carrots	X					Compression–shear	Maximum force
Celery	X					Compression–shear	Maximum force
			X			Cutting	Maximum force
Greens	X					Compression–shear	Maximum force
Corn, sweet	X					Compression–shear	Maximum force
					Succulometer	Compression	Liquid expressed
Eggplant	X					Compression–shear	Maximum force
Onions	X					Compression–shear	Maximum force
Peas	X					Compression–shear	Maximum force
Peppers	X					Compression–shear	Maximum force
Potatoes, white	X					Compression–shear	Maximum force
Potatoes, sweet	X					Compression–shear	Maximum force–curve ratio or slope
			X	X		Cutting	Maximum force
Tomatoes	X					Compression–shear	Maximum force

(*Continued*)

Table AIII.1 (*Continued*)

Commodity	Type of test cell: Shear–compression	Universal	Single blade	Meat shear	Other	Test principle	Parameters measured
Tomatoes, paste		X				Compression – orifice or back extrusion	Maximum force–flow rate

Source: Compiled by Dr B. A. Twigg.

[a]Note: Sample size and method of presenting sample (diced, whole, stripped, etc.) will vary within and among commodities, depending on purpose of test, test cell used, and the nature of the commodity. For example, size could be one discreet unit, full cell filled by volume or weighted sample that best accommodates the commodity and test cell. Various sample sizes and methods of presenting sample should be investigated, unless specific working conditions are recommended by the literature or by the manufacturer.

Table AIII.2 Conditions for Testing Foods in the Instron

Commodity	Test principle	Test cell	Crosshead speed (cm min^{-1})	Chart speed (cm min^{-1})	Full-scale force (N)	Parameter measured
Agar gel	Deformation	Flat plate, 14.5 cm diam	0.1	20	2	ΔD between 1 and 2 N
Agar gel	Puncture	Rectangular punches	30	20	50	Yield point force
Apple, whole, skin off	Puncture	7/16-in.-diam Magness–Taylor tip	20	20	100–200	Yield point force and force at 5/16-in. penetration
Apple, slice	Back extrusion	10.15-cm i.d., 4-mm annulus	20	20	500–1000	Maximum plateau force
Apple, slice	Compression–extrusion–shear	Standard Kramer Shear cell	20	20	1000–2000	Maximum force
Apple, slice	Puncture	1/8-in.-diam punch	30	10	10	Maximum force
Apple, 1.2 cm cube	TPA[a]	Flat plate, 7 cm diam	5	50	50–200	All TPA parameters
Apple, whole	Relaxation, recovery	Flat plate, 14.5 cm diam	1	5	500	ΔF for 2 min
Apricot, whole	Deformation	Flat plate, 14.5 cm diam	1	30	1	ΔD between 0.05 and 0.35 N
Apricot, skin off	Puncture	5/16-in.-diam Magness–Taylor tip	30	10	10–20	Yield point force and force at 5/16-in. penetration
Banana, skin off	Deformation	3/8-in.-diam punch	0.2	50	5	ΔD between 0.5 and 1.5 N
Beans, pea, red kidney soy, cooked	Puncture	1/8-in.-diam punch	30	10	20–50	Maximum force
Beans, green, raw	Puncture	1/8-in.-diam punch	20	10	50	Maximum force
Beans, green, raw	Back extrusion	7.35-cm i.d., 4-mm annulus	20	10	1000–2000	Maximum plateau force
Beans, green, canned	Back extrusion	10.15-cm i.d., 4-mm annulus	30	10	1000	Maximum plateau force
Beef, cooked, 1-cm cube	TPA	Flat plate, 7 cm diam	5	50	100–200	Texture profile parameters
Beets, red, canned	Back extrusion	10.15-cm i.d., 4-mm annulus	20	20	2000	Maximum plateau force
Beets, red, whole, raw	Deformation	Flat plate, 14.5 cm diam	0.5	50	2	ΔD between 0.1 and 1.1 N
Beets, blanched, 1-cm cube	TPA	Flat plate, 7 cm diam	5	50	10	Texture profile parameters
Bologna	Deformation	Flat plate, 14.5 cm diam	1	10	20	ΔD between 0.5 and 10.5 N
Bread, roll	Deformation	Flat plate, 14.5 cm diam	1	10	20	ΔD between 0.5 and 10.5 N
Bread, ½-in. cube	TPA	Flat plate, 7 cm diam	5	50	2	Texture profile parameters

Bun, hamburger	Deformation	Flat plate, 14.5 cm diam	1	5	20	ΔD between 0.5 and 10.5 N
Candy, rock	Deformation	Flat plate, 7 cm diam	0.1	50	20	ΔD between 0.5 and 10.5 N
Carrot, raw, cylinders 2 mm thick × 7.3 mm diam	Deformation	Flat plate, 7 cm diam	0.2	50	2	ΔD between 0.05 and 1.05 N
Carrot, raw	Puncture	3/32-in.-diam punch	20	10	20	Yield point
Carrot, raw, 1 cm diam × 2 cm high	TPA	Flat plate, 7 cm diam	1	20	100–500	Texture profile parameters
Carrot, canned	Back extrusion	10.15-cm-i.d., 4-mm annulus	30	10	1000	Maximum force
Cheese, cream	TPA	Flat plate, 7 cm diam	5	50	500	Texture profile parameters
Cheese, cheddar	Puncture	Rectangular punches	10	10	20	Maximum force
Cherries (sweet and Montmorency)	Puncture	Single Dunkley pitter	20	5	100	Maximum force
Cherries (sweet and Montmorency)	Multiple puncture	Array of 30 Dunkley pitters	10	20	1000–2000	Maximum force
Cherries (sweet and Montmorency), pitted	Puncture	1/8-in.-diam punch	20	5	10	Maximum force
Cherry pie filling	Back extrusion	10.15-cm-i.d., 4-mm annulus	10	20	2000	Maximum force
Chocolate bars	Snap	Triple-beam assembly, 4.3 cm clearance between supporting beams	5	50	200	Maximum force
Cookies, ginger snap	Snap	Triple-beam assembly, 4.3 cm clearance between supporting beams	5	50	20	Maximum force
Corn, sweet, cut kernels	Back extrusion	10.15-cm-i.d., 4-mm annulus	20	20	5000–20,000	Maximum force
Corn, sweet, on cob	Puncture	Diameters of 0.052, 0.076, 0.101, 0.128 in.	20	20	10–20	Maximum force
Cucumber, whole	Deformation	14.5-cm-diam plate	0.5	50	1	ΔD between 0.05 and 0.55 N
Cucumber, whole	Puncture	1/8-in.-diam punch	20	20	20	Yield point
Custard, egg	Puncture	1.13-cm-diam punch	0.5	50	0.2	Yield point
Cranberries, raw	Deformation	2-cm-diam plate	0.2	50	1	ΔD between 0.02 and 0.27 N
Egg, whole	Deformation	Flat plate, 7 cm diam	0.05	50	10	ΔD between 0 and 10 N
Frankfurter, beef	Deformation	Flat plate, 14.5 cm diam	1	10	20	ΔD between 0.5 and 10.5 N
Frankfurter, beef	TPA	Flat plate, 7 cm diam	5	50	1000	Texture profile parameters

(*Continued*)

Table AIII.2 (*Continued*)

Commodity	Test principle	Test cell	Crosshead speed (cm min^{-1})	Chart speed (cm min^{-1})	Full-scale force (N)	Parameter measured
Gari	TPA	Flat plate, 7 cm diam	5	50	20–100	Texture profile parameters
Grapes, single berry	Puncture	1/16-in.-diam punch	2	40	5–20	Maximum force
Grapes, single berry	Deformation	2-cm-diam plate	2	50	1	ΔD between 0.05 and 0.65 N
Lettuce, whole head	Deformation	Flat plate, 14.5 cm diam	1	10	20	ΔD between 0.5 and 10.5 N
Marshmallow	Deformation	Flat plate, 7 cm diam	1	10	2	ΔD between 0.05 and 1.05 N
Onions, boiled	Puncture	1/8-in.-diam punch	30	30	5–10	Yield point
Peas, green, raw	Multiple puncture	Matuometer, 143 × 1/8-in.-diam punches	20	10	2000	Maximum force
Peas, green, raw	Puncture	Single 1/8-in.-diam punch	30	10	20–50	Maximum force
Peas, green, raw	Back extrusion	10.15-cm-i.d., 4-mm annulus	20	20	2000–10,000	Maximum force
Peas, green, canned	Back extrusion	10.15-cm-i.d., 4-mm annulus	20	20	2000	Maximum force
Peas, green, raw	Back extrusion	OTMS	20	20	5000	Maximum force
Peaches, raw, sliced	Puncture	1/8-in.-diam punch	20	20	5–10	Yield point
Peaches, sliced, canned or frozen	Back extrusion	10.15-cm-i.d., 4-mm annulus	20	20	2000–5000	Maximum force
Peaches, whole, raw	Puncture	7/16-in.-diam Magness–Taylor tip	20	20	50	Maximum force
Peaches, fresh, 2 cm diam × 1 cm high	TPA	Flat plate, 7 in. diam	5	50	20–100	Texture profile parameters
Pears, whole, raw	Deformation	Flat plate, 14.5 cm diam	2	50	2	ΔD between 0.25 and 1.75 N
Pears, fresh, 2 cm diam × 1 cm high	TPA	Flat plate, 7 cm diam	5	50	50–200	Texture profile parameters
Pickle, cucumber slice	Puncture	0.086-in.-diam punch	20	10	20	Maximum force
Pretzel, large, 1-cm-high piece	TPA	Flat plate, 7 cm diam	5	50	5000	Texture profile parameters
Potato, whole, raw	Deformation	0.77-cm-diam punch with potato nestled in a bed of sand	0.2	50	1	ΔD between 0.06 and 0.26 N
Potato chip	Deformation	5/16-in.-diam probe, chip rests on a 3-cm-ring	1	50	2	Slope of initial line
Protein foam	Puncture	1.25-cm-diam punch	10	50	0.1–0.5	Inflection point
Plums, fresh, pitted	Back extrusion	10.15-cm-i.d., 4-mm annulus	20	20	20,000	Maximum force
Plums, fresh, pitted	Puncture	1/8-in.-diam punch	20	20	20–50	Yield point

Soymeat analog, 1-cm cube	TPA	Flat plate, 7 cm diam	5	50	100	Texture profile parameters
Strawberries, whole, raw	Punch	Flat face, Dunkley pitter	50	5	20	Maximum force
Sauerkraut, 25-g sample	Compression	Flat plate, compress to 1 mm clearance	5	40	10,000–20,000	Maximum force
Tofu (soy curd)	Punch	1/8-in.-diam punch	10	10	5	Yield point
Tomatoes, raw, whole	Deformation	Flat plate, 7 cm diam	2	50	5	ΔD between 0.1 and 1.1 N
Turkey, roll, sliced	Tensile	Clamp at each end	1	5	100–200	Maximum force

Compiled by M. C. Bourne and S. Comstock.
[a]TPA, Texture Profile Analysis.

Table AIII.3 Conditions for Testing Foods Using the TA.XT2 Texture Analyzer

Commodity	Test principle	Probe/Fixture	Crosshead speed (mm s^{-1})	Parameter measured	Property measured
Apple, whole	Puncture	2 mm diam cylinder probe	1.5	Yield point force and distance and mean plateau force	Bioyield point and flesh firmness
Apple, whole	Relaxation, recovery	Flat plate/cylinder probe larger than sample	0.02	Distance at yield point	Potential to bruising
Apple puree	Back extrusion	40 mm diam extrusion disk	2	Maximum force, area under positive and negative curve regions	Consistency
Baking fats	Forward extrusion	Forward extrusion rig with 3 mm annulus	1	Mean plateau force	Ease of extrusion
Beans (bulk), cooked	Extrusion	Ottawa cell with 17-bladed extrusion plate	5	Mean plateau force	Firmness
Biscuits/cookies/ crackers, whole	Bending	Three-point bending rig	3	Maximum force and distance at break	Hardness and fracturability
Biscuit/cookie dough	Penetration	Dough preparation set and 6 mm cylinder probe	3	Maximum force	Firmness
Boiled sweets, single	Penetration	2 mm diam cylinder probe	1	Maximum force and distance at maximum force	Hardness and fracturability
Breadcrumbs, monolayer	Compression	35 mm diam cylinder probe	1	Maximum force	Hardness
Bread dough	Uniaxial tension	Kieffer dough extensibility rig	3.3	Maximum force and distance at max. force	Resistance to extension and extensibility
Bread dough	Tension	Chen–Hoseney Dough Stickiness cell	10	Maximum force, area under curve and distance to separation	Stickiness, work of adhesion and cohesiveness
Bread, roll	Compression	Flat plate/cylinder probe larger than sample	2	Maximum force	Firmness
Bread, sliced	Penetration	Radiused 36 mm diam cylinder probe (AACC 74-09 standard)	1.7	Force at 25% strain	Firmness
Breakfast cereal, dry and wet	Compression	Ottawa cell and watertight base plate	5	Maximum force, linear distance and no. of +ve force peaks	Hardness and crispness 'Bowl life'
Breakfast toaster pastries, whole	Shearing	Knife blade	1	Peak forces and mean force of plateau region between peaks	Pastry firmness and filling softness

(*Continued*)

Table AIII.3 (*Continued*)

Commodity	Test principle	Probe/Fixture	Crosshead speed (mm s^{-1})	Parameter measured	Property measured
Butter/margarine – contained	Penetration	5 mm diam cylinder probe	2	Maximum force, +ve area under curve	Firmness and work of penetration
Butter/margarine – contained	Penetration	45° conical probe	1	Distance moved during 5 s of applied force	Firmness
Butter/margarine	Penetration/ extrusion	TTC spreadability rig	3	Maximum +ve force and +ve area under curve	Firmness and spreadability
Butter/margarine – block form	Shearing	Wire cutter	0.5	Mean force over plateau region	Firmness
Cake	Compression/ stress-relaxation	Radiused 36 mm diam cylinder probe (AACC standard)	1	Force at 25% strain and ratio of forces at beginning and end of relaxation period	Firmness, springiness (ability to recover)
Caramel	Penetration	0.75 in. Spherical ball probe	5	Maximum +ve force, maximum −ve force and distance to separation	Hardness, stickiness and stringiness
Carrot, raw batons	Bending	3-point bending rig	2	Maximum force and distance at break	Firmness and flexibility
Carrot, cylinders (cooked or raw)	Compression	Flat plate/cylinder probe larger than sample	1	Maximum force	Hardness
Cereal bars	Shearing	5-bladed Kramer shear cell	2	Maximum force	Hardness
Cheese, cream (contained)	Penetration	5 mm diam cylinder probe	1	Maximum force	Softness
Cheese, cream (contained)	Penetration	45° conical probe	1	Maximum force	Softness
Cheese, spread	Penetration/ extrusion	TTC spreadability rig	3	Maximum +ve force and +ve area under curve	Firmness and spreadability
Cheese, spread (contained)	Penetration	1 in. spherical probe	2	Maximum +ve force and maximum −ve force	Firmness and stickiness
Cheese, hard – cubes	Shearing	Fracture wedge set	2	Maximum force and distance at break	Hardness and brittleness
Cherries, single	Penetration	2 mm diam cylinder probe	2	Maximum force and distance at max. force	Bioyield point/firmness
Chewing gum, base pellets	Penetration	2 mm diam cylinder probe	1	Mean force over plateau region	Hardness

(*Continued*)

Table AIII.3 (*Continued*)

Commodity	Test principle	Probe/Fixture	Crosshead speed (mm s^{-1})	Parameter measured	Property measured
Chewing gum, bones	Uniaxial tension	Tensile grips	1	Maximum force and distance at break	Resistance to extension and extensibility
Chewing gum, dragees	Shearing	Craft knife	2	1st peak force, force at 7.5 mm and +ve area under curve	Coating hardness, interior hardness and work of cutting/ toughness
Chewing gum, rope (of uniform thickness)	Uniaxial tension	Kieffer dough extensibility rig	2	Maximum force and distance at break	Resistance to extension and extensibility
Chewing gum, stick	Bending	3-point bending rig	2	Maximum force and distance at flex	Strength and flexibility
Chewing gum, stick	Penetration	2 mm diam cylinder probe	1	Maximum force	Hardness
Chewy confectionery	Penetration	6 mm diam cylinder probe	2	Maximum +ve force and maximum −ve force	Hardness and stickiness
Chicken (bulk), fillets/nuggets	Shearing	5-bladed Kramer shear cell	3	Maximum +ve force and +ve area under curve	Firmness and work of shearing
Chicken, 5 mm core	Shearing	Warner–Bratzler blade	3	Maximum force	Firmness/bite force
Chocolate, bars	Penetration	2 mm diam cylinder probe	1.5	Maximum force	Hardness
Chocolate, bars	Shearing	Craft knife blade	2	Maximum force	Bite force
Chocolate spread	Penetration/ extrusion	TTC Spreadability rig	3	Maximum +ve force and +ve area under curve	Firmness and spreadability
Corn, sweet, kernels	Shearing	10-bladed Kramer shear cell	2	Maximum force	Hardness
Corn, sweet, single kernel	Shearing	Volodkevich Bite Jaws	2	Maximum force	Hardness
Croissants	Shearing	Knife blade	2	Area under curve	Firmness
Croutons (bulk)	Compression	Ottawa cell and watertight base plate	1	Maximum force, linear distance and no. of +ve force peaks	Hardness and crunchiness 'Bowl life'
Egg, whole	Compression	Flat plate/cylinder probe larger than sample	0.5	Maximum force	Breaking force/ shell strength
Extruded snack (bulk)	Compression	Ottawa cell with wide blade extrusion plate	2	Linear distance, no. of major force peaks and area under curve	Crispness and toughness
Fish, raw	Penetration	0.5 in. spherical probe	2	Maximum force	Firmness
Fondant (contained)	Penetration	4 mm diam cylinder probe	2	1st peak force and 2nd peak force	Crust firmness and center firmness

(*Continued*)

Table AIII.3 (*Continued*)

Commodity	Test principle	Probe/Fixture	Crosshead speed (mm s^{-1})	Parameter measured	Property measured
French fries, single	Penetration	2 mm diam cylinder probe	3	1st peak force, force at 4.5 mm	Crust firmness and interior firmness
Gel (any type)	Deformation	Flat plate/cylinder probe larger than sample	2	Maximum force	Firmness
Gel (any type), contained	Puncture	Cylinder probe from 3 to 20 mm diam	2	Yield point force and distance at yield	Rupture strength, elasticity/ brittleness
Gel (any type), cube or disc	TPA	Flat plate/cylinder probe larger than sample	3	Texture profile parameters	
Gel (Gelatine) ISO 9665, contained in bloom jar	Puncture	0.5 in. diam cylinder probe (radiused)	0.5	Force at 4 mm penetration	Bloom strength
Gel (Gelatine) GMIA, contained in bloom jar	Puncture	0.5 in. diam cylinder probe	1	Force at 4 mm penetration	Bloom strength
Gluten	Uniaxial tension	Kieffer dough extensibility rig	3.3	Maximum force and distance at max. force	Resistance to extension and extensibility
Gluten, disc	Compression	Flat plate/cylinder probe larger than sample	10	Gradient of slope over 45 s of holding 100 g force	Strength
Gnocchi, testing of 3 pieces	Compression	Flat plate/cylinder probe larger than sample	2	Maximum force	Firmness
Grapes, single	Penetration	2 mm diam cylinder probe	1	Maximum force and distance at max. force	Skin strength and elasticity
Gummy confectionery	Compression	Flat plate/cylinder probe larger than sample	1	Force at 20% strain and ratio of forces at beginning and end of relaxation period	Firmness, springiness (ability to recover)
Ham, rectangular piece	Shearing	5-bladed Kramer shear cell	2	Maximum force	Firmness/shear force
Ice cream (contained)	Penetration	6 mm diam cylinder probe	2	Maximum force	Hardness
Ice cream	Shearing	Knife blade	3	Maximum force	Hardness
Ketchup (contained)	Back extrusion	35 mm diam extrusion disk	1	Maximum +ve force, +ve area, maximum −ve force and −ve area	Firmness, consistency and cohesiveness
Lasagne, dry	Bending	3-point bending rig	3	Maximum stress, distance to break and gradient	Breaking stress, fracturability and stiffness
Lasagne, cooked	Compression and Tension	Pasta firmness/ stickiness rig	0.5	Maximum force and area under curve	Stickiness

(*Continued*)

Table AIII.3 (*Continued*)

Commodity	Test principle	Probe/Fixture	Crosshead speed (mm s^{-1})	Parameter measured	Property measured
Marmalade (contained)	Penetration	Radiused 1 in. diam cylinder probe	2	Force at 3 mm, maximum force, distance at break and −ve area under curve	Gel strength, rupture strength, brittleness and adhesiveness
Mayonnaise (contained)	Back extrusion	35 mm diam extrusion disk	1	Maximum +ve force, +ve area, maximum −ve force and −ve area	Firmness, consistency and cohesiveness
Mayonnaise (contained)	Penetration	25 mm diam cylinder probe	1	Maximum force and +ve area under curve	Firmness and work of penetration
Mousse (contained)	Penetration	25 mm diam cylinder probe	1	Maximum force	Firmness
Olives (bulk)	Shearing	5-bladed Kramer shear cell	1.5	Maximum force and +ve area under curve	Firmness and work of shear
Noodles, single strand	Tension	Spaghetti tensile grips	3	Maximum force	Tensile strength
Noodles, three strands	Compression	35 mm diam cylinder probe	2	Maximum +ve force and max. −ve force	Firmness and stickiness
Nuts, whole	Shearing	Craft knife blade	1	Force of 1st peak, distance at 1st peak, area to 2 mm	Hardness of exterior, fracturability and work to shear
Pancakes	Biaxial tension	Tortilla/pastry burst rig	1	Maximum force and distance at break	Toughness and extensibility
Pasta shapes (bulk)	Shearing	5-bladed Kramer shear cell	2	Maximum force and area under curve	Firmness and work of shear
Pastry, uniform thickness sheets	Biaxial tension	Tortilla/pastry burst rig	0.5	Maximum force and distance at break	Toughness and extensibility
Pate	Penetration	10 mm diam cylinder probe	1.5	Maximum force	Firmness
Peas (bulk), raw	Shearing	10-bladed Kramer shear cell	2	Maximum force	Hardness
Peas (18 pieces), raw	Penetration	Multiple pea rig	2	1st peak force and 2nd peak force	Upper and lower skin strength
Peaches, sliced	Shearing	Knife blade	5	Maximum force	Firmness
Pears, whole	Penetration	2 mm diam cylinder probe	1.5	Maximum force and mean force over plateau region	Bioyield point and flesh firmness

(*Continued*)

Table AIII.3 (*Continued*)

Commodity	Test principle	Probe/Fixture	Crosshead speed (mm s^{-1})	Parameter measured	Property measured
Peppers	Penetration	3 mm diam cylinder probe	2	Maximum force	Skin strength/ bioyield point
Pickle (bulk)	Shearing	10-bladed Kramer shear cell	3	Maximum force and area under curve	Firmness and work of shearing
Pizza, rectangular section of uniform width	Tension	Pizza tensile rig	5	Area under curve	Toughness
Potato chips (bulk)	Compression	Ottawa cell with wide blade extrusion plate	2	Linear distance, no. of major force peaks and area under curve	Crispness and toughness
Potato (bulk), mashed	Extrusion	Ottawa cell with holed plate	1.5	Maximum force and area under curve	Firmness/work of extrusion
Potato salad (bulk)	Extrusion	Ottawa cell with holed plate	1	Area under curve	Firmness/work of extrusion
Prawns (bulk)	Shearing	5-bladed Kramer shear cell	3	Maximum +ve force and +ve area under curve	Firmness and work of shearing
Pretzels, single	Bending	3-point bending rig	1	Maximum force and distance at break	Hardness and fracturability
Raspberries (bulk)	Extrusion	Ottawa cell with holed plate	1.5	Maximum force and area under curve	Firmness/work of extrusion
Rice, savoury, three grains	Compression	35 mm diam cylinder probe	0.5	Maximum +ve force and max. −ve force	Firmness and stickiness
Rice, pudding (contained)	Back extrusion	40 mm diam extrusion disk	1	Maximum force	Firmness/ consistency
Sausages/ frankfurters	Shearing	Warner–Bratzler blade	2	Maximum force and area under curve	Firmness/ toughness/bite force
Spaghetti, dry	Bending	Spaghetti flexure rig	2.5	Maximum force and distance at break	Breaking strength and flexibility
Spaghetti, cooked, five strands	Shearing	1 mm flat Perspex blade (AACC 16–50)	0.17	Maximum force and area under curve	Firmness and work of shear
Strawberries (bulk)	Extrusion	Ottawa cell with holed plate	1.5	Maximum force and area under curve	Firmness/work of extrusion
Surimi	Shearing	Knife blade	2	Maximum strength, distance at failure and area under curve	Cutting strength/ bite force, work of shear
Surimi	Penetration	5 mm spherical probe	1.1	Maximum force and distance at max. force	Breaking force and distance to rupture

(*Continued*)

Table AIII.3 (*Continued*)

Commodity	Test principle	Probe/Fixture	Crosshead speed (mm s^{-1})	Parameter measured	Property measured
Syrup (contained)	Back extrusion	35 mm diam extrusion disk	1	Maximum force and distance to separation	Surface stickiness and stringiness
Tofu	Penetration	0.25 in. spherical probe	2	Maximum force, mean force over plateau region	Skin firmness and interior firmness
Tomatoes (bulk)	Shearing	5-bladed Kramer shear cell	3	Maximum force and area under curve	Firmness/work of shearing
Tortilla chips, individual	Bending	Crisp fracture rig	1	Maximum force	Firmness
Tortillas, wheat, rectangular section of uniform width	Uniaxial tension	Tensile grips	1	Maximum force and distance at break	Resistance to extension and extensibility
Tortillas, wheat	Biaxial tension	Tortilla/pastry burst rig	1	Maximum force and distance at break	Toughness and extensibility
Yoghurt (contained)	Back extrusion	35 mm diam extrusion disk	1	Maximum +ve force, +ve area, maximum −ve force and −ve area	Firmness, consistency and cohesiveness

Compiled by J. Smewing at Stable Micro Systems.

Examples of Sensory Texture Profiles

APPENDIX IV

Raw Apple

Example 1

Table AIV.1 Raw Apple Texture Definitions and Values. Numbers in parentheses are the range of panel values for this product (0–14 range)

I.	*First Bite*	Place bite size piece of apple between molar teeth and evaluate for:
	Firmness	Force required to bring teeth together (5–8)
	Fracturability	Force with which apple breaks apart (3–5)
	Crispness	Degree to which rupture is heard (2–5)
	Denseness	Degree to which sample is compact and not cellular (2–4)
	Graininess	Degree to which granular particles are perceived (4–9)
	Moisture Release	Amount of juice perceived upon biting (4–7)
	Toothpacking	Degree to which apple packs around teeth (1–3)
II.	*Mastication*	
	Chewiness	Number required to prepare sample for swallow (15–18)
	Coarseness	Degree to which the chewed mass stays in distinct particles the size of oatmeal or larger throughout mastication (4–7)
	Pulpiness of Mass	Degree to which flesh persists in a soft moist uniform mass (3–9)
	Graininess	Degree to which the chewed mass stays in small particles throughout mastication (4–10)
	Moisture Release	Degree to which the release of moisture persists throughout mastication (4–9)
	Fibers	Degree to which fibers are perceived throughout mastication (2–5)
III.	*After Swallow*	
	Particles	Amount perceived (7–9)
	Dry Mouthfeel	Degree to which mouth feels dry (3–4)

Source: Diehl and Hamann (1979). Reprinted from *J. Texture Studies* **10**, page 406. Copyright by Food and Nutrition Press Inc.

Example 2

Restructured Beef Steaks

Table AIV.2 Texture Profile Panel Characteristics, Procedures and Definitions for Restructured Beef Steaks

I. *Visual*
   A. Distortion – Steak is visually evaluated for the degree that the steak has warped or changed in configuration from its original raw-frozen shape. Macro distortion is degree overall steak has distorted. Micro distortion is the degree to which cooked surfaces look uneven or rough.
   B. Fibrousness – Steak is cut in half and the cross section is visually evaluated for the degree that the sample resembles steak or has no disruption of components.

II. *Partial compression*
   A. Springiness – Place a warm 2.54 cm^2 piece in the mouth and using the molars against the cooked surfaces, press lightly five times. Wait 2 s between each press. Springiness is the perceived degree and speed with which the sample returns to original height and thickness.

III. *First bite*

Take a warm 2.54 cm^2 piece and place it in the mouth in the same manner as for partial compression and evaluate for:

   A. Hardness – Amount of force required to bite through sample.
   B. Cohesiveness – The degree to which the sample deforms before shearing.
   C. Moisture release – Amount of juiciness perceived during the first bite.
   D. Uniformity – The degree to which the force needed to shear the sample is the same across the bite area.

IV. *Mastication*

Take one warm 2.54 cm^2 sample, make the first incision as for first bite. Then turn the two pieces 90° and take a second bite. Evaluate for:

   A. Sample breakdown at two chews – Check the appropriate breakdown category(ies).

Continue chewing and evaluate for:

   B. Juiciness – The amount of juice released following seven chews.
   C. Size of chewed pieces – The perceived size of clearly separate pieces or pieces held together only by connective tissue web. Evaluated following 10 chews.
   D. Gristle – The amount of rubbery particles present following 10 chews.
   E. Cohesiveness of mass – The degree to which particles stick together. This is evaluated at its maximum degree between 10 and 35 chews.
   F. Uniformity of mass – Degree to which components of the mass are the same. Evaluated following 25 chews.
   G. Webbed connective tissue – Amount of connective tissue present just before swallowing.
   H. Number of chews – Total number of chews to accurately determine the amount of webbed connective tissue.
   I. Overall gristle – Overall impression of the amount of rubbery particles throughout mastication.
   J. Overall webbed connective tissue – Amount of firm thread-like connective tissue present throughout mastication.

V. *After-swallow*
   A. Tooth pack – Amount of sample remaining in between teeth after swallowing.
   B. Mouthcoating – Amount of film residue left on mouth surface following swallowing.

Source: Berry and Civille (1986). Reprinted from *J. Sensory Studies* **1**, page 24.

Example 3

Brownies

Table AIV.3 Definitions and Evaluation Procedures for the Texture Characterization of Brownies

Surface
Hold the brownie near the mouth so that the tongue and lips can be passed over the sample. Evaluate for:

Roughness:	Degree of abrasiveness on the brownie's surface, as perceived by the tongue.
Surface moistness:	Amount of moisture perceived on the surface of the brownie, when in contact with the upper lip.

Partial compression
Bite a piece of the brownie with your incisors and place it between your tongue and palate. Compress slightly without rupturing the structure. Evaluate for:

Springiness:	Force with which sample returns to its original size/shape, after partial compression.

First bite
Bite through the brownie with your incisors by applying a steady force. Evaluate for:

Firmness:	Force required to bite completely through the product.
Cohesiveness:	Amount of deformation undergone by the material before rupture, when biting completely through the sample.
Uniformity of firmness:	Evenness of force (firmness) required to bite through the sample.

First chew
Take another bite of the brownie and place the piece between your molars. Bite through the sample completely and evaluate for:

Denseness:	Compactness of the cross section.
Stickiness (tooth pull):	Force required to separate molars after chew down.

Chew down
Bite a piece of the brownie and chew it with your molars (8–10 chews). Evaluate for:

Cohesiveness of mass:	Degree to which the mass holds together.
Moisture absorption:	Amount of saliva absorbed by the sample upon mastication.
Type of breakdown:	Description of the brownie's breakdown (mechanical, salivary).

Residual
Expectorate the product and evaluate for:

Tooth pack:	Amount of material left in and around the molar teeth.
Oily mouthcoating:	Degree to which the palate surface feels oily.

Source: Muñoz and Civille (1987). Reprinted from Food Reviews International **3**, page 304 by courtesy of Marcel Dekker Inc.

Example 4

Cookies (Plain Vanilla)

Table AIV.4 Sensory Texture Profiling Technique and Definition of Terms for Plain Vanilla Cookies

Stage I	Hold the cookie near the mouth so that the tongue and lips can be passed over the sample. *Evaluate for:* *Smoothness:* degree to which the top and bottom surfaces lack bumps or particles (geometrical)
Stage II	Place the whole cookie in the mouth so that incisors are positioned in the center of the sample. Bite through the sample by applying a steady force. *Evaluate for:* *Hardness:* force needed to bite through the cookie (hardness) *Fracturability:* force with which the cookie shatters (fracturability)
Stage III	Break the cookie in half and place one half between molars. Bite through the sample by applying a steady force. *Evaluate for:* *Fracturability:* force with which the cookie shatters (fracturability) *Hardness:* force required to bite through the piece (hardness) *Density:* compactness of the cross section (geometrical) *Uniformity:* degree to which the sample is the same from the outside to the center (geometrical)
Stage IV	Chew the whole cookie. *Evaluate for:* *Dryness (2 chews):* degree to which the sample lacks moisture (moisture) *Particle description (3–5 chews):* describe the size and shape of the particles present in the mouth (geometrical) *Rate of moisture absorption:* rate with which the sample absorbs saliva (moisture) *Adhesiveness:* degree to which the chewed material adheres to the mouth surface (adhesiveness) *Cohesiveness of the mass:* degree to which the mass holds together (gumminess) *Description of the mass:* description of all the material in the mouth including particles (geometrical) *Type of breakdown:* description of the changes occurring from the first bite to swallow (description of breakdown) *Number of chews to swallow:* number of chews required to hydrate the sample and bring it to a state ready for swallowing (moisture absorption, hardness, cohesiveness)
Stage V	Swallow the chewed sample. *Evaluate for:* *Ease of swallow:* degree to which the sample can be readily swallowed (gumminess, geometrical) *Molar packing:* amount of material left in and around the molar teeth (adhesiveness) *Mouthcoating:* description and amount of material left in the mouth (geometrical)

Source: Civille and Liska (1975). Reprinted from *J. Texture Studies* **6**, page 24. Copyright by Food and Nutrition Press Inc.

Example 5

Dulce de Leche (a dairy based confectionery popular in most Latin American countries)

Table AIV.5 Descriptors Used for Sensory Profiling of Dulce de Leche

Manual texture	
Sticky	Degree of stickiness to spoon
Stringy	Length of string when lifting spoon from dish
Peaks	Length of time peaks hold their shape
Soft	Degree of softness, as opposed to hardness
Flow rate	Rate/speed at which the Dulce de Leche flows off the spoon
Smooth	Degree of smoothness when spreading the sample against the side of the bowl with back of spoon
Spreadability	Ease required to spread the sample over the bottom of the bowl with back of spoon
Oral texture	
Thinness	Ease required to manipulate sample in mouth
Smooth	Degree of smoothness as opposed to grainy–sandy
Rate of melting	Speed with which the sample melts in the mouth
Sticks to mouth	Degree to which the sample sticks to mouth surface during manipulation
Mouthcoating	Degree of oily mouthcoating after swallowing
Ease of swallow	Ease with which sample can be completely swallowed

Source: Hough *et al*. (1992). Reprinted from *J. Sensory Studies* **7**, page 163. Copyright by Food and Nutrition Press Inc.

Example 6

Frankfurters

Table AIV.6 Sensory Texture Profiling Technique and Definition of Terms for Frankfurters

Stage I	Place frankfurter into mouth: feel surface with the tongue and lips *Evaluate for:* *Surface moisture:* degree to which the surface is wet or oily (moisture) *Type of moisture:* wet or oily *Surface smoothness:* degree to which the surface is smooth: i.e. not rough or uneven (geometrical)
Stage II	Place frankfurter into mouth: compress partially between incisors; release *Evaluate for:* *Elasticity:* degree to which sample returns to original shape after deformation (elasticity)
Stage III	Place frankfurter into mouth: bite down with front teeth at ¾ in. from end *Evaluate for:* *Hardness:* force required to bite through the sample (hardness) *Cohesiveness:* degree to which sample deforms before it ruptures (cohesiveness)

(*Continued*)

Table AIV.6 (*Continued*)

	Uniformity: degree to which sample is same from outside to inside (geometrical, mechanical) *Moisture release:* degree to which sample releases juices (moisture) *Denseness:* compactness of cross section (geometrical) *Coarseness:* degree to which mass feels rough (geometrical) *Graininess:* degree to which sample or juice contain small particles (geometrical)
Stage IV	Place ¾ in. section crosswise between molar teeth *Evaluate for:* *Hardness:* force required to bite through cross section (hardness)
Stage V	*Chewing:* Chew a ¾ in. piece with molar teeth *Evaluate for:* *Chewiness:* number of chews necessary to prepare sample for swallowing (chewiness) *Moisture release:* amount of juices released during chewing (moisture) *Oiliness:* amount of oil or fat in juices (fat) *Moisture absorption:* degree to which the sample mixes with saliva (moisture) *Cohesiveness of the mass:* degree to which mass holds together after 5–7 chews (gumminess) *Lumpy:* degree to which mass is made up of irregular pieces (geometrical) *Grainy:* degree to which sample contains small distinct particles (geometrical) *Skin:* degree to which skin is distinct from mass during the chew (geometrical) *Description of breakdown:* describe changes occurring during breakdown (description of breakdown)
Stage VI	*Swallowing:* Swallow sample *Evaluate for:* *Ease of swallow:* degree to which the chewed mass can be readily swallowed (geometrical) *Mouthcoating:* *Oiliness:* amount of oil or fat coating mouth surfaces (fat) *Particles:* amount and type of particles left in mouth (geometrical)

Source: Civille and Liska (1975). Reprinted from *J. Texture Studies* **6**, page 21. Copyright by Food and Nutrition Press Inc.

Example 7

Honeydew Melon

Table AIV.7 Honeydew Melon Texture Definitions and Values. Numbers in parentheses are the range of panel values for this product (0–14 range)

I.	*First bite*	Place half melon ball between molar teeth, bite and measure for:
	Firmness	Force required to bring teeth together (6–10)
	Moisture release	Amount of juice perceived upon biting (7–11)
	Denseness	Degree to which sample is compact and not cellular (5–9)
	Fibers	Amount of fibers perceived including residue left between teeth (6–9)
	Cohesiveness	Degree to which sample compresses before failure (3–6)
II.	*Mastication*	
	Pulpiness of mass	Degree to which the flesh persists regardless of whether it is soft or hard (6–8)
	Fibers	Degree to which fibers are perceived throughout mastication (8–10)
	Moisture persistence	Degree to which the release of moisture persists throughout mastication (7–9)
III.	*Residual*	
	Fibers	Amount of fibers perceived after swallow (8–10)

Source: Diehl and Hamann (1979). Reprinted from *J. Texture Studies* **10**, page 405. Copyright by Food and Nutrition Press Inc.

Example 8

Cooked Potato

Table AIV.8 Description of Texture Attributes of Cooked Potato

Nonoral

Reflection from surface (reflection): Expresses the percentage of the surface covered by loose white reflecting starch grains (not reflective = 0% of the surface, very reflective = 100% of the surface).

Hardness with knife (hardness-k): Force required to shear through the potato with a knife.

Hardness with finger (hardness-f): Force required to compress one quarter of the potato with one finger, when compressing longitudinally.

Fracturability with finger (fracturability-f): Degree of compression between fingers before the potato fractures. If the potato fractures at low compression degree the potato has high fracturability and oppositely.

Springiness with finger (springiness-f): Expresses the ability of the potato in returning into original shape after compression between fingers.

Oral

First Bite

Hardness in mouth (hardness-m): Force required to divide the potato into two parts by the front teeth.

Fracturability in mouth (fracturability-m): Degree of compression before the potato is separated into two parts by the front teeth. If the potato separates into two parts immediately the potato has high fracturability and oppositely.

Firmness/compactness (firmness): Degree of compression between molar teeth before the item falls apart.

Springiness in mouth (springiness-m): Expresses the ability of the potato in returning into original shape after the first compression with molars.

Following chewings

Adhesiveness: Force required to remove the potato sticking to teeth and palate after chewing.

Graininess: Expresses the content of grainy particles in the mouth after chewing.

Mealiness: Expresses how mealy/crumbly the potato is felt in the mouth after chewing.

Moistness: Expresses how moist the potato is felt in the mouth and how much moisture the item releases in the mouth after chewing.

Chewiness: Expresses the work (amount of mastications) before the potato is ready to swallow.

Source: Thybo and Martens (1998). Reprinted from *J. Texture Studies* **29**, page 458. Copyright by Food and Nutrition Press Inc.

Cooked Sweet Potato

Example 9

Table AIV.9 Texture Profile Panel Notes, Procedure, and Description for Cooked Sweet Potatoes

I. *Initial perception:*
Lightly press the end of the sample to the lips and evaluate for:
Moistness (I-MOIST): degree to which the sample is moist

Press the sample between the lips and evaluate for:
Springiness (I-SPRIN): degree to which the sample returns to its original shape after deformation
Cohesiveness (I-COH): degree to which the sample deforms before rupture

II. *First bite:*
Use a half of a sample, press the end to the roof of the mouth, using the tongue, and evaluate for:
Adhesiveness to palate (B-ADP): the force required to remove the sample from the palate with the tongue
Bite with the front teeth and evaluate for:
Hardness (B-HARD): amount of force necessary to bite completely through the sample
Denseness (B-DNS): degree to which the sample is solid, compactness of the cross section
Moistness (B-MOIST): degree to which the sample is moist

III. *Mastication:*
Chew at a constant rate of one chew per second and evaluate for:
Chewiness (M-CHEW): number of chews required to prepare the sample for swallowing
Adhesiveness of the mass (M-ADHE): degree to which the sample adheres or sticks to any of the mouth surfaces such as teeth, gums, palate
Moistness of mass (M-MOIST): amount of moisture/wetness perceived in the mass
Fibers (M-FIBER): amount of stringy fibers perceived

IV. *Swallow-residual:*
At the time of and immediately after swallow evaluate for:
Ease of swallow (SEOS): ease with which the sample is gathered up and swallowed
Mouth coating (S-MCT): amount of sample remaining in the mouth after swallow
Fibers (S-FIBER): amount of stringy fibers perceived
Chalkiness (S-CHLK): degree to which the mouth feels chalky; very fine particles, if present, often perceived on the roof of the mouth

Source: Truong *et al.* (1997). Reprinted from *J. Texture Studies* **28**, page 167. Copyright by Food and Nutrition Press Inc.

Example 10

Cooked Red Kidney Beans

Table AIV.10 Sensory Texture Profile Procedure for Cooked Red Kidney Beans. Panel Technique and Definition of Terms

Stage 1	Place one bean in mouth, manipulate gently with tongue without breaking the bean. Evaluate bean surface for: *Smoothness of skin:* feel of surface on tongue *Moistness of skin:* degree of moistness of surface
Stage 2	Chew the bean once between molars. Evaluate: *Hardness:* force required to crush bean with teeth *Fracturability:* degree to which bean crumbles, cracks or shatters *Starchiness:* feeling of free starch grains *Lumpiness:* presence of large particles harder than surrounding medium *Moistness:* amount of moisture in crushed cotyledon
Stage 3	Place one bean in mouth and chew until ready to swallow. Evaluate for: *Chewiness:* number of chews to reach final swallowing point *Gumminess:* denseness and cohesion persisting during mastication *Starchiness:* as above *Lumpiness:* as above *Grittiness:* presence of small harder particles that stand out in the medium *Skin toughness:* force to cut skin with incisors *Moistness:* as above
Stage 4	Place one bean in mouth, chew and swallow. Evaluate: Rate of breakdown of cotyledon Rate of breakdown of skin *Pastiness of bolus:* viscous somewhat sticky sensation Lumpiness of bolus (number of lumps) Lumpiness of bolus (hardness of lumps) *Grittiness:* as above *Toughness of skin pieces:* as above Moisture absorption by cotyledon Moisture absorption by skin *Particles around gums and teeth*: degree of coating remaining in mouth *Irritation in throat:* degree of unpleasant coating in throat *Burning on tongue:* sense of chemical irritation

Source: Garruti and Bourne (1985). Reprinted from *J. Food Science* **50**, page 1068. Copyright by Institute of Food Technologists.

Cooked Rice

Example 11

Table AIV.11 Vocabulary for Sensory Texture Attributes of Cooked Rice

Sensory attribute	Definition	Technique	Reference
Surface			
Adhesiveness to lips	Degree to which sample adheres to lips	Compress sample between lips, release, and evaluate	Cherry tomato, 0.0; nougat, 4.0; breadstick, 7.5; pretzel rod, 10.0
First bite			
Hardness	Force required to compress sample	Compress or bite through sample with molars	Cream cheese, 1.0; egg white, 2.5; American cheese, 4.5; hot dog, 5.5; olive, 7.0; peanut, 9.5; almond, 11.0; Life Savers, 14.5
Chewdown			
Cohesiveness of mass after 3 or 8 chews	Amount chewed sample holds together	Chew sample with molars 3 or 8 times and evaluate	Licorice, 0.0; carrot, 2.0; mushroom, 4.0; hot dog, 7.5; American cheese, 9.0; brownie, 13.0
Roughness of mass	Amount of roughness perceived in chewed sample	Chew sample with molars 8 times and evaluate	Jello, 0.0; orange peel, 3.0; cooked, oatmeal, 6.5
Toothpull	Force required to separate jaws during mastication	Chew 3 times and evaluate	Clam, 3.5; caramel, 5.0; Jujubes, 15.0
Particle size	Amount of space particle fills in mouth	Place sample in mouth and evaluate	Rice grain, 0.5; Tic Tac, 2.5; M&M, 4.0; Mike & Ikes, 6.0; Cherry Bite, 11.0
Toothpack	Amount of product packed into crowns of teeth after mastication	Chew sample 8 times, expectorate, and feel surface of crowns of teeth with tongue	Captain Crunch, 5.0; Heath Bar, 10.0
Loose particles	Amount of particles remaining in and on surface of mouth after swallowing	Chew sample 8 times with molars, swallow, and evaluate	Carrot, 10.0

Source: Meullenet *et al.* (1998). Reprinted from *Cereal Chemistry* **75**, page 715. Copyright by American Association of Cereal Chemists.

This Page Intentionally Left Blank

References

Abbott, J. A., and R. Lu. 1996. Anisotropic mechanical properties of apples. *Trans. Am. Soc. Agr. Eng.* **39**, 1451–1459.

Abbott, J. A., N. F. Childers, G. S. Bachman, J. V. Fitzgerald, and F. J. Matusik. 1968a. Acoustic vibration for detecting textural quality of apples. *Proc. Am. Soc. Hortic. Sci*. **93**, 725–737.

Abbott, J. A., G. S. Bachman, R. F. Childers, J. V. Fitzgerald, and F. J. Matusik. 1968b. Sonic techniques for measuring texture of fruits and vegetables. *Food Technol*. **22**, 635–646.

Abbott, J. A., R. Lu, B. L. Upchurch, and R. L. Stroshine. 1997. Technologies for non-destructive quality evaluation of fruits and vegetables. *Hort. Rev.* **20**, 1–120.

Abu-Shakra, A. M., and P. Sherman. 1984. Evaluation of bread firmness by Instron compression tests. *Rheol. Acta* **23**, 446–450.

Adams, M. C., and E. L. Birdsall. 1946. New Consistometer measures corn consistency. *Food Ind*. **18**, 844–846, 992, 994.

Aeschlimann, J.-M., and S. T. Beckett. 2000. International inter-laboratory trials to determine the factors affecting the measuring of chocolate viscosity. *J. Texture Stud.* **31**, 541–570.

Alexander, J. 1906. The grading and use of glues and gelatin. *J. Soc. Chem. Ind., London* **25**, 158–161.

Alexander, J. 1908. Method of and apparatus for testing jelly. U.S. Patent 882, 731.

Aguilera, I. M., and D. W. Stanley. 1999. "Microstructural Principles of Food Processing and Engineering," second ed. Aspen Publishers, Gaithersburg, Maryland.

Ahmed, E. M., F. G. Martin, and R. C. Fluck. 1973. Damaging stresses to fresh and irradiated citrus fruits. *J. Food Sci.* **38**, 230–233.

Allen, F. W. 1932. Physical and chemical changes in the ripening of deciduous fruits. *Hilgardia* **6**, 381–441.

Alvarez, M. D., D. E. J, Saunders, J. F. V. Vincent, and G. Jeronimidis. 2000. An engineering method to evaluate crisp texture of fruits and vegetables. *J. Texture Stud*. **31**, 457–473.

American Association of Cereal Chemists. 1969. "Cereal Laboratory Methods." American Association of Cereal Chemists, St Paul, Minnesota.

American Society of Agricultural Engineers. 1998. "ASAE Standards," 45th ed. St Joseph, Michigan.

Amerine, M. A., R. M. Pangborn, and E. B. Roessler. 1965. "Principles of Sensory Evaluation of Foods." Academic Press, New York.

Andreotti, R., and R. Agosti. 1965. Perfezionamento del Tenderometro modello stazione sperimentale conserve alimentari. *Ind. Conserva* **2**, 103–106.

Ang, J. K., F. M. Isenberg, and J. D. Hartman. 1960. Measurement of firmness of onion bulbs with a shear press and potentiometric recorder. *Proc. Am. Soc. Hortic. Sci*. **75**, 500–509.

Anonymous. 1959. Pectin standardization. Final report of IFT Committee. *Food Technol*. **13**, 496–500.

Anonymous. 1963. New research tool acquired by Station. *Farm Res*. **29**(2), 16.

Anonymous. 1964. Sensory testing guide for panel evaluation of foods and beverages. Prepared by the Committee on Sensory Evaluation of the Institute of Food Technologists. *Food Technol*. **18**, 1135–1141.

Anonymous. 1966. A new instrument for measuring the texture of potato french fries. *Am. Potato J*. **43**, 175.

Anonymous. 1973. "A Study of Consumer Attitudes Toward Product Quality." A. C. Nielsen Co., Northbrook, Illinois.

Anzalduá-Morales, A. 1989. "La Evaluación Sensorial en la Teoriá y la Práctica." Editorial Alhambra, S. A. Mexico City.

Anzalduá-Morales, A. 1990. Spanish words for viscosity and hardness/firmness. *J. Texture Stud.* **20**(4), V–VII0.

AOAC. 2000. "Official Methods of Analysis of AOAC International", 17th ed. AOAC International. Gaithersburg, Maryland.

Arnold, P. C., and N. N. Mohsenin. 1971. Proposed techniques for axial compression tests on intact agricultural products of convex shape. *Trans. ASAE* **14**, 78–84.

Arnott, D. R., H. A. Morris, and W. B. Combs. 1957. Effect of certain chemical factors on the melting quality of process cheese. *J. Dairy Sci.* **40**, 957–963.

Ash, M., and I. Ash. 1995. "Handbook of Food Additives." Aldershot, Hampshire, UK.

Atkin, G., and P. Sherman. 1984. The influence of surface friction on food firmness evaluation by compression testing. *Proc. IX Int. Congress on Rheology* **4**, 123–144.

Babcock, C. J. 1922. The whipping quality of cream. *U.S. Dep. Agric. Bull.* No. 1075.

Babcock, S. M. 1886. "Viscometry." New York State Agricultural Experiment Station. Fifth Annual Report, pp. 297–310.

Baduí, S. 1988. "Diccionario de Tecnología de Alimentos." Editorial Alhambra, S. A. Mexico City.

Bagley, E. B., D. D. Christenson, and D. L. Trebacz. 1990. The computation of viscosity and relaxation time of doughs from biaxial extension data. *J. Texture Stud*. **21**, 339–354.

Bailey, C. H. 1934. An automatic shortometer. *Cereal Chem*. **11**, 160–163.

Ball, C. O., W. E. Claus, and E. F. Stier. 1957. Factors affecting quality of prepackaged meats. 1B. Loss of weight and study of texture. *Food Technol*. **11**, 281–283.

Baltsavias, R., A. Jurgens, and T. Van Vliet. 1997. Factors affecting fracture properties of short-dough biscuits. *J. Texture Stud.* **28**, 205–219.

Barnes, H. A., J. F. Hutton, and K. Walters. 1989. "An Introduction to Rheology." Elsevier Science Publishers, New York.

Barrett, A. M., M. D. Normand, M. Peleg, and E. Ross. 1992. Characterization of the jagged stress-strain relationships of puffed extrudates using the Fast Fourier Transform and Fractal Analysis. *J. Food Sci.* **57**, 227–232, 235.

Barreiro, P., C. Ortiz, M. Ruiz-Altisent, V. deSmeat, S. Schotte, Z. Andani, I. Wakeling, and D. K. Beytes. 1998. Comparison between sensory and instrumental measurements for mealiness assessment in apples. A collaborative test. *J. Texture Stud.* **29**, 509–525.

Barrett, A. H., A. V. Cardello, L. Mair, P. Maguire, L. L. Lesher, M. Richardson, J. Briggs, and E. A. Taub. 2000. Textural optimization shelf-stable bread: effects of glycerol content and dough-forming technique. *Cereal Chem.* **77**, 164–176.

Barringer, S. A., A. T. M. Safiul Azam, B. Heskitt, and S. Sastry. 1998. On-line prediction of Bostwick consistency from pressure differential in pipe flow for ketchup and related tomato products. *J. Food Preservation Processing* **22**, 211–220.

Barry, B. W., and A. J. Grace. 1971. Structural, rheological and textural properties of soft paraffins. *J. Texture Stud.* **2**, 259–279.

Bechtel, W. G., D. F. Meisner, and W. B. Bradley. 1953. The effect of the crust on the staling of bread. *Cereal Chem*. **30**, 160–168.

Benbow, J. J. 1971. The dependence of output rate on die shape during catalyst extrusion. *Chem. Eng. Sci*. **26**(14), 67–73.

Benbow, J. J. 1981. Letter to the Editor. *J. Texture Stud*. **12**, 91–92.

Benedito, J., J. A. Cárcel, R. Gonzales, and N. Sanjúan. 2000a. Prediction of instrumental and sensory textural characteristics of Mahon cheese from ultrasonic measurements. *J. Texture Stud.* **31**, 631–643.

Benedito, J., J. Carcel, G. Clemente, and A. Mulet. 2000b. Cheese maturity assessment using ultrasonics. *J. Dairy Science* **83**, 248–254.

Berry, B. W., and G. V. Civille. 1986. Development of a texture profile panel for evaluating restructured beef steaks varying in meat particle size. *J. Sensory Stud*. **1**, 15–20.

Bhattacharya, S., S. Bhattacharya, and H. Narasimha. 1999. Uniaxial compressibility of blackgram doughs blended with cereal flours. *J. Texture Stud.* **30**, 659–675.

Bice, C. W., and W. F. Geddes. 1949. Studies on bread staling. IV. Evaluation of methods for the measurement of changes which occur during bread staling. *Cereal Chem*. **26**, 440–465.

Bingham, E. C. 1914. A new viscometer for general scientific and technical purposes. *Ind. Eng. Chem*. **6**, 233–237.

Bingham, E. C. 1922. "Fluidity and Plasticity." McGraw-Hill, New York.

Bingham, E. C. 1930. Fundamental definitions of rheology. *J. Rheol*. **1**, 507–516.

Bistany, K. C., and J. L. Kokini. 1983. Dynamic viscoelastic properties of foods in texture control. *J. Rheol.* **27**, 605–620.

Blanpied, G. D., W. J. Bramlage, D. H. Dewey, R. L. La Belle, L. M. Massey, G. E. Mattus., W. C. Stiles, and H. E. Watada. 1978. A standardized method for collecting apple pressure tests. New York's Food and Life Sciences Bulletin 74.

Bloom, O. T. 1925. Machine for testing jelly strength of glues, gelatins and the like. U.S. Patent 1,540,979.

Bookwalter, G. N., A. J. Peplinski, and V. F. Pfeiffer. 1968. Using a Bostwick Consistometer to measure consistencies of processed corn meals and their CSM blends. *Cereal Sci. Today* **13**, 407–410.

Borderias, A. G., M. Lamua, and M. Tejada. 1983. Texture analyses of fish fillets and minced fish by both sensory and instrumental methods. *J. Food Technol.* **18**, 85–95.

Borgale, P. C., and J. Irudayaraj. 1995. Mechanical strength and rheological behaviour of barley kernels. *Int. J. Food Sci. Technol.* **30**, 609–623.

Borges, A., and M. Peleg. 1996. Determination of the apparent fractal dimension of the force-displacement curves of brittle snacks by four different algorithms. *J. Texture Stud.* **27**, 243–255.

Borker, E., and K. G. Sloman. 1969. Dessert gel (gelatin) strength testing. II. Collaborative study. *J. Assoc. Off. Anal. Chem*. **52**, 657–659.

Borker , E., A. Stefanucci, and A. A. Lewis. 1966. Dessert gel strength testing. *J. Assoc. Off. Anal. Chem*. **49**, 528–533.

Botta, J. R. 1991. Instrument for nondestructive texture measurement of raw Atlantic cod (*Gadus morhua*) fillets. *J. Food Sci.* **56**, 962–964, 968.

Bourne, M. C. 1965a. Studies on punch testing of apples. *Food Technol*. **19**, 413–415.

Bourne, M. C. 1965b. How skin affects apple pressure test. *Farm Res* **31**(2), 10–11.

Bourne, M. C. 1966a. A classification of objective methods for measuring texture and consistency of foods. *J. Food Sci*. **31**, 1011–1015.

Bourne, M. C. 1966b. Measurement of shear and compression components of puncture tests. *J. Food Sci*. **31**, 282–291.

Bourne, M. C. 1967a. Deformation testing of foods. I. A precise technique for performing the deformation test. *J. Food Sci*. **32**, 601–605.

Bourne, M. C. 1967b. Squeeze it gently. *Farm Res*. **32**(4), 8–9.

Bourne, M. C. 1968. Texture profile of ripening pears. *J. Food Sci*. **33**, 223–226.

Bourne, M. C. 1972a. Standardization of texture measuring instruments. *J. Texture Stud*. **3**, 379–384.

Bourne, M. C. 1972b. Texture measurement of individual cooked dry beans by the puncture test. *J. Food Sci.* **37**, 751–753.

Bourne, M. C. 1973. Use of the Penetrometer for deformation testing of foods. *J. Food Sci*. **38**, 720–721.

Bourne, M. C. 1974. Textural changes in ripening peaches. *J. Can. Inst. Food Sci. Technol*. **7**, 11–15.

Bourne, M. C. 1975a. Is rheology enough for food texture measurement? *J. Texture Stud*. **6**, 259–262.

Bourne, M. C. 1975b. Method for obtaining compression and shear coefficients of foods using cylindrical punches. *J. Texture Stud*. **5**, 459–469.

Bourne, M. C. 1975c. Texture measurements in vegetables. *In* "Theory, Determination and Control of Physical Properties of Food Materials" (C. Rha, ed.), pp. 131–162. Reidel Publ., Dordrecht, Netherlands.

Bourne, M. C. 1976. Interpretation of force curves from instrumental texture measurements. *In* "Rheology and Texture in Food Quality" (J. M. deMan, P. W. Voisey, V. F. Rasper, and D. W. Stanley, eds), pp. 244–274. Avi, Westport, Connecticut.

Bourne, M. C. 1977. Compression rates in the mouth. *J. Texture Stud*. **8**, 373–376.

Bourne, M. C. 1979a. Rupture tests vs. small strain tests in predicting consumer response to texture. *Food Technol*. **33**(10), 67–70.

Bourne, M. C. 1979b. Theory and application of the puncture test in food texture measurement. *In* "Food Texture and Rheology" (P. Sherman, ed.), pp. 95–142. Academic Press, New York/London.

Bourne, M. C. 1980. Texture evaluation of horticultural crops. *Hortscience* **15**(1), (7)–(13).

Bourne, M. C. 1982. Effect of temperature on firmness of raw fruits and vegetables. *J. Food Sci*. **47**, 440–444.

Bourne, M. C. 1989. Applications of chemical kinetic theory to the rate of thermal softening of vegetable tissue. *In* "Quality Factors of Fruits and Vegetables. Chemistry and Technology" (J. J. Jen, ed.), American Chemical Society Symposium Series No. 405, pp. 98–110. American Chemical Society, Washington, DC.

Bourne, M. C. 1990. Basic principles of food texture measurement. *In* "Dough Rheology and Baked Product Texture" (H. Faridi, and J. M. Faubion, eds), pp. 331–341. Van Nostrand, Reinhold, New York.

Bourne, M. C. 1992. Calibration of rheological techniques used for foods. *J. Food Eng.* **16**, 151–163.

Bourne, M. C., and S. H. Comstock. 1986. Effect of temperature on firmness of thermally processed fruits and vegetables. *J. Food Sci.* **51**, 531–533.

Bourne, M. C., and N. Mondy. 1967. Measurement of whole potato firmness with a universal testing machine. *Food Technol*. **21**, 1387–1406.

Bourne, M. C., and J. C. Moyer. 1968. The extrusion principle in texture measurement of fresh peas. *Food Technol*. **22**, 1013–1018.

Bourne, M. C., and M. A. Rao. 1990. Viscosity measurements of foods. *In* "Instrumental Methods for Quality Assurance of Food" (D. Y. C. Fung, and R. F. Mathews, eds), pp. 211–229. Marcel Dekker, New York.

Bourne, M. C., J. C. Moyer, and D. B. Hand. 1966. Measurement of food texture by a universal testing machine. *Food Technol*. **20**, 522–526.

Bourne, M. C., A. M. R. Sandoval, M. Villalobos C., and T. S. Buckle. 1975. Training a sensory texture profile panel and development of standard rating scales in Colombia. *J. Texture Stud*. **6**, 43–52.

Brabender, C. W. 1965. Physical dough testing, past, present, future. *Cereal Sci. Today* **10**(6), 291–304.

Brandt, M. A., E. Z. Skinner, and J. A. Coleman. 1963. Texture Profile Method. *J. Food Sci*. **28**, 404–409.

Bratzler, L. J. 1932. Measuring the tenderness of meat by means of a mechanical shear. M.S. Thesis, Kansas State Coll., Manhattan.

Bratzler, L. J. 1949. Determining the tenderness of meat by use of the Warner–Bratzler method. *Proc. Annu. Reciprocal Meat Conf*. **2**, 117–120.

Breene, W. M. 1975. Application of texture profile analysis to instrumental food texture evaluation. *J. Texture Stud.* **6**, 53–82.

Breidinger, S. L., and J. F. Steffe. 2001. Texture map of cream cheese. *J. Food Sci*. **66**, 453–456.

Brennan, J. G. 1980. Food texture measurement. *In* "Developments in Food Analysis Techniques – 2" (R.D. King, ed.), pp. 1–78. Applied Science Publishers, Essex.

Brennan, J. G., and M. C. Bourne. 1994. Effect of lubrication on the compression behavior of cheese and frankfurters. *J. Texture Stud.* **25**, 139–150.

Brennan, J. G., R. Jowitt, and A. Williams. 1975. An analysis of the action of the General Foods Texturometer. *J. Texture Stud*. **6**, 83–100.

Briggs, J. L., and J. F. Steffe. 1997. Using Brookfield data and the Mitschka method to evaluate power law fluids. *J. Texture Stud.* **28**, 517–522.

Brinton, R. H., and M. C. Bourne. 1972. Deformation testing of foods. 3. Effect of size and shape of the test piece on the magnitude of deformation. *J. Texture Stud*. **3**, 284–297.

Briskey, E. J., R. W. Bray, W. G. Hoekstra, P. H. Phillips, and R. H. Grummer. 1959. The chemical and physical characteristics of various pork ham muscle classes. *J. Anim. Sci*. **18**, 146–152.

Britton, M. M., and P. T. Callaghan. 2000. NMR velocimetry study of the temperature dependent rheology of butter, semisoft butter and margarine. *J. Texture Stud.* **31**, 245–255.

Brochetti, D., M. P. Penfield, and S. B. Burchfield. 1992. Speech analysis techniques: a potential model for the study of mastication sounds. *J. Texture Stud.* **23**, 111–138.

Brovelli, E. A., S. L. Cuppett, and R. D. Uhlinger. 1998. Textural quality of green and white asparagus. *J. Food Quality* **22**, 497–504.

Brown, W. 1994. Method to investigate differences in chewing behavior in humans: I. Use of electromyography in measuring chewing. *J. Texture Stud.* **25**, 1–16.

Brown, W., M. Shearn, and H. J. H. MacFie. 1994a. Method to investigate differences in chewing behavior in humans. II. Use of electromyography during chewing to assess chewing behavior. *J. Texture Stud.* **25**, 17–31.

Brown, W. E., K. R. Langley, A. Martin, and H. J. H. MacFie. 1994b. Characterization of patterns of chewing behavior in human subjects and their influence on texture perception. *J. Texture Stud.* **25**, 455–468.

Brown, W. E., D. Eves, M. Ellison, and D. Braxton. 1998. Use of combined electromyography and kinesthesiology during mastication to chart the oral breakdown of foodstuffs: relevance to measurements of food texture. *J. Texture Stud.* **29**, 145–167.

Bruhn C., N. Feldman, C. Garlitz, J. Harwood, E. Ivans, M. Marshall, A. Riley, D. Thurber, and E. Williamson. 1991. Consumer perceptions of food quality: apricots, cantaloupes, peaches, pears, strawberries and tomatoes. *J. Food Quality* **14**, 187–195.

Brulle, R. 1893. Méthode générale pour l'analyse des beurres. *C. R. Hebd. Seances Acad. Sci*. **116**, 1255–1277.

Bruns, A. J., and M. C. Bourne. 1975. Effects of sample dimensions on the snapping force of crisp foods. Experimental verification of a mathematical model. *J. Texture Stud*. **6**, 445–458.

Brusewitz, G. H., M. P. Rigney, and A. Anzaldúa-Morales. 1997. Fast Fourier transformation analysis of the force-displacement curve as a texture method related to fruit morphology. *J. Texture Stud.* **28**, 503–516.

Bryan, W. L., B. J. Anderson, and J. M. Miller. 1978. Mechanically assisted grading of oranges for processing. *Tran. A. S. A. E*. **21**, 1226–1231.

Burton, R. I., and W. B. Rockwell. 1994. Hand. *In* "Principles of Surgery," 6th ed. (S. I. Schwartz, T. Shires, F. C. Spencer, and W. C. Hussem, eds.) McGraw-Hill, New York.

Callister, W. D. 1997. "Materials Science and Engineering: An Introduction." John Wiley & Sons, New York.

Campanella, O. H., and M. Peleg. 1987a. Squeezing flow of peanut butter. *J. Food Sci.* **52**, 180–184.

Campanella, O. H., and M. Peleg. 1987b. Determination of the yield stress of semiliquid foods from squeezing flow data. *J. Food Sci.* **52**, 214, 215, 217.

Campanella, O. H., and M. Peleg. 2001. Squeezing flow viscometry for non-elastic semi-liquid foods – Theory and applications. *Crit. Rev. Food Sci.* (in press).

Campanella, O. H., L. M. Popplewell, J. R. Rosenau, and M. Peleg. 1987. Elongational viscosity measurements of melting American process cheese. *J. Food Sci.* **52**, 1249–1251.

Campbell, H. 1942. Temperature and Tenderometer. *Western Canner & Packer* 34(Feb), 39; 34(May), 45.

Campion, D. R., J. D. Crouse, and M. E. Dikeman. 1975. The Armour Tenderometer as a predictor of cooked meat tenderness. *J. Food Sci*. **40**, 886–887.

Caparaso, F., A. L. Cortovarria, and R. W. Mandigo. 1978. Effects of post-cooking sample temperature on sensory and shear analyses of beef steaks. *J. Food Sci*. **43**, 839–841.

Cardello, A. V. 1996a. The role of the human senses in food acceptance. *In* "Food Choice, Acceptance and Consumption" (M. L. Meiselman and H. J. H. MacFie, eds), pp. 1–82. Blackie Academic and Professional, New York.

Cardello, A. V. 1996b. The role of the human senses in food behavior. II. Texture. *Cereal Foods World* **41**, 469, 470.

Cardello, A. V., and R. A. Segars. 1989. Effects of sample size and prior mastication on texture judgment. *J. Sensory Stud.* **4**, 1–18.

Carpenter, Z. L., G. C. Smith, and O. D. Butler. 1972. Assessment of beef tenderness with the Armour Tenderometer. *J. Food Sci*. **37**, 126–129.

Carpi, S. 1884. Die Entdeckung fremder Oele im Olivenöl. *Arch. Pharm.* (*Weinheim, Ger*.) **221**, 963; from *Ann. Chim. Appl. Farm. Med*. **77**, No. 3.

Casimir, D. J., R. S. Mitchell, L. J. Lynch, and J. C. Moyer. 1967. Vining procedures and their influence on yield and quality of peas. *Food Technol*. **21**, 427–432.

Casimir, D. J., G. G. Coote, and J. C. Moyer. 1971. Pea texture studies using a single puncture Maturometer. *J. Texture Stud*. **2**, 419–430.

Casiraghi, E. M., E. B. Bagley, and D. D. Christianson. 1985. Behavior of Mozzarella, cheddar and processed cheese spread in lubricated and bonded uniaxial compression. *J. Texture Stud.* **16**, 281–301.

Casson, N. 1959. A flow equation for pigment oil suspensions of the printing ink type. *In* "Rheology in Disperse Systems" (C. C. Mill, ed.), pp. 84–104. Pergamon, Oxford.

Castell-Perez, M. E., and J. F. Steffe. 1992. Using mixing to evaluate rheological properties. *In* "Viscoelastic Properties of Foods" (M. A. Rao and J. F. Steffe, eds), pp. 247–284. Elsevier Applied Science, London/New York.

Castell-Perez, M. E., J. F. Steffe, and R. G. Morgan. 1987. Adaptation of a Brookfield (HBTD) viscometer for mixer viscometry studies. *J. Texture Stud.* **18**, 359–365.

Cathcart, W. H., and L. C. Cole. 1938. Wide-range volume measuring apparatus for bread. *Cereal Chem*. **15**, 69–79.

Chatraei, S. H., C. W. Macowsko, and H. H. Winter. 1981. Lubricated squeezing flow: a new biaxial extensional rheometer. *J. Rheol.* **25**, 433–444.

Chen, P., and R. B. Fridley. 1972. Analytical method for determining viscoelastic constants of agricultural materials. *Trans. Am. Soc. Agr. Eng.* **15**, 1103–1106.

Chevalley, J. 1975. Rheology of chocolate. *J. Texture Stud*. **6**, 177–196.

Chevalley, J. 1991. An adaptation of the Casson equation for the rheology of chocolate. *J. Texture Stud.* **22**, 219–229.

Child, A. M., and M. Baldwell. 1934. Press fluid from heated fish muscle. *J. Agric. Res.* **48**, 1127–1134.

Christel, W. F. 1938. Texturemeter, a new device for measuring the texture of peas. *Cann. Trade* **60**(34), 10.

Christensen, C. M., and Z. M. Vickers. 1981. Relationships of chewing sounds to judgements of food crispness. *J. Food Sci.* **46**, 574–578.

Chu, C. F., and M. Peleg. 1985. The compression behavior of solid food specimens with small height to diameter ratios. *J. Texture Stud.* **16**, 451–464.

Civille, G. V., and I. H. Liska. 1975. Modifications and applications to foods of the General Foods Sensory Texture Profile Technique. *J. Texture Stud*. **6**, 19–32.

Civille, G. V., and A. S. Szczesniak. 1973. Guidelines to training a texture profile panel. *J. Texture Stud*. **4**, 204–223.

Claassens, J. W. 1958. The adhesion–cohesion, static friction and macrostructure of certain butters. I. A method of measuring the adhesion–cohesion of butter. *S. Afr. Tydskr. Landbouwet*. **1**, 457–463.

Claassens, J. W. 1959a. The adhesion–cohesion, static friction and macrostructure of certain butters. II. Factors affecting the values recorded with the hesion balance. *S. Afr. Tydskr. Landbouwet*. **2**, 89–118.

Claassens, J. W. 1959b. The adhesion–cohesion, static friction and macrostructure of certain butters. V. Friction and hesion measurements on the same test surfaces. *S. Afr. Tydskr. Landbouwet*. **2**, 551–571.

Clark, R. L., and P. S. Shackelford, J. 1976. Resonance and optical properties of peaches as related to firmness. *In* "Quality Detection in Foods" (J. J. Gaffney, ed.), ASAE Publ. No. 1–76, pp. 143–145. Am. Soc. Agric. Eng., St Joseph, Michigan.

Cobb, N. A. 1896. The hardness of the grain in the principal varieties of wheat. *Agric. Gaz. N. S. W*. **7**, 279–298.

Coles, G. D. 1998. Objective estimation of bread visual texture. *Chemistry in Australia* August, 13–15.

Cook, L. R. 1982. "Chocolate Production and its Use." Harcourt Brace Jovanovich, New York.

Cooke, J. R. 1972. An interpretation of the resonant behavior of intact fruits and vegetables. *Trans. ASAE* **15**(6), 1075–1080.

Cooke, J. R., and R. H. Rand. 1973. A mathematical study of resonance in intact fruits and vegetables using a 3-media elastic sphere model. *J. Agric. Eng. Res*. **18**, 141–157.

Corey, H. 1970. Texture in foodstuffs. *CRC Crit. Rev. Food Technol*. **1**, 161–198.

Corradini, M. G., R. Engel, and M. Peleg 2000a. Assessment of the extent of consistency loss in semiliquid foods by compression and shear. *J. Texture Stud*. **31**, 363–378.

Corradini, M. G., V. Stern, T. Suwonsichon, and M. Peleg. 2000b. Squeezing flow of semi-liquid foods between parallel Teflon coated plates. *Rheol. Acta* **39**, 452–460.

Couette, M. M. 1890. Etudes sur le frottement des liquides. *Ann. Chim. Phys*. **21**, 433–510.

Coulter, S. T., and W. B. Combs. 1936. A study of the body and texture of butter. *Minn. Agric. Exp. Stn., Tech. Bull*. No. 115.

Cover, S., S. J. Ritchey, and R. L. Hostetler. 1962. Tenderness of beef. I. The connective tissue component of tenderness. *J. Food Sci*. **27**, 469–475.

Cox, R. E., and R. H. Higby. 1944. A better way to determine the setting power of pectins. *Food Ind*. **16**, 441–443.

Crean, D. E. C., and D. R. Haisman. 1965. Elasticity coefficients and texture of cooked dried peas. *J. Sci. Food Agric*. **16**, 469–474.

Crossland, L. B., and H. H. Favor. 1950. A study of the effects of various techniques on the measurement of firmness of bread by the Baker Compressimeter. *Cereal Chem*. **27**, 15–25.

Culioli, J., and P. Sale. 1981. Spinnability of fababean protein II. Spinnability of dopes and textural properties of protein fibers. *J. Texture Stud*. **12**, 335–350.

Culioli, J., and P. Sherman. 1976. Evaluation of Gouda cheese firmness by compression tests. *J. Texture Stud.* **7**, 353–372.

Cutler, A. N., E. R. Morris, and L. J. Taylor. 1983. Oral perception of viscosity in model systems. *J. Texture Stud.* **14**, 377–395.

Dacremont, C. 1995. Spectral composition of eating sounds generated by crispy, crunchy or crackly foods. *J. Texture Stud.* **26**, 27–43.

Dagbjartsson, B., and M. Solberg. 1972. A simple method to determine the water-holding capacity of muscle foods. *J. Food Sci*. **37**, 499–500.

Daget, N., and M. Joerg. 1991. Creamy perception II. In model soups. *J. Texture Stud.* **22**, 164–190.

Daget, N., M. Joerg, and M. C. Bourne. 1987. Creamy perception I. In model dessert creams. *J. Texture Stud.* **18**, 367–388.

Damrau, E., and M. Peleg. 1997. Imperfect squeezing flow viscometry of Newtonian liquids – theoretical and practical considerations. *J. Texture Stud.* **28**, 187–206.

Daubert, C. R., J. A. Tkachuk, and V. D. Truong. 1998. Quantitative measurement of food spreadability using the vane method. *J. Texture Stud.* **29**, 427–435.

Davey, C. L., and K. V. Gilbert. 1969. The effect of sample dimensions on the cleaving of meat in the objective assessment of tenderness. *J. Food Technol*. **4**, 7–15.

Davey, K. R. 1983. An instrument for the measurement of hardness of fat on sides of chilled beef. *J. Texture Stud.* **14**, 419–430.

Davey, K. R. 1986. Measurement of the hardness and mouthful of cheese using a sliding pin consistometer. *J. Texture Stud.* **17**, 267–274.

Davey, K. R., and P. N. Jones. 1985. Evaluation of a sliding pin consistometer for measurement of the hardness and spreadability of butter and margarine. *J. Texture Stud.* **16**, 75–84.

Davis, C. E. 1921. Shortening: Its definition and measurement. *Ind. Eng. Chem*. **13**, 797–799.

Davis, J. G. 1937. The rheology of cheese, butter, and other milk products. *J. Dairy Res*. **8**, 245–264.

Davis, S. S. 1973. Rheological properties of semi-solid foodstuffs. *J. Texture Stud.* **4**, 15–40.

Dealy, J. M. 1994. Official nomenclature for material functions describing the response of a viscoelastic fluid to various shearing and extensional deformations. *J. Rheol.* **38**, 179–183.

DeBeaukelaer, F. L., J. R. Powell, and E. F. Bahlmann. 1930. Standard methods (revised) for determining viscosity and jelly strength of glue. *Ind. Eng. Chem., Anal. Ed*. **2**, 348–351.

DeBeaukelaer, F. L., O. T. Bloom, and J. T. DeRose. 1945. Determining jelly strength of gelatin-dessert jellies. *Ind. Eng. Chem., Anal. Ed*. **17**, 64.

Decker, R. W., J. N. Yeatman, A. Kramer, and A. P. Sidwell. 1957. Modifications of the shear press for electrical indicating and recording. *Food Technol*. **11**, 343–347.

DeLong, J. M., R. K. Prange, P. A. Harrison, and K. B. McRao. 2000. Comparison of new apple firmness penetrometer with three standard instruments. *Postharvest Biol. Technol.* **19**, 201–209.

deMan, J. M. 1969. Food texture measurements with the penetration method. *J. Texture Stud*. **1**, 114–119.

deMan, J. M. 1975. Texture of foods. *Lebensm.-Wiss. Technol*. **8**, 101–107.

deMan, J. M., and B. S. Kamel. 1981. Instrumental methods of measuring texture of poultry meat. *In* "Quality of Poultry Meat," Spelderholt Jubilee Symposia, pp. 157–164. Apeldoorn, Netherlands.

Diehl, K. C., and D. D. Hamann. 1979. Relationships between sensory profile parameters and fundamental mechanical properties for raw potatoes, melons and apples. *J. Texture Stud.* **10**, 401–420.

Diehl, K. C., D. D. Hamann, and J. K. Whitfield. 1979. Structural failure in selected raw fruits and vegetables. *J. Texture Stud*. **10**, 371–400.

Dikeman, M. E., J. H. Tuma, H. A. Glimp, R. E. Gregory, and D. M. Allen. 1972. Evaluation of the Tenderometer for predicting bovine muscle tenderness. *J. Anim. Sci*. **34**, 960.

Dixon, G. D., and J. V. Parekh. 1979. Use of the cone penetrometer for testing the firmness of butter. *J. Texture Stud*. **10**, 421–434.

Dogan, I. S., and C. E. Walker. 1999. Effects of impingement oven parameters and formulation on sugar snap cookies. *Cereal Food World* **44**, 597–603.

Drake, B. K. 1961. An attempt at a geometrical classification of rheological apparatus. Unpublished manuscript. Göteborg, Sweden.

Drake, B. K. 1963. Food crushing sounds. An introductory study. *J. Food Sci*. **28**, 233–241.

Drake, B. K. 1965. Food crushing sounds: Comparison of objective and subjective data. *J. Food Sci*. **30**, 556–559.

Drake, B. 1971. A quasi-rheological model element for fracture. *J. Texture Stud*. **2**, 365–372.

Drake, B. 1989. Sensory textural/rheological properties – a polyglot list. *J. Texture Stud.* **20**, 1–27.

Duizer, L. M., E. A. Gullett, and C. J. Findlay. 1996. The relationship between sensory time-intensity, physiological electromyography and instrumental texture profile analysis measurements of beef tenderness. *Meat Science* **42**, 215–224.

Edelman, E. C., W. H. Cathcart, and C. B. Berquist. 1950. The effect of various ingredients on the rate of firming of bread crumb in the presence of polyoxyethylene (mono) stearate and glycerylmonostearate. *Cereal Chem*. **27**, 1–14.

Edminster, J. A., and Z. M. Vickers. 1985. Instrumental acoustical measures of crispness in foods. *J. Texture Stud.* **16**, 153–167.

Elliott, J. J., and A. J. Ganz. 1977. Salad dressings – preliminary rheological characterization. *J. Texture Stud.* **8**, 359–371.

Ferry, J. D. 1977. Oscillation viscometry – effects of shear rate and frequency. *Meas. Control*. **11**(5), 89–91.

Feuge, R. D., and W. A. Guice. 1959. Effect of composition and polymorphic form on the hardness of fats. *J. Am. Oil. Chem. Soc*. **36**, 531–534.

Finney, E. E., Jr. 1970. Mechanical resonance within Red Delicious apples and its relation to fruit texture. *Trans. ASAE* **13**, 177–180.

Finney, E. E., Jr. 1971a. Dynamic elastic properties and sensory quality of apple fruit. *J. Texture Stud*. **2**, 62–74.

Finney, E. E., Jr. 1971b. Random vibration techniques for non-destructive evaluation of peach firmness. *J. Agric. Eng. Res*. **16**, 81–87.

Finney, E. E., Jr. 1971c. Vibration technique for testing fruit. *Pap. – Am. Soc. Agric. Eng*. No. 71–802.

Finney, E. E., Jr. 1972. Vibration techniques for testing fruit firmness. *J. Texture Stud*. **3**, 263–283.

Finney, E. E. 1973. Elementary concepts of rheology relevant to food texture studies. *In* "Texture Measurements of Foods" (A. Kramer, and A. S. Szczesniak, eds), pp. 33–70. Reidel Publishing Co., Dordrecht, Holland.

Finney, E. E., Jr., and J. A. Abbott. 1972. Sensory and objective measurements of peach firmness. *J. Texture Stud*. **3**, 372–378.

Finney, E. E., Jr., and C. W. Hall. 1967. Elastic properties of potatoes. *Trans. ASAE* **10**, 4–8.

Finney, E. E., Jr., and K. H. Norris. 1968. Instrumentation for investigating dynamic mechanical properties of fruits and vegetables. *Trans. ASAE* **11**, 94–97.

Finney, E. E., Jr., I. Ben-Gera, and D. R. Massie. 1968. An objective evaluation of changes in firmness of ripening bananas using a sonic technique. *J. Food Sci*. **32**, 642–646.

Finney, E. E., Jr., J. A. Abbott, A. E. Watada, and D. R. Massie. 1978. Nondestructive sonic resonance and the texture of apples. *J. Am. Soc. Hortic. Sci*. **103**, 158–162.

Finney, K. F., and M. D. Shogren. 1972. A ten-gram Mixograph for determining and predicting functional properties of wheat flours. *Bakers Dig*. **46**(2), 32–35, 38–42, 77.

Fisher, J. D. 1933. Shortening value of plastic fats. *Ind. Eng. Chem*. **25**, 1171–1173.

Fitzgerald, J. V., and F. J. Matusik. 1976. Applications of a vibratory viscometer. *Am. Lab*. **8**(6), 63–68.

Fletcher, S. W. 1975. Mechanical damage to the processed fruits and vegetables. *In* "Theory, Determination and Control of Physical Properties of Food Materials" (C. Rha, ed.), pp. 163–179. D. Reidel Pub. Co., Dordrecht, Holland.

Freundlich, H., and W. Seifriz. 1923. Über die Elastizität von Solen und Gelen. *Z. Phys. Chem., Stoechiom. Verwandschaftsl*. **104**, 233–261.

Friedman, H. H., J. E. Whitney, and A. S. Szczesniak. 1963. The Texturometer – a new instrument for objective texture measurement. *J. Food Sci*. **28**, 390–396.

Friend, C. P., R. D. Waniska, and L. W. Rooney. 1993. Effects of hydrocolloids on processing and qualities of wheat tortillas. *Cereal Chem.* **70**, 252–256.

Fujii, K., R. Kajita, M. Kurosawa, and T. Fujii. 2000. Mechanical properties of two-phase disperse agar/gelatin mixed gels. *J. Texture Stud.* **31**, 273–286.

Fukushima, M., and T. Kimura. 1992. "General Dictionary for Milk," (K. Yamauchi, and K. Yokoyama, eds), p. 88. Asakura Shaten, Tokyo.

Funk, K., M. E. Zabik, and D. A. Elgidaily. 1969. Objective measurements for baked products. *J. Home Econ*. **61**, 119–123.

Gardner, H. A., and A. W. VanHeuckeroth. 1927. Some further applications of a Mobilometer. *Ind. Eng. Chem*. **19**, 724–726.

Garruti, R. D.-S., and M. C. Bourne. 1985. Effect of storage conditions of dry bean seeds (*Phaseolus vulgaris* L.) on texture profile parameters after cooking. *J. Food Sci.* **50**, 1067–1071.

Genovese, D. B., and J. E. Lozano. 2000. Particle size determination of food suspensions: application to cloudy apple juice. *J. Food Process Eng.* **23**, 437–452.

Gillett, T. A., C. L. Brown, R. L. Leutzinger, R. D. Cassidy, and S. Simon. 1978. Tensile strength of processed meats determined by an objective Instron technique. *J. Food Sci*. **43**, 1121–1124, 1129.

Gilmont, R. 1963. A falling-ball viscometer. *Instru. Control Sys*. **36**(9), 121–122.

Goh, H. C., and P. Sherman. 1987. Influence of surface friction on the stress relaxation of Gouda cheese. *J. Texture Stud.* **18**, 389–404.
Goldthwaite, N. E. 1909. Contribution on the chemistry and physics of jelly-making. *Ind. Eng. Chem*. **1**, 333.
Goldthwaite, N. E. 1911. The principles of jelly making. *Univ. Ill. Bull*. **3**, No. 7.
Gonzalez, J. J., K. L. McCarthy, and M. J. McCarthy. 2000. Textural and structural changes in cooked lasagna pasta. *J. Texture Stud.* **31**, 93–108.
Gould, W. A. 1949. Instruments to quickly reveal quality of snap and wax beans. *Food Packer* **30**(12), 26–27.
Grawemeyer, E. A., and M. C. Pfund. 1943. Line-spread as an objective test for consistency. *Food Res.* **8**, 105–108.
Green, H. 1949. "Industrial Rheology and Rheological Structures." Wiley, New York.
Guinee, T. P., and D. J. O'Callaghan. 1997. The use of a simple empirical method for objective quantification of the stretchability of cheese on cooked pizza pies. *J. Food Eng.* **31**, 147–161.
Guinee, T. P., M. A. E. Auty, and C. Mullins. 1999. Observations on the microstructure and heat-induced changes in the viscoelasticity of commercial cheese. *Aust. J. Dairy Technol.* **54**, 84–89.
Guinee, T. P., M. A. E. Auty, C. Mullins, M. O. Corcoran, and E. O. Mulholland. 2000. Preliminary observations on effects of fat content and degree of fat emulsification on the structure-functional relationship of cheddar-type cheese. *J. Texture Stud.* **31**, 645–663.
Guraya, H. S., and R. T. Toledo. 1996. Microscopical characteristics and compression resistance as indices of sensory texture in a crunchy snack product. *J. Texture Stud*. **27**, 687–701.
Guritno, P., and E. Hague. 1994. Relationship between energy and size reduction of grains using a three-roller mill. *Am. Soc. Agr. Eng.* **37**, 1243–1248.
Guthrie, E. S. 1952. A study of the body of cultured cream. *Cornell Agric. Exp. Stn. Bull.* (*Ithaca*) No. 880.
Guthrie, E. S. 1963. Further studies of the body of cultured cream. *Cornell Agric. Exp. Stn. Bull.* (*Ithaca*) No. 986.
Hack, J. K., Y. K. Byung, and T. H. Yang. 1995. Prediction of failure stress of tofu texture using a delay time of ultrasonic wave. *Agr. Chem. Biotechnol.* **38**, 325–329.
Hagberg, S. 1960. A rapid method for determining alpha-amylase activity. *Cereal Chem*. **37**, 218–222.
Hagberg, S. 1961. Note on a simplified rapid method for determining alpha-amylase activity. *Cereal Chem*. **38**, 202–203.
Hagen, G. 1839. Ueber die Bewegung des Wassers in engen zylindrischen Roehren. *Pogg. Ann*. **46**, 423.
Haighton, A. J. 1959. The measurement of hardness of margarine and fats with cone penetrometers. *J. Am. Oil Chem. Soc*. **36**, 345–348.
Haller, M. H. 1941. Fruit pressure testers and their practical applications. *U.S. Dep. Agric., Circ*. No. 627.
Halmos, A. L. 1997. Food texture and sensory properties of dairy ingredients. *Food Aust.* **49**, 169–173.
Halmos, A. L., and C. Tiu. 1981. Liquid foodstuffs exhibiting yield stress and shear-degradability. *J. Texture Stud*. **12**, 39–46.

Halton, P., and G. W. Scott Blair. 1937. A study of some physical properties of flour doughs in relation to their bread-making properties. *Cereal Chem*. **14**, 201–219.
Hamann, D. D. 1983. Structural failure in solid foods. *In* "Physical Properties of Foods" (M. Peleg, and E. B. Bagley, eds), pp. 351–383. Avi Publishing Co. Inc., Westport.
Hamann, D. D. 1988. Rheology as a means of evaluating muscle functionality of processed foods. *Food Technol.* **42**(6), 66–71.
Hamann, D. D. 1994. Rheological studies of fish proteins. *In* "Food Hydrocolloids: Structures, Properties and Function" (K. Nishinari, and E. Dol, eds), pp. 225–234. Plenum Press, New York.
Hamann, D. D., and D. E. Carroll. 1971. Ripeness sorting of muscadine grapes by use of low-frequency vibrational energy. *J. Food Sci*. **36**, 1049–1051.
Hamann, D. D., and G. A. MacDonald. 1992. Rheology and texture properties of surimi and surimi-based foods. *In* "Surimi Technology" (T. C. Lanier, and C. M. Lee, eds), pp. 429–500. Marcel Dekker Inc., New York.
Hamann, D. D., L. J. Kushman, and W. E. Ballinger. 1973. Sorting blueberries for quality by vibration. *J. Am. Soc. Hortic. Sci*. **98**, 572–576.
Hamm, R. 1960. Biochemistry of meat hydration. *Adv. Food Res*. **10**, 355–463.
Hansen, L. J. 1971. Meat tenderness testing. U.S. Patent 3,602,038 (W. Armour & Co.).
Hansen, L. R. 1972. Development of the Armour Tenderometer for tenderness evaluation of beef carcases. *J. Texture Stud*. **3**, 146–164.
Harrington, G., and A. M. Pearson. 1962. Chew count as a measure of tenderness of pork loins with various degrees of marbling. *J. Food Sci*. **27**, 106–110.
Harris, P. V. 1975. Meat chilling. *CSIRO Food Res. Q*. **35**, 49–56.
Hartman, H. 1924. Studies relating to the harvesting and storage of apples and pears. *Oregon Agr. Exp. Sta. Bull*. 206.
Hartman, H., and D. E. Bullis. 1929. Investigations relating to the handling of sweet cherries. *Oregon Agr. Exp. Sta. Bull*. 247.
Hashimoto, Y., T. Fukazawa, R. Niki, and T. Yasui. 1959. Effects of storage conditions on some of the biochemical properties of meats and on the physical properties of an experimental sausage. *Food Res*. **24**, 185–197.
Haugh, R. R. 1937. The Haugh unit for measuring egg quality. *U.S. Egg Poult. Mag*. **43**, 552–555, 572.
Hawkins, L. A., and C. E. Sando. 1920. Effect of temperature on the resistance to wounding of certain small fruits and cherries. *USDA Bull*. 830.
Hayakawa, M., and J. M. de Man. 1982. Interpretation of cone penetrometer consistency of fats. *J. Texture Stud.* **13**, 201–210.
Heath, M. R. 1982. The effect of maximum biting force and bone loss on masticatory function and dietary selection in the elderly. *Int. Dent. J.* **32**, 345–351.
Henrickson, R. L., J. L. Marsden, and R. D. Morrison. 1972. An evaluation of the Armour Tenderometer for an estimation of beef tenderness. *J. Food Sci*. **37**, 857–859.
Henry, W. F., and M. H. Katz. 1969. New dimensions relating to the textural quality of semi-solid foods and ingredient systems. *Food Technol*. **23**, 822–825.
Henry, W. F., M. H. Katz, F. J. Pilgrim, and A. J. May. 1971. Texture of semi-solid foods: sensory and physical correlates. *J. Food Sci.* **36**, 155–161.
Herschel, W. H., and C. Bergquist. 1921. The consistency of starch and dextrin pastes. *Ind. Eng. Chem*. **13**, 703–706.

Herschel, W. H., and R. Bulkley. 1926. Konsistenzmessungen von gummibenzollösungen. *Kolloid-Z*. **39**, 291–300.

Hickson, D. W., C. W. Dill, R. G. Morgan, V. E. Sweat, D. A. Suter, and Z. L. Carpenter. 1982. Rheological properties of two heat-induced protein gels. *J. Food Sci.* **47**, 783–785, 791.

Hiiemae, K. M., and J. B. Palmer. 1999. Food transport and bolus formation during complete feeding sequences on foods of different initial consistency. *Dysphagia* **14**, 31–42.

Hilker, L. D. 1947. A method for measuring the body of cultured cream. *J. Dairy Sci*. **30**, 161–164.

Hill, R. L. 1923. A test for determining the character of the curd from cow's milk and its application to the study of curd and variance as an index to the food value of milk for infants. *J. Dairy Sci*. **6**, 509–526.

Hill, R. L. 1933. A decade and a half of soft-curd milk studies. *Utah Agric. Exp. Stn. Circ.* No. 101.

Hinton, C. J. 1970. *In* "Twenty Years of Confectionery and Chocolate Progress" (C. D. Pratt, E. de H. W. Vadetzky, K. E. Langwill, K. E. McCloskey, and H. W. Schuemann, eds), p. 111. Avi Publishing Co., Westport.

Hogarth, J. 1889. A new or improved mode of and means or appliance for testing and recording the characteristics or properties of flour and dough. U.K. Patent 16,389.

Holdsworth, S. D. 1971. Applicability of rheological models to the interpretation of flow and processing behavior of fluid food products. *J. Texture Stud*. **2**, 393–418.

Holt, S. 1999. The satiety index: a new method to measure the filling powers of foods. *Food Aust.* **51**(3), 74, 75.

Hoseney, R. C., and J. Smewing. 1999. Instrumental measurement of stickiness of doughs and other foods. *J. Texture Stud.* **30**, 123–136.

Hoseney, R. C., K. H. Hsu, and R. C. Junge. 1979. A simple spread test to measure the rheological properties of fermenting dough. *Cereal Chem*. **56**, 141–143.

Hostetler, R. L., and S. J. Ritchey. 1964. Effect of coring methods on shear values determined by Warner–Bratzler shear. *J. Food Sci*. **29**, 681–685.

Hough, G., N. Bratchell, and D. B. MacDougal. 1992. Sensory profiling of dulce de leche, a dairy based confectionery product. *J. Sensory Stud.* **7**, 157–178.

Houwink, R. 1958. "Elasticity, Plasticity and Structure of Matter." Dover, New York.

Howe, J. R., D. D. Hamann, T. C. Lanier, and J. W. Park. 1994. Fracture of Alaska pollock gels in water: effects of minced muscle processing and test temperature. *J. Food Sci.* **59**, 777–780.

Howe, P. E., and S. Bull. 1927. A study of factors which influence the quality and palatability of meat. *U.S. Dep. Agric., Natl. Coop. Proj., Bur. Anim. Ind*. Rev. ed.

Hubbard, R. M., and G. G. Brown. 1943. The rolling ball viscometer. *Ind. Eng. Chem., Anal. Ed*. **15**, 212–218.

Huffman, D. L. 1974. An evaluation of the Tenderometer for measuring beef tenderness. *J. Anim. Sci*. **38**, 287–294.

Hulbert, E. 1913. Improved apparatus for testing the jelly strength of glues. *Ind. Eng. Chem*. **5**, 235.

Hunziker, O. E., H. C. Mills, and G. Spitzer. 1912. Moisture control of butter. *Indiana Agric. Exp. Stn., Stn. Bull*. No. 159, p. 347, 359.

Hutchings, J. B., and P. L. Lillford. 1988. The perception of food texture – the philosophy of the breakdown path. *J. Texture Stud.* **19**, 103–115.

Imai, E., K. Saito, M. Hatakeyama, K. Hatae, and A. Shimada. 1999. Effect of physical properties of food particles on the degree of graininess perceived in the mouth. *J. Texture Stud.* **30**, 59–88.

Jack, F. R., and F. Gibbon. 1995. Electropalatography in the study of tongue movement during eating and swallowing (a novel procedure for measuring texture-related behaviour). *Int. J. Food Sci. Technol.* **30**, 415–423.

Jackman, R. L., and D. W. Stanley. 1992. Area- and perimeter-dependent properties and failure of mature-green and red-ripe tomato pericarp tissue. *J. Texture Stud.* **23**, 461–474.

Jackman, R. L., and D. W. Stanley. 1995. Creep behaviour of tomato pericarp tissue as influenced by ambient temperature ripening and chilled storage. *J. Texture Stud.* **26**, 537–552.

Jansen, K. 1961. Hesion and consistency of butter. *J. Dairy Res*. **28**, 15–20.

Jauregui, C. A., J. M. Regenstein, and R. C. Baker. 1981. A simple centrifugal method for measuring expressible moisture, a water-binding property of muscle food. *J. Food Sci*. **46**, 1271, 1273.

Jenkins, G. N. 1978. "The Physiology and Biochemistry of the Mouth." 4th ed. Blackwell, Oxford.

Jerome, N. W. 1975. Flavor preferences and food patterns of selected U.S. and Caribbean blacks. *Food Technol*. **29**(6), 46.

Jones, D., R. Chinnaswamy, Y. Tan, and M. Hanna. 2000. Physicochemical properties of ready-to-eat breakfast cereals. *Cereal Chem.* **45**, 164–168.

Jowitt, R. 1974. The terminology of food texture. *J. Texture Stud*. **5**, 351–358.

Ju, J., and G. S. Mittal. 1999. Effect of fat substitutes, fat levels and cooking methods on quality of fish patties. *J. Food Processing Preservation* **23**, 87–107.

Kachru, R. P., N. Kotwaliwale, and D. Balasubramanian. 1995. Physical and mechanical properties of green banana (*Musa paradisiaca*) fruit. *J. Food Eng.* **26**, 369–378.

Kapur, K. K., S. Soman, and A. Yurkstas. 1964. Test food for measuring masticatory performance of denture wearers. *J. Prosthet. Dent*. **14**, 483–491.

Kapur, K. K., H. H. Chauncey, and I. M. Sharon. 1966. Oral physiological factors concerned with ingestion of food. *In* "Nutrition in Clinical Dentistry" (A. E. Nizel, ed.), 2nd ed., pp. 296–304. Saunders, Philadelphia, Pennsylvania.

Karacsonyi, L. P., and A. C. Borsos. 1961. An apparatus for measuring the torsional strength of macaroni. *Cereal Chem*. **38**, 14–21.

Karmas, E., and K. Turk. 1976. Water binding of cooked fish in combination with various proteins. *J. Food Sci*. **41**, 977–979.

Kastner, C. L., and R. L. Henrickson. 1969. Providing uniform meat cores for mechanical shear force measurement. *J. Food Sci*. **34**, 603–605.

Katz, R., A. B. Caldwell, N. D. Collins, and A. E. Hostetter. 1959. A new grain hardness tester. *Cereal Chem*. **36**, 393–401.

Katz, R., N. D. Collins, and A. B. Caldwell. 1961. Hardness and moisture content of wheat kernels. *Cereal Chem*. **38**, 364–368.

Kawanari, M., D. D. Hamann, K. R. Swartzel, and A. P. Hansen. 1981. Rheological and texture properties of butter. *J. Texture Stud.* **12**, 483–505.

Kean, C. E. 1958. Method for determining the sub-sieve particle size distribution of pulverized sugar. *Food Res.* **23**, 677–683.

Kemsley, E. K., J. C. Sprunt, M. Defernz, and A. C. Smith. 2001. Multivariate analyses of electromyographic frequency spectra to characterize mastication. Submitted to *J. Texture Stud.*

Kerr, W. L., R. Li, and R. T. Toledo. 2000. Dynamic mechanical analyses of marinated chicken breast meat. *J. Texture Stud.* **31**, 421–436.

Kertesz, Z. I. 1935. The quality of canned whole kernel corn as determined by the simplified method for alcohol insoluble solids. *Canner* **80**(11), 12–13.

Khan, N., and M. Elahi. 1980. A rapid batter expansion method for testing the baking quality of wheat flours. *J. Food Technol*. **15**, 43–46.

Khan, A. A., and J. F. V. Vincent. 1993. Compressive stiffness and fracture properties of apple and potato. *J. Texture Stud.* **24**, 423–435.

Kilborn, R. H., and C. J. Dempster. 1965. Power-input meter for laboratory dough mixers. *Cereal Chem*. **42**, 432.

Kilcast, D., and C. Roberts. 1998. Perception and measurement of stickiness in sugar-rich foods. *J. Texture Stud.* **29**, 81–100.

Kimball, L. B., and Z. I. Kertesz. 1952. Practical determination of size distribution of suspended particles in macerated tomato product. *Food Technol.* **6**, 68–71.

Kissling, R. 1893. Zur Prüfung des Tatelleimes. *Chem.-Ztg*. **17**, 726–727.

Kissling, R. 1898. Zur Prüfung der Leimsorten des Handels. *Chem.-Ztg*. **22**, 171–172.

Klatsky, M. 1942. Masticatory stresses and their relation to dental caries. *J. Dent. Res*. **21**, 389.

Knaysi, G. 1927. Some factors other than bacteria that influence the body of artificial buttermilk. *J. Agric. Res.* (*Washington, D.C.*) **34**, 771–784.

Kohyama, K., and M. Nishi. 1997. Direct measurement of biting pressures for crackers using a multiple-point sheet sensor. *J. Texture Stud.* **28**, 605–617.

Kohyama, K., K. Ohtsubo, H. Toyoshima, and K. Shiozawa. 1998. Electromyographic study on cooked rice with different amylase contents. *J. Texture Stud.* **29**, 101–113.

Kohyama, K., S. Kobayashi, E. Hatakeyama, and T. Suzuki. 2000. Electromyographic study of mastication of kelp snack. *J. Texture Stud.* **31**, 577–590.

Kokini, J. L., and A. Dickie. 1982. A model of food spreadability from fluid mechanics. *J. Texture Stud.* **13**, 211–227.

Kokini, J. L., J. B. Kadane, and E. L. Cussler. 1977. Liquid texture perceived in the mouth. *J. Texture Stud.* **8**, 195–218.

Kokini, J. L., M. Poole, P. Mason, S. Miller, and E. F. Stier. 1984. Identification of key textural attributes of fluid and semi-solid foods using regression analysis. *J. Food Sci.* **49**, 47–51.

Konstance, R. P., C. I. Onwulata, E. D. Strange, D. Lu, M. H. Tunick, P. W. Smith, and V. H. Holsinger. 1999. Variation of corn-soy blends for overseas distribution. *Cereal Foods World* **49**, 477–479.

Kosutány, T. 1907. "Der ungarische Weizen und das ungarische Mehl." Budapest. Cited by D. W. Kent-Jones and A. J. Amos in "Modern Cereal Chemistry," 6th ed., 1967. Food Trade Press, Ltd. London.

Kramer, A. 1951. Objective testing of vegetable quality. *Food Technol*. **5**, 265–269.

Kramer, A. 1973. Food texture – definition, measurement and relation to other food quality attributes. *In* "Texture Measurements of Foods" (A. Kramer and A. S. Szczesniak, eds), pp. 1–9. Reidel Publ., Dordrecht, Netherlands.

Kramer, A., and H. R. Smith. 1946. The succulometer, an instrument for measuring the maturity of raw and canned whole kernel corn. *Food Packer* **27**(8), 56–60.

Kramer, A., and B. A. Twigg. 1959. Principles and instrumentation for the physical measurement of food quality with special reference to fruit and vegetable products. *Adv. Food Res*. **9**, 153–220.

Kramer, A., R. B. Guyer, and L. E. Ide. 1949. Factors affecting the objective and organoleptic evaluation in sweet corn. *Proc. Am. Soc. Hortic. Sci*. **54**, 342–356.

Kramer, A., K. Aamlid, R. B. Guyer, and H. Rogers. 1951. New shear-press predicts quality of canned limas. *Food Eng*. **23**(4), 112–113, 187.

Krieger, I. M. 1979. Golden anniversary for rheology. *Phys. Today* **32**(10), 128.

Krumel, K. L., and N. Sakar. 1975. Flow properties of gums useful to the food industry. *Food Technol*. **29**(4), 36, 38, 40, 41, 43, 44.

La Belle, R. L. 1964. Bulk density – a versatile measure of food texture and bulk. *Food Technol*. **18**, 879–884.

Lamb, F. C. 1967. Collaborative study of capillary viscometer method for consistency of fruit nectars and fruit juice products. *J. Assoc. Off. Anal. Chem*. **50**, 288–292.

Lamb, F. C., and L. D. Lewis. 1959. Consistency measurement of fruit nectars and fruit juice products. *J. Assoc. Off. Agric. Chem*. **42**, 411–416.

Larmond, E. 1970. Methods of sensory evaluation of food. *Publ. – Can. Dep. Agric*. No. 1284.

Larmour, R. K., E. B. Working, and C. W. Ofelt. 1939. Quality tests on hard red winter wheats. *Cereal Chem*. **16**, 733–752.

Lawless, H., M. Vanne, and H. Tuorila. 1997. Categorization of English and Finnish texture terms among consumers and food professionals. *J. Texture Stud.* **28**, 687–708.

Lee, C. M., and K. M. Patel. 1984. Analysis of juiciness of commercial frankfurters. *J. Texture Stud*. **15**, 67–73.

Lee, H. O., H. Luan, and D. G. Daut. 1992. Use of an ultrasonic technique to evaluate the rheological properties of cheese and dough. *J. Food Eng.* **16**, 127–150.

Lee, S.-J., and M. Peleg. 1992. Imperfect squeezing flow viscometry with a wide plate and a shallow container. *J. Texture Stud.* **23**, 267–278.

Lee, W. E. III, A. E. Derbel, C. T. Glembin, and E. G. Munday. 1988. Analysis of food crushing sounds during mastication: frequency-time studies. *J. Texture Stud.* **19**, 27–38.

Lee, W. E., and M. A. Camps. 1991. Tracking foodstuff location within the mouth in real time: A sensory method. *J. Texture Stud.* **22**, 277–287.

Lehmann, K. B. 1907a. Studien über die Zähigkeit des Fleisches und ihre Ursachen. *Arch. Hyg*. **63**, 134–179.

Lehmann, K. R. 1907b. Die Festigkeit (Zähigkeit) vegetabilischer Nahrungsmittel und ihre Veränderung durch das Kochen. *Arch. Hyg*. **63**, 180–182.

Leick, A. 1904a. Über Künstliche Doppelbrechung und Elastizität von Gelatineplatten. *Ann. Phys.* (*Leipzig*) **14**, 139–152.

Leick, A. 1904b. Über Künstliche Doppelchrechung und Elastizität von gelatineplatten. *J. Phys. Theor. Appl*. **3**, 866, 877.

Leighton, A., A. Leviton, and O. E. Williams. 1934. The apparent viscosity of ice cream. I. The sagging beam method of measurement. II. Factors to be controlled. III. The effects of milk fat, gelatin and homogenization temperature. *J. Dairy Sci*. **17**, 639–650.

Lewis, C. I., A. E. Murneek, and C. C. Cate. 1919. Pear harvesting and storage investigations in Rouge River Valley. *Ore. Agric. Exp. Stn., Bull*. No. 162.

Lichtensteiger, M. J., R. G. Holmes, M. Y. Hamdy, and J. C. Blaisdell. 1988. Impact parameters of spherical viscoelastic objects and tomatoes. *Trans. Am. Soc. Agr. Eng.* **31**, 595–602.

Lillford, P. J. 1991. Texture and acceptability of human foods. *In* "Feeding and the Texture of Foods" (J. F. V. Vincent, and P. L. Lillford, eds), p. 231. Cambridge University Press, New York.

Lindsay, J. B. 1901. Effect of feed on the composition of milk, butter fat, and on the consistency or body of butter. *13th Annu. Rep., Mass. Hatch Exp. Stn*. p. 29.

Lindsay, J. B., E. B. Holland, and P. H. Smith. 1909. Effect of soybean meal and soybean oil upon the composition of milk and butter fat, and upon the consistency or body of butter. *21st Annu. Rep., Mass. Agric. Exp. Stn*. Part II, pp. 66–110.

Lipowitz, A. 1861. "Neue Chemisch-Technische Abhandlungen." Bosselman, Berlin.

Locken, L., S. Loska, and W. Shuey. 1960. "The Farinograph Handbook." Am. Assoc. Cereal Chem., St Paul, Minnesota.

Lorenzo, M. A., C. Gerhayds, and M. Peleg. 1997. Imperfect squeezing flow viscometry of selected tomato products. *J. Texture Stud.* **26**, 543–567.

Love, R. M. 1983. Texture and fragility of fish muscle cells. Research at the Torry Research Station. Review Paper. *J. Texture Stud.* **14**, 323–352.

Love, R. M., and E. Mackay. 1962. Protein denaturation in frozen fish. V. Development of the cell fragility method for measuring cold storage changes in muscle. *J. Sci. Food Agric*. **13**, 200–212.

Love, R. M., and M. Muslemuddin. 1972a. Protein denaturation in frozen fish, XII. The pH effect and cell fragility determinations. *J. Sci. Food Agric*. **23**, 1224–1238.

Love, R. M., and M. Muslemuddin. 1972b. Protein denaturation in frozen fish, XIII. A modified cell fragility method insensitive to the pH of the fish. *J. Sci. Food Agric*. **23**, 1239–1251.

Low, W. H. 1920. Testing the strength of glue jellies. *Ind. Eng. Chem*. **12**, 355.

Lu X.-Y., R. H. MacMillan, R. P. Burrow, G. P. Kadkol, and G. M. Halleran. 1994. Pendulum test for evaluation of the rupture strength of seed pods. *J. Texture Stud.* **25**, 179–189.

Lucey, J. A., P. A. Munro, and H. Singh. 1998. Whey separation in acid skim milk gels made with gluconodeltalactone: effects of heat treatment and gelation temperature. *J. Texture Stud.* **29**, 413–426.

Lucisano, M., E. Casiraghi, and C. Pompei. 1989. Optimization of an instrumental method for the evaluation of spreadability. *J. Texture Stud.* **20**, 301–315.

Luyten, H., T. Van Vliet, and P. Walstra. 1992. Comparison of various methods to evaluate fracture phenomena in food materials. *J. Texture Stud.* **23**, 245–260.

Lynch, L. J., and R. S. Mitchell. 1950. The physical measurement of quality in canning of peas. *CSIRO Aust. Bull*. No. 254.

Lynch, L. J., and R. S. Mitchell. 1952. Short term prediction of maturity and yield of canning peas. *Food Technol.* **6**(9), 24, 28, 30.

MacFarlane, P. G., and J. M. Marer. 1966. An apparatus for determining the tenderness of meat. *Food Technol*. **20**, 838–839.

MacMichael, R. F. 1915. A new direct reading viscometer. *Ind. Eng. Chem*. **7**, 961–963.

Magness, J. R., and G. F. Taylor. 1925. An improved type of pressure tester for the determination of fruit maturity. *U.S. Dep. Agric. Circ*. No. 350.

Makower, R. U., M. M. Boggs, H. K. Burr, and H. S. Olcott. 1953. Comparison of methods of measuring the maturity factor in frozen peas. *Food Technol.* **7**, 43–48.

Maleki, M., and W. Siebel. 1972. Uber das Altbackenwerden von Brot. I. Beziehungen zwischen Sensorik Penetrometer und Panimeter beim Messen des Altbacken werdens von Weizenbrot. *Getreide Mehl Brot* **26**, 58.

Mancini, M., M. Mores, and R. Rancini. 1999. Uniaxial compression and stress relaxation tests on alginate gels. *J. Texture Stud.* **30**, 639–657.

Mao, R., J. Tang, and B. G. Swanson. 1999. Texture properties of gellan gels as affected by temperature. *J. Texture Stud.* **30**, 409–433.

Margules, M. 1881. Ueber die Bestimmung des Reibungs- und Gleitungscoefficienten aus ebenen Bewegungen einer Fluessigkeit. *Wien Sitzungsberger, Abt. 2A* **83**, 588: see also **84**, 491 (1882).

Markovitz, H. 1985. Rheology: in the beginning. *J. Rheol.* **29**, 777–798.

Marshall, R. J., and S. P. J. Kirby. 1988. Sensory measurement of food texture by free-choice profiling. *J. Sensory Stud.* **3**, 63–80.

Martin, W. McK. 1937. The Tenderometer, an apparatus for evaluating tenderness in peas. *Canner* **84**(12), 108–112.

Martin, W. McK., R. H. Lueck, and E. D. Sallee. 1938. Practical application of the Tenderometer in grading peas. *Cann. Age* **19**(3), 146–149; (4), 193.

Mathevon, E., L. Mioche, W. E. Brown, and J. Culioli. 1994. Texture analysis of meat cooked at various temperatures by mechanical measurements, sensory assessments and masticatory muscle electromyography. *J. Texture Stud.* **26**, 175–192.

Mathevon, E., L. Mioche, W. E. Brown, and J. Culioli. 1995. Texture analysis of meat cooked at various temperatures by mechanical measurements, sensory assessments and electromyography recordings. *J. Texture Stud.* **26**, 175–192.

Mathoniere, C., L. Mioche, E. Dransfield, and J. Culioli. 2000. Meat texture characterizations comparison of chewing patterns, sensory and mechanical measures. *J. Texture Stud.* **31**, 183–203.

Matsuo, R. R., and G. N. Irvine. 1969. Spaghetti tenderness testing apparatus. *Cereal Chem.* **46**, 1–6.

Matsuo, R. R., and G. N. Irvine. 1971. Note on our improved apparatus for spaghetti tenderness. *Cereal Chem.* **48**, 554–558.

Matz, S. A. 1962. "Food Texture." Avi. Westport, Connecticut.

McCarthy, K. L., and J. D. Seymour. 1993. A fundamental approach for the relationship between Bostwick measurement and Newtonian fluid viscosity. *J. Texture Stud.* **24**, 1–10.

McCarthy, O. J. 1987. Large deformation testing of solid foods. *Food Technology in New Zealand* July, 40–43.

McClements, D. J. 1997. Ultrasonic characterization of food and drinks: principles, methods and application. *Crit. Rev. Food Sci. Nutr.* **37**, 1–46.

McComber, D. R., R. A. Lohnes, and E. M. Osman. 1987. Double direct shear test for potato texture. *J. Food Sci.* **52**, 1302–1304, 1307.

Meullenet, J.-F., J. Gross, B. P. Marks, and M. Daniels. 1998. Sensory descriptive texture analyses of cooked rice and its correlation to instrumental parameters using an extrusion cell. *Cereal Chem.* **75**, 714–720.

Meyer, G. S. 1929. Some critical comments on the methods employed in the expression of leaf saps. *Plant Physiol*. **4**, 103–111.

Meyeringh, W. 1911. Studie over het factoren op het vochgehalte der botter van invloed. 51–55. 's Gravenhage: De Gebroeders van Cleef. Diss. Delft. (From Mulder, 1953.)

Miles, C. A., G. A. J. Fursey, and R. C. D. Jones. 1985. Ultrasonic estimation of solid/liquid ratios in fats, oils and adipose tissue. *J. Sci. Food Agric.* **36**, 215–228.

Mioche, L., and J.-F. Martin. 1998. Training and sensory judgement effects on mastication as studied by electromyography. *J. Food Sci.* **63**, 1–5.

Missaire, F., C.-G. Qiu, and M. A. Rao. 1990. Yield stress of structured and unstructured food suspensions. *J. Texture Stud*. **21**, 479–480.
Mitchell, R. S., D. J. Casimir, and L. J. Lynch. 1961. The Maturometer – instrumental test and redesign. *Food Technol*. **15**, 415.
Mitschka, P. 1982. Simple conversion of Brookfield R.V.T. readings into viscosity functions. *Rheol. Acta* **12**, 207–209.
Miyada, D. S., and A. L. Tappel. 1956. Meat tenderization I. Two mechanical devices for measuring texture. *Food Technol*. **10**, 142–145.
Mizrach, A., and V. Flitsanov. 1999. Nondestructive ultrasonic determination of avocado softening process. *J. Food Eng.* **40**, 139–144.
Mizrach, A., N. Galili, and G. Rosenhouse. 1994. Determining quality of fresh products by ultrasonic excitation. *Food Technol.* **48**(12), 68–71.
Mohsenin, N. N., and J. P. Mittal. 1977. Use of rheological terms and correlation of compatible measurements in food texture research. *J. Texture Stud*. **8**, 395–408.
Mohsenin, N. N., H. E. Cooper, and L. D. Tukey. 1963. Engineering approach to evaluating textural factors in fruits and vegetables. *Trans. ASAE* **6**, 85–88, 92.
Montejano, J. G., D. D. Hamann, and T. C. Lanier. 1983a. Comparison of two instrumental methods with sensory texture of protein gels. *J. Texture Stud.* **16**, 403–424.
Montejano, J. G., D. D. Hamann, and T. C. Lanier. 1983b. Final strengths and rheological changes during processing of thermally induced fish muscle gels. *J. Rheol.* **27**, 557–574.
Mor, Y., C. F. Shoemaker, and M. Rosenberg. 1999. Compressive properties of whey protein composite gels containing fractionated milkfat. *J. Food Sci.* **64**, 1078–1083.
Morris, O. M. 1925. Studies in apple storage. *Bull.–Wash. Agric. Exp. Stn*. No. 193.
Morrow, C. T., and N. N. Mohsenin. 1966. Consideration of selected agricultural products as viscoelastic materials. *J. Food Sci*. **31**, 686–698.
Morrow, C. T., and N. N. Mohsenin. 1976. Mechanics of a multiple needle Tenderometer for raw meat. *J. Texture Stud*. **7**, 115–128.
Moskowitz, H., and J. Kapsalis. 1974. Towards a general theory of texture psychophysics. *Proc. IV Int. Congr. Food Sci. Technol*. **2**, 102–120.
Mottram, F. J. 1961. Evaluation of pseudoplastic materials by cone penetrometers. *Lab. Prac*. **10**, 767–770.
Mueller, W. S. 1935. A method for the determination of the relative stiffness of cream during the whipping process. *J. Dairy Sci*. **18**, 177–180.
Mulet, A., J. Benedito, J. Bon, and C. Rossello. 1999. Ultrasonic velocity in cheddar cheese as affected by temperature. *J. Food Sci.* **64**, 1038–1041.
Muller, H. G. 1969a. Mechanical properties, rheology and haptaesthesis of food. *J. Texture Stud*. **1**, 38–42.
Muller, H. G. 1969b. Routine rheological tests in the British food industry. *J. Food Technol*. **4**, 83–92.
Muller, H. G. 1973. An introduction to food rheology. Crane Russak, New York.
Muñoz, A. M. 1986. Development and application of texture reference scales. *J. Sensory Stud.* **1**, 55–83.
Muñoz, A. M., and G. V. Civille. 1987. Factors affecting perception and acceptance of food texture by American consumers. *Food Rev. Int.* **3**, 285–322.
Munz, E., and C. W. Brabender. 1940. Prediction of baking value from measurements of plasticity and extensibility of dough I. Influence of mixing and molding treatments upon physical dough properties of typical American wheat varieties. *Cereal Chem*. **17**, 79–100.

Murneek, A. E. 1921. A new test for maturity of the pear. *Ore. Agric. Exp. Stn. Bull*. No. 186.
Murray, D. C., and L. R. Luft. 1973. Low DE corn starch hydrolysates. *Food Technol*. **27**(3), 33.
Navarro, A. S., C. Ferrero, and N. E. Zaritsky. 1999. Rheological characterization of "dulce de leche" by dynamic and steady shear. *J. Texture Stud.* **30**, 45–58.
Nemitz, G. 1963. A new apparatus for measuring the course of rigor mortis in fish and mammalian muscle. (In Ger.) *Fleischwirtschaft* **15**, 18, 21.
Nemitz, G., W. Portman, and D. Sharra. 1960. Eine neue method zur Messung der Totenstarre. (A new method for measuring death rigor.) *Z. Lebensm.-Unters. -Forsch*. **112**(4), 261–272.
Nielsen, M., and H. J. Martens. 1997. Low frequency ultrasonics for texture measurements on cooked carrots (*Daucus carota* L.). *J. Food Sci.* **62**, 1167–1170, 1175.
Norton, C. R. T., J. R. Mitchell, and J. M. V. Blanshard. 1998. Fractal determination of crisp or crackly textures. *J. Texture Stud.* **29**, 239–253.
Numata, K., H. Saegvsa, and K. Hirose. 1997. Quality of soybean curd prepared from fine powder. *J. Tokyo Food Technol. Center* **6**, 7–12.
Nussinovitch, A., M. Steffens, P. Chinachoti, and M. Peleg. 1992. Effect of strain level and storage time on the recoverable work of compressed bread crumb. *J. Texture Stud.* **23**, 13–24.
Oakenfull, D. G., and A. G. Scott. 1985. Gelation of high methoxyl pectins. *Food Aust.* **37**, 156–158.
Oakes, E. F., and C. E. Davis. 1922. Jell strength and viscosity of gelatin solutions. *J. Ind. Eng. Chem*. **14**, 706–710.
Oka, S. 1960. The principles of rheometry. *In* "Rheology, Theory and Applications" (F. R. Eirich, ed.), pp. 17–82. Academic Press, New York.
Okabe, T. 1979. Texture measurement of cooked rice and its relationship to eating quality. *J. Texture Stud*. **10**, 131–152.
Oldfield, R. C. 1960. Perception in the mouth. *In* "Texture in Foods." Monograph, No. 7, pp. 3–9. Soc. Chem. Ind., London.
Olorunda, A. O., and M. A. Tung. 1984. Effects of calcium pretreatments and freezing rates on fluid loss in plantain products. *J. Food Technol.* **19**, 133–139.
Omura, A. P., and J. F. Steffe. 2001. Centrifugal slump test to measure yield stress. *J. Food Sci.* **66**, 137–140.
Onozuka, M., K. Watanabe, S. M. Mirbod, S. Ozono, K. Nishiyamo, N. Karasawa, and I. Nagatsu. 1999. Reduced mastication stimulates impairment of spatial memory and degeneration of hippocampal neurons in aged SAMP8 mice. *Brain Res.* **826**, 148–153.
Onozuka, M., K. Watanabe, S. Nagasaki, Y. Jiang, S. Ozono, K. Nishiyama, T. Kawase, N. Karasawa, and I. Nagatsu. 2000. Impairment of spatial memory and changes in astroglial responsiveness following loss of molar teeth in aged SAMP8 mice. *Behav. Res.* **108**, 145–155.
Oppliger, H. R., F. J. Matusik, and J. V. Fitzgerald. 1975. New technique accurately measures low viscosity on-line. *Control Eng*. **22**(7), 39–40.
Oram, N. 1998. Texture and chemical feeling descriptors that 6–11 year olds and adults associate with food in the mouth. *J. Texture Stud.* **29**, 185–197.
Osorio, F. A., and J. F. Steffe. 1987. Back extrusion of power law fluids. *J. Texture Stud.* **18**, 43–63.
Ourecky, D. K., and M. C. Bourne. 1968. Measurement of strawberry texture with an Instron machine. *Proc. Am. Soc. Hort. Sci*. **93**, 317–325.

Park, B., A. D. Whitaker, R. K. Miller, and D. S. Hale. 1994. Ultrasonic spectral analysis for beef sensory attributes. *J. Food Sci.* **37**, 1583–1589.

Parrish, E. C., Jr., D. G. Olson, B. E. Miner, R. B. Young, and R. L. Small. 1973. Relationship of tenderness measurements made by the Armour Tenderometer to certain objective, subjective and organoleptic properties of bovine muscle. *J. Food Sci*. **38**, 1214–1219.

Pashias, N., D. V. Bogor, J. Summers, and D. J. Glenister. 1996. A fifty cent rheometer for yield stress measurement. *J. Rheol*. **40**, 1179–1189.

Pavlov, I. P. 1927. "Conditioned Reflexes. An investigation of the Physiological Activity of the Cerebral Cortex." Oxford Univ. Press, London. (Eng. trans.)

Pearson, C. A., and D. Raynor. 1975. Comments on article by Peter Voisey. *J. Texture Stud*. **6**, 393–394.

Pedrero, D., and R. M. Pangborn. 1989. "Evaluación Sensorial de los Alimentos Métodos Analyticos." Editorial Alhambra Mexicana, S. A. Mexico City.

Peleg, M. 1974. Determination of fresh papaya's texture by penetration tests. *J. Food Sci.* **39**, 156–159.

Peleg, M. 1980. A note on the sensitivity of fingers, tongue and jaws as mechanical testing instruments. *J. Texture Stud*. **10**, 245–251.

Peleg, M. 1985. Comparison between various correction factors in the calculation of creep compliance. *J. Texture Stud.* **16**, 119–127.

Peleg, M. 1993. Do irregular stress-strain relationship of crunchy foods have regular periodicities? *J. Texture Stud.* **24**, 215–227.

Peleg, M. 1997. Measures of line jaggedness and their use in foods textural evaluation. *Crit. Rev. Food Sci. Nutr.* **37**, 491–518.

Peleg, M., and O. H. Campanella. 1988. On the mathematical form of psychophysical relationships with special focus on the perception of mechanical properties of solid objects. *Perception and Psychophysics* **44**, 451–455.

Peleg, M., and M. D. Normand. 1995. Stiffness assessment from jagged force–deformation relationships. *J. Texture Stud.* **26**, 353–370.

Perkins, A. E. 1914. An apparatus and method for determining the hardness of butterfat. *Ind. Eng. Chem*. **6**, 136–141.

Personius, C. J., and G. F. Sharp. 1938. Adhesion of potato tuber cells as influenced by temperature. *Food Res*. **3**, 513–514.

Perten, H. 1964. Application of the falling number method for evaluating alpha-amylase activity. *Cereal Chem*. **41**, 127–140.

Perten, H. 1967. Factors influencing falling number values. *Cereal Sci. Today* **12**, 516, 518, 519.

Pierson, A., and J. LeMagnen. 1970. Study of food textures by recording and chewing and swallowing movements. *J. Texture Stud*. **1**, 327–337.

Pitman, G. 1930. Further comparison of California and imported almonds. *Ind. Eng. Chem*. **22**, 1129–1131.

Platt, W., and P. D. Kratz. 1933. Measuring and recording some characteristics of test sponge cakes. *Cereal Chem*. **10**, 73–90.

Platt, W., and R. Powers. 1940. Compressibility of bread crumb. *Cereal Chem*. **17**, 601–621.

Poiseuille, J. L. M. 1846. Recherches expérimentales sur le mouvement des liquides dans les tubes de très petits diamètres. *Mem. Acad. R. Sci. Inst. Fr. Sci., Math. Phys*. **9**, 433–545. [Eng. trans., Rheol. Mem. **1**, No. 1 (1940).]

Ponte, J. G., Jr., S. T. Titcomb, and R. H. Cotton. 1962. Flour as a factor in bread firming. *Cereal Chem*. **39**, 437–444.

Pool. M. F. 1967. Objective measurement of connective tissue tenacity of poultry meat. *J. Food Sci*. **32**, 550–553.

Pool, M. F., and A. A. Klose. 1969. The relation of force to sample dimensions in objective measurements of tenderness of poultry meat. *J. Food Sci*. **34**, 524.

Poole, H. J. 1925. The elasticity of gelatin jellies and its bearing on their physical structure and chemical equilibria. *Trans. Faraday Soc*. **21**, 114–137.

Porst, E. G., and Moskowitz. 1922. Comparison of the various corn products starches as shown by the Bingham–Greene Plastometer. *Ind. Eng. Chem*. **14**, 49–52.

Povey, M. J. W., and C. A. Harden. 1981. An application of the ultrasonic pulse echo technique to the measurement of crispness of biscuits. *J. Food Technol.* **16**, 167–175.

Povey, M. J. W., and D. J. McClements. 1988. Ultrasonics in food engineering Part I: Introduction and experimental methods. *J. Food Eng*. **8**, 217–245.

Pradipasena, P., and C. Rha. 1977. Pseudoplastic and rheopectic properties of a globular protein (β-lactoglobulin) solution. *J. Texture Stud.* **8**, 311–325.

Prentice, J. H., and D. Huber. 1983. Results of a collaborative study on measuring rheological properties of foodstuffs. *In* "Physical Properties of Foods" (R. Jowitt, F. Escher, B. Hallstrom, H. F. Th. Meffert, W. E. L. Spiess, and G. Vos, eds), pp. 123–183. Applied Science Publishers, London.

Priel, Z., M. Sasson, and A. Silverberg. 1973. Method for determining the time of flow in a capillary viscometer with an absolute accuracy of 3×10^{-6}. *Rev. Sci. Instrum*. **44**, 135.

Prinz, J. F., and P. W. Lucas. 2000. Saliva tannin interactions. *J. Oral Rehabil.* **27**, 991–994.

Psotka, J. 2001. Digital image analysis of finished food products. *Cereal Foods World* **46**, 20–23.

Pszczola, D. 1997. *Food Technol.* **51**(11), 82.

Ramirez-Wong, B., V. E. Sweat, P. I. Torres, and L. W. Rooney. 1996. Evaluation of the rheological properties of fresh corn masa using squeezing flow viscometry. *J. Texture Stud.* **27**, 185–198.

Ramkumar, C., O. H. Campanella, P. J. Watkinson, R. J. Bennett, and L. K. Creamer. 1998. The effects of pH and time on rheological changes during early cheese maturation. *J. Texture Stud.* **29**, 633–644.

Rao, M. A. 1975. Measurement of flow properties of food suspensions with a mixer. *J. Texture Stud.* **6**, 533–539.

Rao, M. A. 1977. Rheology of liquid foods – A review. *J. Texture Stud.* **8**, 135–168.

Rao, M. A., and M. C. Bourne. 1977. Analysis of the Plastometer and correlation of Bostwich Consistometer data. *J. Food Sci*. **42**, 261–264.

Rao, M. A., and H. J. Cooley. 1984. Determination of effective shear rates in rotational viscometers with complex geometries. *J. Texture Stud.* **15**, 327–335.

Rao, M. A., and S. S. M. Rizvi. 1986. "Engineering Properties of Foods." Marcel Dekker, New York.

Rao, M. A., T. O. Palomino, and L. W. Bernhardt. 1974. Flow properties of tropical fruit purees. *J. Food Sci.* **39**, 160, 161.

Rao, M. A., M. C. Bourne, and H. J. Cooley. 1981. Flow properties of tomato pastes of high concentrations. *J. Texture Stud*. **12**, 521–538.

Rao, P. H., K. Laelavathi, and S. R. Shurpalekar. 1986. Objective measurements of the consistency of chapati dough using a research water absorption meter. *J. Texture Stud.* **17**, 401–420.

Rasper, V. F. 1975. Dough rheology at large deformations in simple tensile mode. *Cereal Chem*. **52**, 24r–41r.

Rasper, V. F., J. Rasper, and J. M. deMan. 1974. Stress strain relationships of chemically improved unfermented doughs. *J. Texture Stud*. **4**, 438–466.

Reiner, M. 1964. The Deborah number. *Physics Today* January 1964, p. 62.

Reyes-Vega, M. I., R. D. Peralta-Rodríguez, A. Anzaldúa-Morales, J. D. Figueroa, and F. Martínez-Bustos. 1998. Relating sensory textural attributes of corn tortillas to some instrumental measurements. *J. Texture Stud*. **29**, 361–373.

Reynolds, D. 1883. An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels. *Philos. Trans. R. Soc. London* **174**, 935–982.

Rha, C. 1980. Food rheology principles and practice. Lecture notes, Food Mater. Sci. Fabr. Lab., Mass. Inst. Technol., Cambridge, Massachusetts.

Rhodes, D. N., R. C. D. Jones, B. B. Chrystal, and J. M. Harries. 1972. Meat texture II. The relationship between subjective assessments and a compressive test on roast beef. *J. Texture Stud*. **3**, 298–309.

Richardson, N. J., D. A. Booth, and D. Stanley. 1993. Effect of homogenization and fat content on oral perception of low and high viscosity creams. *J. Sensory Stud.* **8**, 133–143.

Roark, R. J. 1965. "Formulas for Stress and Strain." McGraw-Hill, New York.

Roberts, H. F. 1910. A quantitative method for the determination of hardness in wheat. *Kans. Agric. Exp. Stn., Bull*. No. 167, pp. 371–390.

Robertson, G. H., and S. H. Emani. 1974. Liquid jet penetrometry for physical analysis. Application to bread aging. *J. Food Sci*. **39**, 1247–1253.

Rogers, L. A., and G. P. Sanders. 1942. Devices for measuring physical properties of cheese. *J. Dairy Sci*. **25**, 203–210.

Rohde, F., M. D. Normand, and M. Peleg. 1993. Characterization of the power spectrum of force-deformation relationship of crunchy foods. *J. Texture Stud.* **24**, 45–92.

Rohm, H. 1990. Consumer awareness of food texture in Austria. *J. Texture Stud.* **21**, 363–373.

Rohm, H., D. Jaros, V. Fischer, and S. Lailach. 1994. Foods associated with descriptive texture terms. *Lebensm.-Wiss. Ui. Technol.* **27**, 406–414.

Rohm, H., D. Jaros, and M. de Haan. 1997. A video-based method for determination of average stress strain relations in uniaxial compression of selected foods. *J. Texture Stud.* **20**, 245–255.

Rose, D. H., M. H. Haller, and P. L. Harding. 1934. Relation of temperature of fruit to firmness in strawberries. *Proc. Am. Soc. Hort. Sci*. **32**, 429–431.

Ross, A. S., C. E. Walker, R. I. Booth, R. A. Orth, and C. W. Wrigley. 1987. The Rapid ViscoAnalyzer: A new technique for estimation of sprout damage. *Cereal Foods World* **32**, 827–829.

Ross, L. R., and W. L. Porter. 1968. Interpretation of multiple-peak shear force curves obtained on French fried potatoes. *Am. Potato J*. **45**, 461–471.

Ross, L. R., and W. L. Porter. 1969. Objective measurements of French fried potato quality. Laboratory techniques for research use. *Am. Potato J*. **46**, 192–200.

Ross, L. R., and W. L. Porter. 1971. Objective measurement of texture variables in raw and processed French fried potatoes. *Am. Potato J*. **48**, 329–343.

Ross, L. R., and W. L. Porter. 1976. Textural quality prediction of reheated frozen French fried potatoes by objective testing of raw stock. *J. Food Sci*. **41**, 206–208.

Rostagno, W. 1969. Chocolate particle size and its organoleptic influence. *The Manufacturing Confectioner* May, 81–86.

Rostagno, W. 1974. Rheological properties of chocolate. *In* "Lebensmittel-Einfluss der Rheologie" (D. Behrens and K. Fischbeck, eds), DECHEMA Monograph, Vol. 77, No. 1505–1536, pp. 283–293. Verlag Chemie, Weinheim.

Roth, W., and S. R. Rich. 1953. A new method for continuous viscosity measurement. General theory of the Ultra-Viscoson. *J. Appl. Phys*. **24**, 940–950.

Rousset-Akrim, S., J.-F. Martin, C. Pilandron, and C. Touraite. 1995. Research of selective tests for discerning "an efficient assessor" in texture profiting. *J. Sensory Stud.* **10**, 217–237.

Rovedo, C. O., M. M. Pedrero-Navarro, and R. P. Singh. 1999. Mechanical properties of a corn starch product during the post-frying period. *J. Texture Stud.* **30**, 279–290.

Rutgers, G. 1958. The consistency of starch-milk puddings. I. Preparation of puddings and measurement of consistency. *J. Sci. Food Agric*. **9**, 61–68.

Sachs, F. 1988. The intimate sense. Understanding the mechanisms of touch. *The Sciences* January, 28–34.

Sakamoto, H., T. Harada, T. Matsukobu, Y. Takaeso, and M. Tazaki. 1989. Electromyographic measurement of textural changes of foodstuffs during chewing. *Agric. Biol. Chem.* **53**, 2421–2433.

Sakurai, Y., M. Fujimaki, and H. Kato. 1993. "Processing and Storage of Foods" 2nd ed., p. 85. Koseikan, Tokyo.

Saravacos, G. D. 1968. Tube viscometry of fruit purees and juices. *Food Technol.* **22**, 1585–1588.

Saravacos, G. D. 1970. Effect of temperature on viscosity of fruit juices and purees. *J. Food Sci.* **35**, 122–125.

Sayre, J. D., and V. H. Morris. 1931. Use of expressed sap in physiologic studies of corn. *Plant Physiol*. **6**, 139–148.

Sayre, J. D., and V. H. Morris. 1932. Use of expressed sap in determining the composition of corn tissue. *Plant Physiol*. **7**, 261–271.

Schiffman, S. 1977. Food recognition by the elderly. *J. Gerontol.* **32**, 586–592.

Schiffman, S., G. Musante, and J. Conger. 1978. Application of multidimensional scaling to ratings of foods for obese and normal weight individuals. *Physiol. Behav.* **21**, 417–422.

Schultz, E. F., Jr., and G. W. Schneider. 1955. Sample size necessary to estimate size and quality of fruit growth of trees, and per cent fruit set of apples and peaches. *Proc. Am. Soc. Hortic. Sci*. **66**, 36–44.

Schutz, H. G., and O. L. Wahl. 1981. Consumer perception of the relative importance of appearance flavor and texture to food acceptance. *In* "Criteria for Food Acceptance. How Man Chooses What He Eats" (J. Solms, and R. C. Hall, eds), pp. 97–116. Foster Publishing Ltd, Zurich.

Schwartz, N. D. 1975. Adaptation of the sensory texture profile method to skin care products. *J. Texture Stud.* **6**, 35–42.

Schwedoff, T. 1889. Recherches experimentales sur la cohesion des liquides. *J. Phys. Theor. Appl*. **8**, 341–359.

Scott Blair, G. W., and J. Burnett. 1963. A simple method for detecting an early stage in coagulation of rennetted milk. *J. Dairy Res*. **30**, 383–390.

Scott Blair, G. W., and F. M. V. Coppen. 1940. An objective measure of the consistency of cheese curd at the pitching point. *J. Dairy Res*. **11**, 187–195.

Scott Blair, G. W., G. Watts, and H. J. Denham. 1927. Effect of concentration on viscosity of flour suspensions. *Cereal Chem*. **4**, 63–67.

Segars, R. A., H. A. Nordstrom, and J. G. Kapsalis. 1974. Textural characteristics of beef muscles. *J. Texture Stud.* **5**, 283–297.

Segars, R. A., G. H. Roger, J. G. Kapsalis, and R. A. Kluter. 1975. A punch and die test cell for determining the textural qualities of meat. *J. Texture Stud.* **6**, 211–225.

Segars, R. A., R. G. Hamel, and J. G. Kapsalis. 1977. Use of Poisson's ratio for objective–subjective texture correlations in beef. An apparatus for obtaining the required data. *J. Texture Stud*. **8**, 433–447.

Segnini, S., P. Demjek, and R. Oste. 1999. Reproducible texture analysis of potato chips. *J. Food Sci*. **64**, 309–312.

Seideman, S. C., and L. K. Theer. 1986. Relationships of instrumental textural properties and muscle fiber types to the sensory properties of beef. *J. Food Quality* **9**, 251–261.

Shama, F., and P. Sherman. 1973a. Evaluation of some textural properties of foods with the Instron Universal Testing Machine. *J. Texture Stud*. **4**, 344–353.

Shama, F., and P. Sherman. 1973b. Identification of stimuli controlling the sensory evaluation of viscosity. II. Oral methods. *J. Texture Stud*. **4**, 111–118.

Shama, F., C. Parkinson, and P. Sherman. 1973. Identification of stimuli controlling the sensory evaluation of viscosity. I. Non oral methods. *J. Texture Stud*. **4**, 102–110.

Sharma, M. G., and N. N. Mohsenin. 1970. Mechanics of deformation of a fruit subjected to hydrostatic pressure. *J. Agric. Eng. Res*. **15**(1), 65–74.

Sheppard, S. E., and S. S. Sweet. 1923. A preliminary study of a plunger type of jelly-strength tester. *Ind. Eng. Chem*. **15**, 571–576.

Sheppard, S. E., S. S. Sweet, and J. W. Scott, Jr. 1920. The jelly strength of gelatins and glues. *Ind. Eng. Chem*. **12**, 1007–1011.

Sherman, P. 1970. "Industrial Rheology." Academic Press, New York.

Sherman, P. 1973. Structure and textural properties of food. *In* "Texture Measurements of Foods" (A. Kramer, and A. S. Szczesniak, eds), pp. 52–70. Reidel Publishing Co., Dordrecht, Netherlands.

Showalter, W. R., and G. Christenson. 1998. Toward a rationalization of the slump test for fresh concrete: Comparisons of calculations with experiments. *J. Rheol.* **42**, 865–870.

Sigurgisladottir, S., A. Hafsteinsson, A. Jenssen, O. Lie, R. Nortviet, M. Thomassen, and O. Torrissen. 1999. Textural properties of raw salmon fillets as affected by sampling method. *J. Food Sci*. **64**, 99–104.

Simon, S., J. C. Field, W. E. Kramlich, and F. N. Tauber. 1965. Factors affecting frankfurter texture and a method of measurement. *Food Technol*. **14**, 410–413.

Sindall, R. W., and W. Bacon. 1914. The examination of commercial gelatins with regard to their suitability for papermaking. *Analyst* (*London*), **39**, 20–27.

Skinner, G. H., and Rao, V. N. M. 1986. Linear viscoelastic behavior of frankfurter. *J. Texture Studies* **17**, 421–432.

Slattery, J. C. 1961. Analysis of the cone-plate viscometer. *J. Colloid Sci*. **16**, 431–437.

Smeets, H. S., and H. Cleve. 1956. Determination of conditioning by measuring softness. *Milling Prod*. **21**(4), 5, 12–13, 16.

Smith, C. R. 1920. Determination of jellying power of gelatins and glue by the polariscope. *Ind. Eng. Chem*. **12**, 878–881.

Smith, E. S. 1909. Glue-Tester. U.S. Patent 911, 277.
Smith, G. C., and Z. L. Carpenter. 1973. Mechanical measurements of meat tenderness using the Nip Tenderometer. *J. Texture Stud*. **4**, 196–203.
Sohn, C. E. 1893. Simple appliances for testing the consistency of semi-solids, with a note on a new method of examining butter. *Analyst* (*London*) **18**, 218–221.
Somers, G. F. 1965. Citric-induced loss of rigidity in potato tuber slices. *Plant Physiol.* **40**, 388–395.
Sone, T. 1972. "Consistency of Foodstuffs." Reidel Publ., Dordrecht, Netherlands.
Spanier, A. M., B. W. Berry, and M. B. Solomon. 2000. Variation in tenderness of beef strip loins and improvement in tenderness by use of hydrodynamic pressure processing (HDP). *J. Muscle Foods* **11**, 183–196.
Steffe, J. F. 1992. "Rheological Methods in Food Process Engineering." Freeman Press, East Lansing.
Steffe, J. F., and E. W. Ford. 1985. Rheological techniques to evaluate the shelf-stability of starch-thickened strained apricots. *J. Texture Stud.* **16**, 179–192.
Steffe, J. F., and F. A. Osorio. 1987. Back extrusion of non-Newtonian fluids. *Food Technol.* **41**(3), 72–77.
Sterling, C., and M. Simone. 1954. Crispness in almonds. *Food Res*. **19**, 276–281.
Stevens, S. S. 1970. Neural events and the psychophysical law. *Science* **170**, 1043–1050.
Stewart, F. C. 1923. The relation of moisture content and certain other factors to the popping of popcorn. *Bull. – N.Y. Agric. Exp. Stn.* (*Geneva*) No. 505.
Stone, H., and S. Oliver. 1966. Effect of viscosity on the detection of relative sweetness intensity of sucrose solutions. *J. Food Sci*. **31**, 129–134.
Studman, C. J., and Yuwana. 1992. Twist test for measuring fruit firmness. *J. Texture Stud.* **23**, 215–227.
Su, C. S., and E. G. Humphries. 1972. Rupture properties of cucumber skin. *Pickle Pak Sci.* **2**(1), 3–10.
Sucharipa, E. 1923. Experimental data on pectin–sugar acid gels. *J. Assoc. Off. Agric. Chem*. **7**, 57–68.
Suhendro, E. L., H. D. Almeida-Dominguez, C. W. Rooney, and R. D. Waniska. 1998. Objective rollability method for corn tortilla measurement. *Cereal Chem*. **75**, 320–324.
Suwonsichon, T., and M. Peleg. 1999a. Rheological characterization of Ricotta cheeses by imperfect squeezing flow viscometry. *J. Texture Stud.* **30**, 89–103.
Suwonsichon, T., and M. Peleg. 1999b. Rheological characterization of almost intact and stirred yogurt by imperfect squeezing flow viscometry. *J. Sci. Food Agric.* **79**, 911–921.
Suwonsichon, T., and M. Peleg. 1999c. Imperfect squeezing flow viscometry of mustards with suspended particulates. *J. Food Eng.* **39**, 217–226.
Swanson, C. O., and E. B. Working. 1933. Testing the quality of flour by the recording dough mixer. *Cereal Chem*. **10**, 1–29.
Swyngedau, S., and M. Peleg. 1992. A model for the compressibility of food-finger(s) arrays. *J. Rheol.* **36**, 45–56.
Szczesniak, A. S. 1963a. Classification of textural characteristics. *J. Food Sci*. **28**, 385–389.
Szczesniak, A. S. 1963b. Objective measurements of food texture. *J. Food Sci*. **28**, 410–420.
Szczesniak, A. S. 1968. Correlations between objective and sensory measurements. *Food Technol.* **22**, 981–985.

Szczesniak, A. S. 1971. Consumer awareness of texture and of other food attributes. *J. Texture Stud*. **2**, 196–206.
Szczesniak, A. S. 1972. Consumer awareness of and attitudes to food texture. II. Children and teenagers. *J. Texture Stud*. **3**, 206–217.
Szczesniak, A. S. 1975a. Textural characterization of temperature sensitive foods. *J. Texture Stud*. **6**, 139–156.
Szczesniak, A. S. 1975b. General Foods texture profile revisited – ten years perspective. *J. Texture Stud*. **6**, 5–17.
Szczesniak, A. S. 1979. Classification of mouthfeel characteristics of beverages. *In* "Food Rheology and Texture" (P. Sherman. ed.), pp. 1–20. Academic Press, New York.
Szczesniak, A. S. 1990. Texture: It is still an overlooked food attribute? *Food Technol.* **44**(9), 86, 88, 90, 92, 95.
Szczesniak, A. S. 1995. Texture profile analysis – methodology interpretation clarified. *J. Food Sci.* **60**(6), vii. (Reprinted in *J. Texture Stud.* **27**(6), vi, 1996.)
Szczesniak, A. S. 1997. Effect of storage on texture. *In* "Food Storage Stability" (I. A. Taub and R. P. Singh, eds), pp. 191–243. CRC Press, New York.
Szczesniak, A. S. and M. C. Bourne. 1969. Sensory evaluation of food firmness. *J. Texture Stud*. **1**, 52–64.
Szczesniak, A. S., and E. Farkas. 1962. Objective characterization of the mouthfeel of gum solutions. *J. Food Sci*. **27**, 381–385.
Szczesniak, A. S., and B. J. Hall. 1975. Application of the General Foods Texturometer to specific food products. *J. Texture Stud*. **6**, 117–138.
Szczesniak, A. S., and R. Ilker. 1988. The meaning of textural characteristics – juiciness in plant food stuffs. *J. Texture Stud.* **19**, 61–78.
Szczesniak, A. S., and E. L. Kahn. 1971. Consumer awareness of and attitudes to food texture. I. Adults. *J. Texture Stud*. **2**, 280–295.
Szczesniak, A. S., and D. H. Kleyn. 1963. Consumer awareness of texture and other foods attributes. *Food Technol*. **17**, 74–77.
Szczesniak, A. S., and E. Z. Skinner. 1973. Meaning of texture words to the consumer. *J. Texture Stud*. **4**, 378–384.
Szczesniak, A. S., and K. Torgeson. 1965. Methods of meat texture measurement viewed from the background of factors affecting tenderness. *Adv. Food Res*. **14**, 53–165.
Szczesniak, A. S., M. A. Brandt, and H. H. Friedman. 1963. Development of standard rating scales for mechanical parameters of texture and correlation between the objective and sensory methods of texture evaluation. *J. Food Sci*. **28**, 397–403.
Szczesniak, A. S., P. R. Humbaugh, and H. W. Block. 1970. Behavior of different foods in the standard shear compression cell of the shear press and the effect of sample weight on peak area and maximum force. *J. Texture Stud*. **1**, 356–378.
Szczesniak, A. S., B. J. Loew, and E. Z. Skinner. 1975. Consumer texture profile technique. *J. Food Sci*. **40**, 1253–1256.
Takahashi, J., and F. Nakazawa. 1991a. Palatal pressure patterns of gelatin gels in the mouth. *J. Texture Stud.* **22**, 1–11.
Takahashi, J., and F. Nakazawa. 1991b. Effects of viscosity of liquid foods on palatal pressure. *J. Texture Stud.* **22**, 13–24.
Takahashi, J., and F. Nakazawa. 1992. Effects of dimensions of agar and gelatin gels on palatal pressure patterns. *J. Texture Stud.* **23**, 139–152.

Tan, J., X. Gao, and F. Hsieh. 1994. Extrudate characterization by image processing. *J. Food Sci.* **59**, 1247–1250.

Tan, J., H. Zhang, and X. Gao. 1997. SEM image processing for food structure analysis. *J. Texture Stud.* **28**, 657–672.

Tanaka, M. 1975. General Foods Texturometer applications to food texture research in Japan. *J. Texture Stud*. **6**, 101–116.

Tang, A., O. J. McCarthy, and P. A. Munro. 1995. Effects of pH on whey protein concentrate gel properties: comparisons between small deformation (dynamic) and large deformation (failure) testing. *J. Texture Stud.* **26**, 255–272.

Tarr, L. W. 1926. Fruit Jellies III. Jelly strength measurements. *Del. Agric. Exp. Stn., Bull*. No. 142.

Tauti, M., I. Hirose, and H. Wada. 1931. A physical method of testing the freshness of raw fish. *J. Imp. Fish. Inst.* (*Jpn.*) **26**, 59–66.

Templeton, H. L., and H. H. Sommer. 1933. Studies on whipping cream. *J. Dairy Sci*. **16**, 329–345.

Thompson, J. B., and D. F. Meisner. 1950. The lever system of the Baker compressimeter. *Cereal Chem*. **27**, 71–73.

Thompson, R. L., H. P. Fleming, and D. D. Hamann. 1992. Delineation of puncture forces for exocarp and mesocarp tissues in cucumber fruit. *J. Texture Stud.* **23**, 169–184.

Thybo, A. K., and M. Martens. 1998. Development of a sensory texture profile of cooked potatoes by multi-variate data analyses. *J. Texture Stud.* **29**, 453–468.

Thybo, A. K., M. Nielsen, and M. Martens. 2000. Influence of uniaxial compression rate on rheological parameters and sensory texture prediction of cooked potatoes. *J. Texture Stud*. **31**, 25–40.

Tornberg, E., S. F. Jelkner-Modig, H. Ruderus, P.-O. Glantz, K. Randow, and D. Stafford. 1985. Clinically recorded masticatory patterns as related to the sensory evaluation of meat and meat products. *J. Food Sci.* **50**, 1059–1066.

Tracy, A. F. 1928. A new jelly strength tester and some experiments on gelatin gels. *J. Soc. Chem. Ind., London, Trans. Commun*. **47**, 94T–96T.

Trant, A. S., R. M. Pangborn, and A. C. Little. 1981. Potential fallacy of correlating hedonic responses with physical and chemical measurements. *J. Food Sci.* **46**, 583–588.

Tressler, D. K., and W. T. Murray. 1932. Tenderness of meat. II. Determination of period of aging of grade A beef required to produce a tender quick-frozen product. *Ind. Eng. Chem*. **24**, 890–892.

Tressler, D.K., C. Birdseye, and W. T. Murray. 1932. Tenderness of meat. *Ind. Eng. Chem*. **24**, 242–245.

Truong, V. D., and C. R. Daubert. 2000. Comparative study of large strain methods for assessing failure characteristics of selected food gels. *J. Texture Stud.* **31**, 335–353.

Truong, V. D., W. M. Walter, Jr., and D. D. Hamann. 1997. Relationship between instrumental and sensory parameters of cooked sweet potato texture. *J. Texture Stud.* **28**, 163–185.

Tschoegl, N. W., J. A. Rinde, and T. L. Smith. 1970. Rheological properties of wheat flour doughs. I. Method for determining the large deformation and rupture properties in simple tension. *J. Sci. Food Agric*. **21**, 65–70.

Twigg, B. A. 1963. New Shear Press method for measuring quality of raw and canned sweet corn. *The Canning Trade*. March 25–April 1.

Ulbricht, D., M. D. Normand, and M. Peleg. 1995. Creating typical jagged force-deformation relationship from the irregular and irreproducible compression data of crunchy foods. *J. Sci. Food Agric.* **67**, 453–459.

Underwood, J. C., and G. J. Keller. 1948. A method for measuring the consistency of tomato paste. *Fruit Prod. J. Am. Food Manuf*. **28**(4), 103–105.

Vaisey-Genser, M., B. K. Vane, and S. Johnson. 1989. Graininess, crystal size, and firmness of stored canola oil margarines. *J. Texture Stud.* **20**, 347–361.

Valenta, E. 1909. Neuer Apparat zur Bestimmung der Druckfestigkeit von Leimgallerten. *Chem.-Ztg*. **33**, 94.

Vanderheiden, G. J. 1970. An instrument for objective characterization of the consistency and texture of cheese. *Aust. J. Dairy Technol*. **25**(1), 37, 38.

Van der Reijden, W. A., E. C. I. Veerman, and A. V. Nieuw Amerongen. 1994. Rheological properties of commercially available polysaccharides with potential use in saliva substitutes. *Biorheol.* **31**, 631–642.

Van Hecke, E., K. Alla, and J. M. Bouvier. 1995. Texture and structure of crispy-puffed food products. I. Mechanical properties in bending. *J. Texture Stud.* **26**, 11–25.

VanWazer, J. R., J. W. Lyons, K. Y. Kim, and R. E. Colwell. 1963. "Viscosity and Flow Measurement. A Laboratory Handbook of Rheology." Wiley (Interscience), New York.

Vas, K. 1928. Koagulometer zur Beurteilung des Kasebruches. *Milchwirtsch. Forsch*. **6**, 231–235.

Velez-Ruiz, J. F., and G. V. Barbosa-Canovas. 1998. Rheological properties of concentrated milk as a function of concentration, temperature and storage time. *J. Food Eng.* **35**, 177–190.

Venkateswara Rao, G., K. Leelavathi, P. Haridas Rao, and S. R. Shurpalekar. 1986. Changes in quality characteristics of chapati during storage. *Cereal Chem.* **63**, 131–135.

Vernon Carter, E. J., and P. Sherman. 1980. Rheological properties and applications of mesquite tree (*Prosopis juliflora*) gum. I. Rheological properties of aqueous mesquite gum solutions. *J. Texture Stud*. **11**, 339–344.

Vickers, Z. M. 1985. Crispness and crunchiness – A difference in pitch? *J. Texture Stud*. **15**, 157–163.

Vickers, Z. M. 1991. Sound perception and food quality. *J. Food Quality* **14**, 87–96.

Vickers, Z. M., and M. C. Bourne. 1976a. Crispness in foods – a review. *J. Food Sci*. **41**, 1153–1157.

Vickers, Z. M., and M. C. Bourne. 1976b. A psychoacoustical theory of crispness. *J. Food Sci*. **41**, 1158–1164.

Vincent, A. 1986. World production of food texturizers 1985. *Proc. Int. Food Sci. Technol.* **19**(3), 107.

Vincent, J. F. V., G. Jeronomidis, A. A. Khan, and H. Luyten. 1991. Wedge fracture test. A new method for measurement of food texture. *J. Texture Stud.* **22**, 45–57.

Voisey, P. W. 1971a. Modernization of texture instrumentation. *J. Texture Stud*. **2**, 129–195.

Voisey, P. W. 1971b. The Ottawa texture measuring system. *Can. Inst. Food Technol. J*. **4**, 91–103.

Voisey, P. W. 1972. Updating the shear press. *Can. Inst. Food Sci. Technol. J*. **5**, 6–12.

Voisey, P. W. 1974. Design and operational details of the Ottawa Tenderometer. *Agric. Can., Eng. Res. Serv. Rep*. No. 6820–8.

Voisey, P. W. 1975. Reply to C. A. Pearson and D. Raynor. *J. Texture Stud*. **6**, 394–398.

Voisey, P. W. 1976. Engineering assessment and critique of instruments used for meat tenderness evaluations. *J. Texture Stud*. **7**, 11–48.
Voisey, P. W. 1977a. Examination of operational aspects of fruit pressure tests. *Can. Inst. Food Sci. Technol. J*. **10**, 284–294.
Voisey, P. W. 1977b. Effect of blade thickness on readings from the FTC shear compression cell. *J. Texture Stud*. **7**, 433–440.
Voisey, P. W. 1977c. Some applications of the Ottawa Texture Measuring System. *Eng. Res. Serv., Agric. Can. Rep*. No. 7024–694.
Voisey, P. W., and R. Crête. 1973. A technique for establishing instrumental conditions for measuring food firmness to simulate consumer evaluations. *J. Texture Stud*. **4**, 371–377.
Voisey, P. W., and J. M. deMan. 1970. An electronic recording viscometer for food products. *Can. Inst. Food Technol. J*. **3**, 130–135.
Voisey, P. W., and J. M. deMan. 1976. Applications of instruments for measuring food texture. *In* "Rheology and Texture in Food Quality" (J. M. deMan, P. W. Voisey, V. F. Rasper, and D. W. Stanley, eds), pp. 142–242. Westport. Connecticut.
Voisey, P.W. and E. Larmond. 1972. The comparison of textural and other properties of cooked spaghetti by sensory and objective methods. Canada Agriculture Engineering Research Service Publication No. 297.
Voisey, P. W., and E. Larmond. 1973. Exploratory evaluation of instrumental techniques for measuring some textural characteristics of cooked spaghetti. *Cereal Sci. Today* **18**, 126–143.
Voisey, P. W., and E. Larmond. 1974. Examination of factors affecting performance of the Warner–Bratzler meat shear test. *Can. Inst. Food Sci. Technol. J*. **7**, 243–249.
Voisey, P. W., and E. Larmond. 1977. The effect of deformation rate on the relationship between sensory and instrumental measurements of meat tenderness by the Warner–Bratzler method. *Can. J. Food Sci. Technol*. **10**, 307–312.
Voisey, P. W., and I. L. Nonnecke. 1971. Measurement of pea tenderness. I. An appraisal of the FMC pea Tenderometer. *J. Texture Stud*. **2**, 348–364.
Voisey, P. W., and I. L. Nonnecke. 1972a. Measurement of pea tenderness. III. Field comparison of several methods of measurement. *J. Texture Stud*. **3**, 329–358.
Voisey, P. W., and I. L. Nonnecke. 1972b. Measurement of pea tenderness. IV. Development and evaluation of the test cell. *J. Texture Stud*. **3**, 459–477.
Voisey, P. W., and I. L. Nonnecke. 1973a. Some observations regarding pea Tenderometer standardization. *Agric. Can., Eng. Res. Serv., Rep*. No. 6820–5.
Voisey, P. W., and I. L. Nonnecke. 1973b. Summary of results. Pea Tenderometer tests. *Agric. Can., Eng. Res. Serv., Rep*. No. 6820–7.
Voisey, P. W., and I. L. Nonnecke. 1973c. Measurement of pea tenderness. V. The Ottawa Pea Tenderometer and its performance in relation to the Pea Tenderometer and the FTC Texture Test System. *J. Texture Stud*. **4**, 323–343.
Voisey, P. W., D. C. MacDonald, M. Kloek, and W. Foster. 1972. The Ottawa Texture Measuring System. An operational manual. *Agric. Can., Eng. Spec*. No. 7024.
Voisey, P. W., E. Larmond, and R. J. Wasik. 1978. Measuring the texture of cooked spaghetti. I. Sensory and instrumental evaluation of firmness. *Can. Inst. Food Sci. Technol. J.* **11**, 142–148.
Voisey, P. W., M. Kloek, K. Summers, and M. Gillette. 1979. A method for testing the ease of extrusion of icing marketed in plastic containers. *J. Texture Stud*. **10**, 435–448.

Volodkevich, N. N. 1938. Apparatus for measurement of chewing resistance or tenderness of foodstuffs. *Food Res*. **3**, 221–225.

Wade, P. 1968. A texture meter for the measurement of biscuit hardness. *In* "Rheology and Texture of Foodstuffs," Monograph No. 27, pp. 225–234. Soc. Chem. Ind., London.

Warner, K. F. 1928. Progress report of the mechanical test for tenderness of meat. *Proc. Am. Soc. Anim. Prod*. 114–116.

Washburn, R. M. 1910. Principles and practice of ice cream making. *Bull.–Vt. Agric. Exp. Stn*. No. 155.

Waugh, F. A. 1901. "Fruit Harvesting, Storing, Marketing," p. 44. Orange Judd Co., New York.

Waugh, L. M. 1937. Dental observations among Eskimos. *J. Dent. Res*. **16**, 356.

Weinrichter, B., H. Rohm, and D. Jaros. 2000. Mechanical properties of unpressed semi-hard cheeses by uniaxial compression. *J. Texture Stud*. **31**, 141–152.

Weissenberg, K. 1949. Abnormal substances and abnormal phenomena of flow. *Proc. Int. Rheol. Cong., 1st, Scheveningen, Neth., 1948* pp. I-29–I-46.

Wender, N. 1895. The viscometer examination of butter for foreign fats. *J. Am. Chem. Soc*. **17**, 719–723.

Wheeler, T. L., S. D. Shackelford, and M. Koohmaraie. 1996. Sampling, cooking and coring effects on Warner–Bratzler shear force values in beef. *J. Anim. Sci*. **74**, 1553–1562.

Wheeler, T. L., S. D. Shackelford, L. P. Johnson, M. F. Miller, R. K. Miller, and M. Koohmaraie. 1997. A comparison of Warner–Bratzler shear force assessment within and among institutions. *J. Anim. Sci.* **75**, 2423–2432.

White, G. W. 1970. Rheology in food research. *J. Food Technol*. **5**, 1–32.

White, K., and N. N. Mohsenin. 1967. Apparatus for determination of bulk modulus and compressibility of materials. *Trans. ASAE* **10**, 670–671.

Whittle, K. J. 1973. A multiple sampling technique for use with the cell-fragility method of determining deteriorative changes in frozen fish. *J. Sci. Food Agric*. **24**, 1383–1389.

Whittle, K. J. 1975. Improvement of the Torry–Brown homogenizer for the cell fragility method. *J. Food Technol*. **10**, 215–220.

Whorlow, R. W. 1980. "Rheological Techniques." Ellis Harwood, Chichester, England.

Wilder, H. K. 1947. Measurement of fiber content in canned asparagus. *Natl. Canners' Assoc., Res. Lab Rep*. No. 12313B.

Wiley, R. C., N. Elehwany, A. Kramer, and F. J. Hager. 1956. The shear press – an instrument for measuring the quality of foods. IV. Application to asparagus. *Food Technol*. **10**, 439–443.

Willard, J. T., and R. H. Shaw. 1909. Analysis of eggs. *Kans. Agric. Exp. Stn., Bull*. No. 159. pp. 143–177.

Willhoft, E. M. A. 1970. An empirical equation describing the firming of the crumb of bread. *Chem. Ind. (London)* 1017, 1018.

Willhoft, E. M. A. 1973. Mechanism and theory of staling of bread and baked goods, and associated changes in textural properties. *J. Texture Stud*. **4**, 292–322.

Williamson, R. V. 1929. The flow of pseudoplastic materials. *Ind. Eng. Chem*. **21**, 1108–1111.

Wium, H., M. Gross, and K. B. Qvist. 1997. Uniaxial compression of UF-Feta cheese related to sensory texture analysis. *J. Texture Stud*. **28**, 455–476.

Woll, F. W. 1895. The effect of pasteurization and sterilization on the viscosity and fat globules of milk and cream. 12th Annual Report, Agricultural Experiment Station, University of Wisconsin. pp. 164–173.

Wood, A. H., and C. L. Parsons. 1891. Hardness of butter. *N. H. Agric. Exp. Stn., Bull*. No. 13, p. 8.

Wood, F. W. 1974. An approach to understanding creaminess. *Die Starke* **26**, 127–130.

Woodruff, S., and H. V. Gilder. 1931. Photomicrographic studies of sucrose crystals. *J. Phys. Chem*. **35**, 1355–1367.

Worthington, J. T., and J. H. Yeatman. 1968. A statistical evaluation of objective measurement of apple firmness. *Proc. Am. Soc. Hortic. Sci*. **92**, 739–747.

Xu, Zi, and S. N. Raphaelides. 1998. Flow behavior of concentrated starch dispersions using a tube rheometer of novel design. *J. Texture Stud.* **29**, 1–13.

Yang, Y. M., and N. Mohsenin. 1974. Analysis of the mechanics of the fruit pressure tester. *J. Texture Stud*. **5**, 213–238.

Yoo, B., and M. A. Rao. 1994. Effect of unimodel particle size and pulp content on rheological properties of tomato puree. *J. Texture Stud.* **25**, 421–430.

Yoshikawa, S., S. Nishimaru, T. Tashiro, and M. Yoshida. 1970a. Collection and classification of words for description and food texture. I. Collection of words. *J. Texture Stud*. **1**, 437–442.

Yoshikawa, S., S. Nishimaru, T. Tashiro, and M. Yoshida. 1970b. Collection and classification of words for description of food texture. II. Texture profiles. *J. Texture Stud*. **1**, 443–451.

Yoshikawa, S., S. Nishimaru, T. Tashiro, and M. Yoshida. 1970c. Collection and classification of words for description of food texture. III. Classification of multivariate analysis. *J. Texture Stud*. **1**, 452–463.

Yurkstas, A. A. 1965. The masticatory act. A review. *J. Prosthet. Dent*. **15**, 248–260.

Yurkstas, A., and W. A. Curby. 1953. Force analyses of prosthetic appliances during function. *J. Prosthet. Dent*. **3**, 82–87.

Zhang, M., G. S. Mittal, and S. Barbut. 1993. Optimum conditions for determining water holding capacity of beef by the press method. *J. Muscle Foods* **4**, 255–268.

Zimmer, L. A., T. A. Haley, and O. H. Campanella. 2001. A comparative study of the performance of selected in-line viscometers on Newtonian and shear-thinning fluids. *J. Texture Stud.* **32**, 75–103.

Zorrilla, S. E., C. U. Rovedo, and R. P. Singh. 2000. A new approach to correlate textural and cooking parameters with operating conditions during double-sided cooking of meat patties. *J. Texture Stud.* **31**, 499–523.

This Page Intentionally Left Blank

Index

This Page Intentionally Left Blank

Food Science and Technology
International Series

Maynard A. Amerine, Rose Marie Pangborn, and Edward B. Roessler, *Principles of Sensory Evaluation of Food*. 1965.
Martin Glicksman, *Gum Technology in the Food Industry*. 1970.
Maynard A. Joslyn, *Methods in Food Analysis*, second edition. 1970.
C. R. Stumbo, *Thermobacteriology in Food Processing*, second edition. 1973.
Aaron M. Altschul (ed.), *New Protein Foods*: Volume 1, *Technology, Part A* – 1974. Volume 2, *Technology, Part B* – 1976. Volume 3, *Animal Protein Supplies, Part A* – 1978. Volume 4, *Animal Protein Supplies, Part B* – 1981. Volume 5, *Seed Storage Proteins* – 1985.
S. A. Goldblith, L. Rey, and W. W. Rothmayr, *Freeze Drying and Advanced Food Technology*. 1975.
R. B. Duckworth (ed.), *Water Relations of Food*. 1975.
John A. Troller and J. H. B. Christian, *Water Activity and Food*. 1978.
A. E. Bender, *Food Processing and Nutrition*. 1978.
D. R. Osborne and P. Voogt, *The Analysis of Nutrients in Foods*. 1978.
Marcel Loncin and R. L. Merson, *Food Engineering: Principles and Selected Applications*. 1979.
J. G. Vaughan (ed.), *Food Microscopy*. 1979.
J. R. A. Pollock (ed.), *Brewing Science*, Volume 1 – 1979. Volume 2 – 1980. Volume 3 – 1987.
J. Christopher Bauernfeind (ed.), *Carotenoids as Colorants and Vitamin A Precursors: Technological and Nutritional Applications*. 1981.
Pericles Markakis (ed.), *Anthocyanins as Food Colors*. 1982.
George F. Stewart and Maynard A. Amerine (eds.), *Introduction to Food Science and Technology*, second edition. 1982.
Malcolm C. Bourne, *Food Texture and Viscosity: Concept and Measurement*. 1982.
Hector A. Iglesias and Jorge Chirife, *Handbook of Food Isotherms: Water Sorption Parameters for Food and Food Components*. 1982.

Colin Dennis (ed.), *Post-Harvest Pathology of Fruits and Vegetables*. 1983.
P. J. Barnes (ed.), *Lipids in Cereal Technology*. 1983.
David Pimentel and Carl W. Hall (eds.), *Food and Energy Resources*. 1984.
Joe M. Regenstein and Carrie E. Regenstein, *Food Protein Chemistry: An Introduction for Food Scientists*. 1984.
Maximo C. Gacula, Jr., and Jagbir Singh, *Statistical Methods in Food and Consumer Research*. 1984.
Fergus M. Clydesdale and Kathyrn L. Wiemer (eds.), *Iron Fortification of Foods*. 1985.
Robert V. Decareau, *Microwaves in the Food Processing Industry*. 1985.
S. M. Herschdoerfer (ed.), *Quality Control in the Food Industry*, second edition. Volume 1 – 1985. Volume 2 – 1985. Volume 3 – 1986. Volume 4 – 1987.
F. E. Cunningham and N. A. Cox (eds.), *Microbiology of Poultry Meat Products*. 1987.
Walter M. Urbain, *Food Irradiation*. 1986.
Peter J. Bechtel, *Muscle as Food*. 1986.
H. W.-S. Chan, *Autoxidation of Unsaturated Lipids*. 1986.
Chester O. McCorkle, Jr., *Economics of Food Processing in the United States*. 1987.
Jethro Jagtiani, Harvey T. Chan, Jr., and William S. Sakai, *Tropical Fruit Processing*. 1987.
J. Solms, D. A. Booth, R. M. Dangborn, and O. Raunhardt, *Food Acceptance and Nutrition*. 1987.
R. Macrae, *HPLC in Food Analysis*, second edition. 1988.
A. M. Pearson and R. B. Young, *Muscle and Meat Biochemistry*. 1989.
Dean O. Cliver (ed.), *Foodborne Diseases*. 1990.
Marjorie P. Penfield and Ada Marie Campbell, *Experimental Food Science*, third edition. 1990.
Leroy C. Blankenship, *Colonization Control of Human Bacterial Enteropathogens in Poultry*. 1991.
Yeshajahu Pomeranz, *Functional Properties of Food Components*, second edition. 1991.
Reginald H. Walter, *The Chemistry and Technology of Pectin*. 1991.
Herbert Stone and Joel L. Sidel, *Sensory Evaluation Practices*, second edition. 1993.
Robert L. Shewfelt and Stanley E. Prussia, *Postharvest Handling: A Systems Approach*. 1993.
R. Paul Singh and Dennis R. Heldman, *Introduction to Food Engineering*, second edition. 1993.
Tilak Nagodawithana and Gerald Reed, *Enzymes in Food Processing*, third edition. 1993.
Dallas G. Hoover and Larry R. Steenson, *Bacteriocins*. 1993.
Takayaki Shibamoto and Leonard Bjeldanes, *Introduction to Food Toxicology*. 1993.

John A. Troller, *Sanitation in Food Processing*, second edition. 1993.
Ronald S. Jackson, *Wine Science: Principles and Applications*. 1994.
Harold D. Hafs and Robert G. Zimbelman, *Low-fat Meats*. 1994.
Lance G. Phillips, Dana M. Whitehead, and John Kinsella, *Structure–Function Properties of Food Proteins*. 1994.
Robert G. Jensen, *Handbook of Milk Composition*. 1995.
Yrjö H. Roos, *Phase Transitions in Foods*. 1995.
Reginald H. Walter, *Polysaccharide Dispersions*. 1997.
Gustavo V. Barbosa-Cánovas, M. Marcela Góngora-Nieto, Usha R. Pothakamury, and Barry G. Swanson, *Preservation of Foods with Pulsed Electric Fields*. 1999.
Ronald S. Jackson, *Wine Science: Principles, Practice, Perception*, second edition. 2000.
R. Paul Singh and Dennis R. Heldman, *Introduction to Food Engineering*, third edition. 2001.
Ronald S. Jackson, *Wine Tasting: A Professional Handbook*. 2002.