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Effect of chia (*Sativa hispanica* L.) and hydrocolloids on the rheology of gluten-free doughs based on chestnut flour

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ABSTRACT

The rheological characterisation of chestnut flour doughs with chia flour at 4.0 g/100 g flour basis and a hydrocolloid (guar gum, hydroxypropyl methyl cellulose (HPMC) or tragacanth gum) at different concentrations (0.5, 1.0, 1.5, 2.0 g/100 g, f.b.) was carried out at 30 °C using a controlled stress rheometer. Previously, the mixing behaviour was determined using Mixolab® apparatus. Measurements of shear (0.01–10 s^{-1}), oscillatory (1–100 rad s^{-1} at 0.1% strain), creep-recovery (loading of 50 Pa for 60 s) and temperature sweep (30–100 °C) were performed. The simultaneous presence of chia and hydrocolloids modified significantly the rheological properties of doughs. Apparent viscosity at constant shear rate and storage and loss moduli at constant angular frequency decreased with increasing hydrocolloid content, except for tragacanth gum which loss modulus exhibited a reverse trend. Creep-recovery data showed that doughs elasticity improved with the presence of guar (65.9%), HPMC (64.8%) or tragacanth (45.8%) at 1.0, 2.0 and 1.0 (g/100 g, f.b.), respectively. Flow curves, mechanical spectra and creep-recovery curves obtained experimentally were satisfactorily fitted using Cross, power and Burgers models, respectively. Gelatinization temperatures decreased with increasing additive content for all systems.

1. Introduction

A diet based on gluten-free products is characterised by low content of some nutritional components such as proteins and essential fatty acids, as well as non-nutritional but physiologically important components like dietary fibre. Therefore, the prospecting of components supplementing gluten-free products to increase the nutritional and dietary content is important (Wronkowska & Soral-Śmietana, 2008). In this sense, chia flour (CHF), a rich source of essential fatty acids, fibre and protein (Vázquez-Ovando, Rosado-Rubio, Chel-Guerrero, & Betancur-Ancona, 2009), could be a good complement to this kind of products, and particularly for chestnut flour (CF) doughs as it was previously reported (Moreira, Chenlo & Torres, in press-a).

The gluten absence provokes a lack of suitable flow-mechanical properties for the processing of flour doughs. Hydrocolloids are usually added on doughs to mimic the viscoelastic properties of gluten and improve the structure, mouthfeel, acceptability and shelf-life of gluten-free products (Ahlborn, Pike, Hendrix, Hess, & Huber, 2005). Specifically, several hydrocolloids have been investigated for making acceptable quality gluten-free products, including hydroxypropyl methyl cellulose (HPMC) and guar gum (GG) (Lazaridou, Duta, Papageorgiou, Belc, & Biliaderis, 2007), whereas scarce information about other like tragacanth gum (TG) was found to be used as additive of flour dough. In baked doughs, hydrocolloids have been used for retarding the staling and improving the quality of products. They help to minimize the negative effects of the freezing and frozen storage (Wronkowska & Soral-Śmietana, 2008). Hydrocolloids can induce structural changes in the main components of flour along the breadmaking steps and product storage. Hydrocolloids are used either alone or in combination to achieve specific synergies between their respective functional properties. Many rheological studies of dough reported relevant interactions between different hydrocolloids (Demirkesen, Mert, Sumnu, & Sahin, 2010), but data about the combined effect of hydrocolloids and chia flour were not found. The influence of fibres or proteins combined with gums in other gluten-free doughs as rice flour was determined, resulting in further improvement on quality properties (Ahlborn et al., 2005; Singh, Haros, & Rosell, 2004). In terms of fluffiness, rice flour or isolated starches combined with gums (mainly HPMC) gave better results than those previously obtained (Nishita, Roberts, & Bean, 1976). The functionality of ingredients is modified by the (antagonistic or synergistic) interactions of all matrix components (Arendt & Bello, 2008).

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Experimental results obtained in previous works (Moreira, Chenlo, & Torres, 2011a, 2011b, in press-a) about the effects of different additives on the rheological behaviour of CF dough showed that CHF (at content 4 g/100 g) and some hydrocolloids (GG, HPMC and TG) gave the best results in the improvement on the viscoelastic characteristics of the CF doughs. Nevertheless, these doughs still are very viscous and presented inadequate viscoelastic properties in comparison to wheat flour doughs. In this sense, it is interesting to evaluate the combined effect of both kinds of additives because positive effects could be expected. Hence, the main objectives of this work were to provide experimental data in order to determine the mixing properties of CF doughs with CHF (CS) and GG, HPMC or TG, to study the combined effect of both additives (CHF and each hydrocolloid) on the rheological properties by analysis of the corresponding parameters from steady-shear, oscillatory and creep-recovery tests and to assess the temperature effect.

2. Materials and methods

2.1. Raw materials

Commercial CF with moisture content of 9.1 ± 0.4 g/100 g (d.b.) and average particle size of 167.9 ± 5.5 μm was employed. The chemical composition of assayed flour and the corresponding protocols were previously reported (Moreira et al., 2011a). Chia (*Sativa hispanica* L.) seeds were provided by a warehouse (Valencia, Spain). The CHF with moisture content of 5.1 ± 0.3 g/100 g (d.b.) and average particle size of 178.6 ± 4.6 μm was obtained by milling of chia seeds in a stainless steel grinder (Retsch GmbH, ZM 200, Haan, Germany). CF with CHF (at 4.0 g/100 g, f.b.) was considered as control sample (CS). The hydrocolloids employed were GG (Sigma–Aldrich, St. Louis, MO), HPMC (Sigma–Aldrich, St. Louis, MO) and TG (Merck, Darmstadt, Germany). CF doughs with the simultaneous presence of CHF (4.0 g/100 g, f.b.) and GG, HPMC or TG (0.5, 1.0, 1.5, 2.0 g/100 g, f.b.) were tested. Amounts of CHF and hydrocolloids were added following previous results (Moreira et al., 2011a,b, in press-a).

2.2. Mixing properties

Doughs were prepared according to the ICC-Standard Method No. 173 (ICC, 2008) using mixing tests of Mixolab® apparatus (Chopin Technologies, France). These tests consisted of dough mixing at 80 rpm during 30 min at 30 °C. All assays were performed in triplicate at the dough target consistency (C1: 1.10 ± 0.07 Nm) (Rosell, Collar, & Haros, 2007). At this consistency, dough mixing properties (water absorption (WA), stability (St) and development time (DT)) were determined. More details about the protocol and Mixolab® parameters were reported in previous studies (Rosell et al., 2007).

2.3. Rheological properties

Rheological characteristics of doughs at target consistency (C1) were conducted on a controlled stress rheomether (MCR 301, Anton Paar Physica, Austria). The measuring system consisted of parallel plate geometry (50 mm diameter). Dough sample (around 5 g) was loaded between the parallel plates of the rheometer and compressed up to obtain a gap of 2 mm. Edges of doughs were trimmed with a cotton wool bud and coated with paraffin (Panreac Química S.A.). Doughs remained between the plates in rest time (15 min) before measure. Rheological measurements of steady-shear flow, oscillatory shear and creep-recovery at 30 °C were separately performed in triplicate.

Steady-shear flow tests were carried over the range of shear rates ($\dot{\gamma}$) from 0.01 to 10 s^{-1}. Tests were carried out in automatic mode to ensure that steady state at each shear rate was reached. Maximum duration of each test was 30 min. Experimental data of flow curves were fitted by Cross (1965) model:

$$\eta = \eta_\infty + \frac{\eta_0 - \eta_\infty}{1 + (k\dot{\gamma})^{(1-n)}} \tag{1}$$

where η (Pa s) is the apparent viscosity, η_0 and η_∞ (Pa s) are the zero-shear and infinite-shear rate viscosities, respectively; k (s) is the time constant and n (−) is the flow index.

Strain sweeps at standard angular frequency (ω) of 1 Hz were previously carried out to oscillatory shear tests to determine the linear viscoelastic region (strain, $\gamma < 1.0\%$). Oscillatory shear tests were carried out in controlled-strain mode over the range of ω from 1 to 70 rad s^{-1} at 0.1% strain value. Storage, G', and loss, G'', moduli (Pa) were determined. Experimental G' and G'' were fitted by the following equations:

$$\log G' = \log a' + b' \log \omega \tag{2}$$

$$\log G'' = \log a'' + b'' \log \omega \tag{3}$$

where a' (Pa $s^{-b'}$), b', a'' (Pa $s^{-b''}$), b'' are the fitting parameters.

Creep-recovery tests were performed applying on dough samples, during creep phase, a constant normal stress, $\sigma = 50$ Pa, during 60 s, obtaining data out of linear viscoelastic region, and during recovery phase load was removed, $\sigma = 0$ Pa, and the promoted strain is partially recovered. Creep data were described with creep compliance rheological parameters, $J(t)$ (1/Pa) $= \gamma/\sigma$ (Steffe, 1996). Burgers (1935) model was used to fit the compliance curve data of CF doughs with the following equations for creep (C) and recovery (R) phase, respectively:

$$J(t)_C = J_{0C} + J_{mC}(1 - \exp(-t/\lambda_C)) + t/\eta_{0C} \tag{4}$$

$$J(t)_R = J_{max} - J_{0R} - J_{mR}(1 - \exp(-t/\lambda_R)) \tag{5}$$

where J_{0C} and J_{0R}, J_{mC} and J_{mR} are the instantaneous and viscoelastic compliance of creep and recovery phases, respectively; J_{max} is the maximum compliance, λ_C and λ_R (s) are mean retardation time of creep and recovery phases, t (s) is the phase time; and η_{0C} (Pa s) is the zero shear viscosity. The recovery compliance, J_r was calculated by the sum of J_{0R} and J_{mR}, Eq. (5).

Table 1
Mixing assessment: parameters of mixing tests at 30 °C for chestnut flour doughs without (CF) and with (CS) chia flour (CHF) and hydrocolloids (guar (GG), tragacanth (TG) or HPMC) on the target consistency value (C1: 1.10 ± 0.07 Nm).[a]

Additives	Content (g/100 g, f.b.)	WA (g/100 g, f.b.)	DT (min)	St (min)
-, CF		41.5 ± 0.3^{j}	4.5 ± 0.3^{a}	11.9 ± 0.1^{c,d}
CHF (CS)	4.0	45.1 ± 0.5^{i}	3.4 ± 0.2^{b}	5.1 ± 0.5^{g}
CHF/GG	4.0/0.5	46.8 ± 0.1^{h}	4.7 ± 0.2^{a}	12.2 ± 0.1^{b,c}
	4.0/1.0	49.9 ± 0.1^{f}	4.6 ± 0.1^{a}	12.5 ± 0.1^{a,b}
	4.0/1.5	52.8 ± 0.2^{d}	4.5 ± 0.2^{a}	12.8 ± 0.1^{a}
	4.0/2.0	55.5 ± 0.3^{b}	4.5 ± 0.1^{a}	12.9 ± 0.1^{a}
CHF/TG	4.0/0.5	47.2 ± 0.1^{g,h}	3.5 ± 0.1^{b}	7.4 ± 0.2^{e}
	4.0/1.0	50.3 ± 0.1^{f}	3.0 ± 0.1^{c}	6.6 ± 0.2^{f}
CHF/HPMC	4.0/0.5	47.6 ± 0.1^{g}	4.6 ± 0.1^{a}	11.7 ± 0.2^{d}
	4.0/1.0	50.9 ± 0.1^{e}	4.6 ± 0.1^{a}	11.9 ± 0.1^{c,d}
	4.0/1.5	53.5 ± 0.2^{c}	4.5 ± 0.1^{a}	12.3 ± 0.2^{b,c}
	4.0/2.0	56.3 ± 0.2^{a}	4.5 ± 0.2^{a}	12.5 ± 0.1^{a,b}

[a] Data are presented as means ± standard deviation. Data value with different superscript letters in columns are significantly different, $p \leq 0.05$. WA: Water absorption, DT: development time, St: stability.

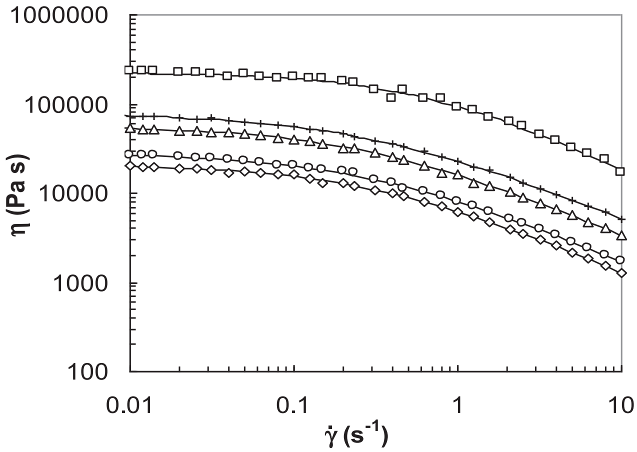

Fig. 1. Steady-shear flow data at 30 °C for chestnut flour dough without (□) and with chia flour (+) at 4.0 g/100 g, f.b. combined with guar gum (◇), HPMC (○) and tragacanth gum (Δ) at 1.0 g/100 g, f.b. Lines (—) correspond to the Cross model, Eq. (1).

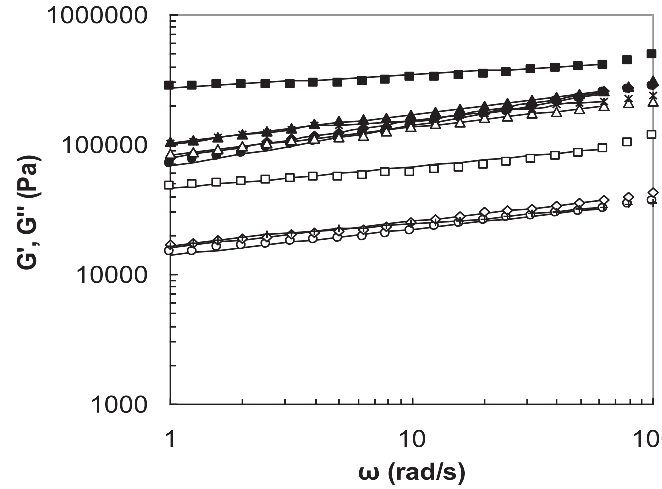

Fig. 2. Storage (G') and loss (G'') moduli data at 30 °C for chestnut flour dough without (■, □) and with chia flour (*, +) at 4.0 g/100 g, f.b. combined with guar gum (◆, ◇), HPMC (●,○) and tragacanth gum (▲, Δ) at 1.0 g/100 g, f.b. Lines (—) correspond to Eqs. (2) and (3).

2.4. Thermal properties

Doughs were thermally characterised according to the ICC-Standard Method No. 173 (ICC, 2008) using complete tests of Mixolab®. Complete tests, after a mixing step (8 min), involved a heating–cooling cycle (37 min). Complete tests were performed in triplicate at target consistency (C1). Several parameters such as C2 (related to proteins characteristics), C3 (related to gelatinization temperatures), C4 (related to amylase activity), C5 (related to retrogradation), α (proteins network weakening rate), β (gelatinization rate), γ_e (enzymatic activity rate), T_0 and T_1 (gelatinization temperature range) were determined. Additional details about these parameters were previously reported (Moreira, Chenlo, Torres, & Prieto, 2010).

2.5. Statistical analysis

Experimental data and fitting parameters of the employed models for all systems were statistically analysed by one-factor analysis of variance (ANOVA) using PASW Statistics (v.18, IBM SPSS Statistics, New York, USA). Duncan test was performed to differentiate means with 95% confidence when variance analysis indicated differences among means. The fittings goodness was evaluated employing the coefficient of determination, R^2, and standard deviation, s.

3. Results and discussion

3.1. Mixing behaviour

Table 1 shows WA, DT and St values obtained for CF doughs with CHF at 4.0 g/100 g, f.b. (CS) combined with GG (0.5, 1.0, 1.5, 2.0 g/100 g, f.b.), HPMC (0.5, 1.0, 1.5, 2.0 g/100 g, f.b.) or TG (0.5, 1.0 g/100 g, f.b.) prepared at target torque value (C1). The presence of hydrocolloids modified significantly the WA level in relation to CS (45.1 g/100 g, f.b.). The WA level increased significantly with increasing hydrocolloid content. At the same hydrocolloid content, the highest WA values were observed with HPMC and the lowest with GG. The combined effect of CHF/hydrocolloid involved a more enhanced increase in WA level of CF doughs than each component separately at the same additive content (Moreira et al., 2011a,b). This behaviour is broad agreement with the results found for rice flour when combinations of hydrocolloids and other components as fibre were added (Singh et al., 2004).

The DT values of CF doughs increased significantly ($p < 0.05$) when compared with CS with HMPC and GG addition, whereas the presence of TG decreased significantly DT with increasing additive content. St values also increased significantly in comparison to CS with the addition of hydrocolloids. However, according to

Table 2
Rheological assessment: parameters of Cross model, Eq. (1), for steady-shear flow at 30 °C for chestnut flour doughs without (CF) and with (CS) chia flour (CHF) and hydrocolloids (guar (GG), tragacanth (TG) or HPMC).[a]

Additives	Content (g/100 g, f.b.)	k (s)	n (–)	η_0 10^{-3} (Pa s)	η_∞ (Pa s)	R^2	s (Pa s)
-, CF		1.49 ± 0.04^{g}	0.10 ± 0.01^{g}	226.0 ± 0.4^{a}	32.3 ± 0.2^{a}	0.991	0.008
CHF (CS)	4.0	3.30 ± 0.10^{b,c}	0.24 ± 0.01^{a,b}	79.2 ± 0.4^{b}	19.3 ± 0.1^{b}	0.998	0.004
CHF/GG	4.0/0.5	2.53 ± 0.08^{e,f}	0.18 ± 0.01^{f}	42.5 ± 0.3^{f}	17.9 ± 0.3^{c}	0.996	0.004
	4.0/1.0	2.92 ± 0.03^{d}	0.19 ± 0.01^{d,e,f}	21.1 ± 0.2^{h}	17.5 ± 0.2^{c,d}	0.998	0.003
	4.0/1.5	3.21 ± 0.02^{c}	0.21 ± 0.01^{c,d,e}	15.8 ± 0.2^{i,j}	17.3 ± 0.1^{c,d}	0.998	0.003
	4.0/2.0	3.41 ± 0.03^{b}	0.25 ± 0.01^{a}	12.5 ± 0.2^{k}	16.9 ± 0.2^{e}	0.997	0.004
CHF/TG	4.0/0.5	2.31 ± 0.01^{f}	0.13 ± 0.01^{g}	69.1 ± 0.6^{c}	20.0 ± 0.3^{b}	0.994	0.006
	4.0/1.0	3.12 ± 0.03^{c}	0.20 ± 0.01^{d,e,f}	56.3 ± 0.5^{b}	18.0 ± 0.2^{c}	0.993	0.007
CHF/HPMC	4.0/0.5	2.40 ± 0.05^{f}	0.17 ± 0.01^{f}	44.9 ± 0.5^{e}	18.1 ± 0.4^{c}	0.995	0.005
	4.0/1.0	3.11 ± 0.05^{c}	0.20 ± 0.01^{d,e,f}	28.2 ± 0.3^{g}	18.0 ± 0.2^{c}	0.997	0.004
	4.0/1.5	3.42 ± 0.02^{b}	0.22 ± 0.01^{b,c}	16.5 ± 0.5^{i}	18.1 ± 0.2^{c}	0.998	0.003
	4.0/2.0	3.73 ± 0.04^{a}	0.24 ± 0.01^{a,b}	14.9 ± 0.3^{j}	18.1 ± 0.3^{c}	0.998	0.003

[a] Data are presented as means ± standard deviation. Data value with different superscript letters in columns are significantly different, $p \leq 0.05$.

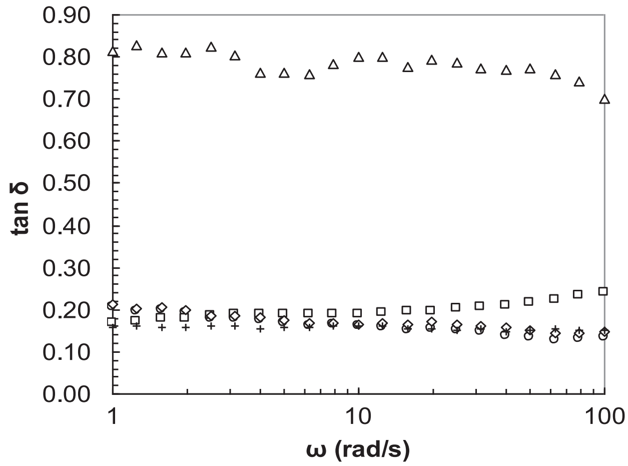

Fig. 3. Values of tan δ for chestnut flour dough without (□) and with chia flour (+) at 4.0 g/100 g, f.b. combined with guar gum (◇), HPMC (○) and tragacanth gum (Δ) at 1.0 g/100 g, f.b. at 30 °C.

St values, CF dough properties only improved slightly with CHF/GG and CHF/HPMC since CHF/TG exhibited again a reverse trend, suggesting softer CF doughs with CHF/TG. Specifically, no significant differences ($p < 0.05$) when compared with CF were found in this parameter below 4.0/1.5 g/100 g, f.b. for CHF/HPMC and 4.0/0.5 g/100 g, f.b. for CHF/GG. The specific synergies between CHF and HPMC or GG did not modify St values of CF doughs, preventing the low St values of dough with the addition of each component added separately (Moreira et al., 2011a,b).

3.2. Rheological behaviour

The viscous properties for doughs at target torque value (C1) were determined using steady-shear flow tests. Experimental data of apparent viscosity against shear rate at 30 °C for CS with each hydrocolloid (1.0 g/100 g, f.b.) compared to CF are presented in Fig. 1. A Newtonian plateau typical for CS (shear rate < 0.1 s^{-1}) was noticed. After plateau, studied doughs showed shear thinning behaviour. At each shear rate, the apparent viscosity decreased with increasing hydrocolloid content. The largest reduction was achieved with GG, followed by HPMC and TG. Table 2 shows the parameters of Cross model, Eq. (1), determined by means of fitting of experimental data and the goodness of fitting ($R^2 > 0.991$ and $s < 0.008$ Pa s). The fitting lines of Cross model are also included in Fig. 1.

The zero-shear rate viscosity, η_0, values decreased significantly with increasing additives content (Table 2). Higher WA level was necessary for CF doughs with studied additives and this fact improved the flow properties of assayed doughs. The obtained values were in the range that those previously found for other gluten-free flours as rice flour and slightly larger to those reported for wheat flour (Sivaramakrishnan, Senge, & Chattopadhyay, 2004). The infinite-shear rate viscosity, η_∞, values decreased significantly with additives when compared with CS, whereas slight differences in a narrow range were observed with increasing additive content. Flow index, n, increased significantly in comparison to CF with CHF/GG, CHF/HPMC and CHF/TG addition, although slight differences with increasing hydrocolloid content were found. Anyway, flow index were low (from 0.10 to 0.25) corroborating the strong shear-thinning behaviour of these doughs. It was also observed that n values increased with increasing WA. The time constant, k, also increased significantly with increasing hydrocolloids content when compared with CF dough. The k values seemed to be more influenced by CHF addition, since the obtained values for CHF/HPMC and CHF/TG were close to those found for CS. Likewise, the presence of CHF/GG did not show a threshold value with increasing GG content as in the case of GG addition separately (Moreira et al., 2011b).

Linear viscoelastic properties for all doughs at fixed C1 (1.10 ± 0.07 Nm) were analysed using oscillatory shear measurements. Fig. 2 shows data of G' and G'' versus angular frequency at 30 °C for the same systems presented in steady-shear assays. G' and G'' values increased with increasing angular frequency from 1 to 100 rad s^{-1}. Overall, both moduli dropped in comparison to CS with increasing hydrocolloids content at constant angular frequency, except for TG where G'' increased with increasing additive content. GG showed the largest effect on G', with the most enhanced softening effects in CF dough at the lowest hydrocolloid content. The combined effect of CHF and GG or HPMC seemed to be the most suitable option because involved the largest reduction in both moduli and, thus the most pronounced positive effects in CF dough firmness.

In this sense, the additives varied significantly the tan δ (G''/G') when compared with CS and, hence, the viscoelastic behaviour of doughs, Fig. 3. In all cases, the value of tan δ was lower than unit. It is noteworthy the large increase of tan δ values observed with TG in whole range of angular frequency. This fact was directly related to the reduction of elastic properties and increase in viscous properties promoted by TG into CS dough. Overall, the additives modified the slope of tan δ with angular frequency for CF doughs by the increasing elastic contribution at high angular frequencies. Specifically, the tan δ values decreased with the presence of CHF/GG, and CHF/HPMC with increasing angular frequency. The GG or HPMC addition at the same content gave as result similar viscoelastic properties. This fact can be explained considering the possible

Table 3
Rheological assessment: parameters of oscillatory shear modelling, Eqs. (2) and (3) at 30 °C for chestnut flour doughs without (CF) and with (CS) chia flour (CHF) and hydrocolloids (guar (GG), tragacanth (TG) or HPMC).[a]

Additives	Content (g/100 g, f.b.)	$a' \cdot 10^{-3}$ (Pa $s^{-b'}$)	b'	R^2	a'' 10^{-3} (Pa $s^{-b''}$)	b''	R^2
-, CF		275.0 ± 0.2^{a}	0.10 ± 0.01^{d}	0.993	45.9 ± 0.1^{c}	0.17 ± 0.01^{b}	0.985
CHF (CS)	4.0	105.4 ± 0.2^{c}	0.17 ± 0.01^{c}	0.991	17.1 ± 0.1^{e}	0.16 ± 0.01^{b}	0.994
CHF/GG	4.0/0.5	91.0 ± 0.3^{d}	0.30 ± 0.01^{a}	0.997	18.3 ± 0.2^{d}	$0.20 \pm 0.01^{a,b}$	0.994
	4.0/1.0	79.2 ± 0.2^{e}	0.28 ± 0.01^{a}	0.996	16.2 ± 0.3^{f}	$0.20 \pm 0.01^{a,b}$	0.994
	4.0/1.5	63.5 ± 0.5^{g}	0.24 ± 0.01^{b}	0.987	12.4 ± 0.2^{h}	$0.20 \pm 0.01^{a,b}$	0.993
	4.0/2.0	52.9 ± 0.3^{h}	0.24 ± 0.01^{b}	0.985	9.9 ± 0.1^{j}	$0.20 \pm 0.01^{a,b}$	0.995
CHF/TG	4.0/0.5	121.3 ± 0.1^{b}	0.22 ± 0.01^{b}	0.999	72.8 ± 0.5^{b}	0.21 ± 0.01^{a}	0.997
	4.0/1.0	103.1 ± 0.5^{c}	0.22 ± 0.01^{b}	0.998	83.7 ± 0.5^{a}	0.21 ± 0.01^{a}	0.997
CHF/HPMC	4.0/0.5	102.9 ± 0.4^{c}	0.31 ± 0.01^{a}	0.996	18.3 ± 0.2^{d}	$0.20 \pm 0.01^{a,b}$	0.994
	4.0/1.0	68.6 ± 0.2^{f}	0.31 ± 0.01^{a}	0.996	14.1 ± 0.3^{g}	$0.20 \pm 0.01^{a,b}$	0.994
	4.0/1.5	52.8 ± 0.1^{h}	0.31 ± 0.01^{a}	0.997	10.8 ± 0.2^{i}	$0.20 \pm 0.01^{a,b}$	0.993
	4.0/2.0	44.3 ± 0.4^{i}	0.31 ± 0.01^{a}	0.995	9.0 ± 0.2^{k}	$0.20 \pm 0.01^{a,b}$	0.993

[a] Data are presented as means ± standard deviation. Data value with different superscript letters in columns are significantly different, $p \leq 0.05$.

presence of agglomerates in the doughs which are broken at the highest frequencies. At constant angular frequency no significant variations were noticed in the tan δ values with increasing additive content of HPMC (above 1.0) and for GG. This fact involved the stabilization of viscoelastic behaviour of CF dough over the tested additive concentration range.

Oscillatory data for all doughs were modelled using Eqs. (2) and (3) in the range of angular frequency from 1 to 70 rad s^{-1} showing a good fit ($R^2 > 0.985$ for G' and $R^2 > 0.985$ for G''). The values of oscillatory shear modelling parameters (a', a", b', b") for tested doughs and the corresponding coefficients of determination are featured in Table 3. Values of a' and a" decreased significantly when compared with CS with the presence of hydrocolloid, except for TG. The obtained values are in the range that those previously found for other gluten-free flours as rice flour and slight larger to those reported for wheat flour (Sivaramakrishnan et al., 2004). The slope b' increased when compared with CS by the presence of additives, remaining practically constant with increasing additive content, except for GG where the slope dropped with increasing hydrocolloid content. The largest slope was observed with HPMC addition followed by GG, indicating stronger frequency dependence and interactions between components. This behaviour was reported for other flour doughs enriched in fibre and hydrocolloids (Gómez, Ronda, Blanco, Caballero, & Apesteguía, 2003). Values of b" were invariant with additive content.

The non-linear viscoelastic properties for all doughs at C1 were determined using creep-recovery measures. Different effects achieved with each tested hydrocolloid were found. The obtained trends are in according with those previously reported (Moreira et al., 2011a,b, in press-a) when CHF or hydrocolloids were assayed separately, however the obtained magnitudes are again more pronounced with the simultaneous presence of both additives. The curves shape and $J(t)$ values were in the range (below $0.008 \cdot 1/Pa$) to those found for other gluten-free formulations obtained from rice flour and several hydrocolloids (below $0.005 \cdot 1/Pa$) (Lazaridou et al., 2007), for wheat flour, rice flour and hydrocolloids blends (below $0.02 \cdot 1/Pa$) (Sivaramakrishnan et al., 2004) or those obtained for gluten-free starches batter (below $0.002 \cdot 1/Pa$) (Onyango, Unbehend, & Lindhauer, 2009).

Burgers model, Eqs. (4) and (5), was successfully used to fit ($R^2 > 0.997$ and $s < 0.006$ Pa s) the experimental creep-recovery data for studied doughs and the obtained parameters are in Table 4. The hydrocolloids addition clearly influences the shape of the creep curves. The creep compliance (J_{0C}, J_{mC}, J_{max}) values increased when compared with CS with increasing HMPC content, except for J_{max} at 0.5 g/100 g, f.b. of HPMC. These parameters also increased with TG, but the parameters value dropped with increasing additive content. In the case of GG, each creep compliance value showed a different behaviour, J_{0C} decreased with increasing additive content, J_{mC} showed the opposite trend and J_{max} showed a maximum value between 1.0 and 1.5 g/100 g, f.b. of GG. The γ_{max} ranged from 22.7 to 57.3% and depended on the type and additive content. The most pronounced improvements in comparison to CS (40.2%) were obtained with HPMC (57.3%) at 2.0 g/100 g, f.b. and GG (56.2%) at 1.0 g/100 g, f.b. The values showed the reduction of the dough resistance to deformation. According to the classification reported by Edwards, Dexter, Scanlon, and Cenkowski (1999) for durum wheat doughs, where γ_{max} ranged from <5.0% for the strongest to >25% for the weakest doughs, the classification of tested hydrocolloids as function softening effect was different below (GG > HPMC > TG) and above (HPMC > GG) 1.0 g/100 g, f.b. The presence of TG reduced the elastic properties of doughs and this fact was according to the results found in oscillatory assays where

Table 4
Rheological assessment: parameters of creep-recovery phases modelling, Eqs. (4) and (5) at 30 °C for for chestnut flour doughs without (CF) and with (CS) chia flour (CHF) and hydrocolloids (guar (GG), tragacanth (TG) or HPMC).[a]

Tests	Parameters		CHF (g/100 g, f.b.)	CHF/GG (g/100 g, f.b.)				CHF/TG (g/100 g, f.b.)		CHF/HPMC (g/100 g, f.b.)			
		CF	4.0	0.5	1.0	1.5	2.0	0.5	1.0	1.5	2.0	0.5	1.0
Creep phase	J_{0C} (1/Pa) 10^5	27.1 ± 0.4^{e}	1.9 ± 0.1^{i}	28.1 ± 0.5^{e}	22.9 ± 0.3^{f}	18.7 ± 0.2^{g}	9.1 ± 0.1^{h}	58.7 ± 0.3^{a}	30.2 ± 0.2^{d}	23.0 ± 0.3^{f}	29.5 ± 0.5^{e}	36.7 ± 0.3^{c}	46.2 ± 0.4^{b}
	J_{mc} (1/Pa) 10^5	110.8 ± 0.3^{i}	368.1 ± 0.6^{e}	285.7 ± 0.5^{g}	359.2 ± 0.6^{f}	382.2 ± 0.4^{d}	405.8 ± 0.6^{c}	425.1 ± 0.8^{b}	260.2 ± 0.7^{h}	372.0 ± 0.5^{e}	401.9 ± 0.5^{c}	420.9 ± 0.6^{b}	445.6 ± 0.5^{a}
	λ_C (s)	3.9 ± 0.1^{f}	12.8 ± 0.3^{b}	3.4 ± 0.2^{g}	2.9 ± 0.3^{g}	2.7 ± 0.2^{g}	$2.5 \pm 0.2^{g,h}$	3.1 ± 0.1^{g}	3.3 ± 0.2^{g}	8.7 ± 0.1^{e}	9.9 ± 0.1^{d}	10.4 ± 0.1^{c}	11.6 ± 0.1^{b}
	η_{0C} (Pa s) 10^{-3}	18.5 ± 0.3^{c}	$13.7 \pm 0.3^{e,f}$	10.2 ± 0.2^{g}	8.1 ± 0.1^{h}	18.6 ± 0.4^{c}	20.3 ± 0.3^{b}	18.0 ± 0.2^{c}	21.7 ± 0.3^{a}	15.7 ± 0.1^{d}	14.1 ± 0.2^{e}	12.4 ± 0.3^{f}	10.3 ± 0.2^{g}
	J_{max} (1/Pa) 10^5	453.1 ± 0.4^{l}	804.1 ± 0.5^{g}	903.7 ± 0.5^{d}	1124.6 ± 1.8^{a}	723.8 ± 0.5^{j}	711.1 ± 0.6^{k}	816.9 ± 0.6^{f}	762.8 ± 0.6^{i}	781.7 ± 0.6^{h}	856.6 ± 0.5^{e}	940.3 ± 0.9^{c}	1074.2 ± 1.3^{b}
	γ_{max} (%)	22.7 ± 0.1^{k}	40.2 ± 0.1^{f}	45.2 ± 0.1^{d}	56.2 ± 0.2^{b}	36.2 ± 0.1^{i}	35.6 ± 0.1^{j}	40.8 ± 0.1^{f}	38.1 ± 0.1^{h}	39.1 ± 0.1^{g}	42.8 ± 0.1^{e}	47.0 ± 0.1^{c}	57.3 ± 0.1^{a}
	R^2	0.999	0.999	0.999	0.998	0.998	0.998	0.997	0.999	0.999	0.999	0.998	0.997
	s (1/Pa)	0.004	0.004	0.004	0.005	0.005	0.005	0.006	0.004	0.004	0.004	0.005	0.006
Recovery phase	J_{0R} (1/Pa) 10^5	95.7 ± 0.2^{j}	17.4 ± 0.2^{l}	139.9 ± 0.7^{f}	243.7 ± 0.6^{a}	211.8 ± 0.9^{b}	189.9 ± 0.8^{c}	71.8 ± 0.3^{k}	123.9 ± 0.6^{i}	128.8 ± 0.6^{h}	135.7 ± 0.6^{g}	150.7 ± 0.4^{e}	171.1 ± 0.8^{d}
	J_{mR} (1/Pa) 10^5	9.1 ± 0.2^{l}	364.1 ± 1.2^{e}	296.2 ± 0.8^{f}	498.2 ± 1.3^{b}	235.1 ± 0.8^{i}	240.1 ± 0.6^{h}	260.5 ± 0.7^{g}	225.2 ± 0.7^{j}	221.4 ± 0.9^{k}	386.3 ± 0.7^{d}	440.1 ± 0.9^{c}	525.3 ± 0.9^{a}
	λ_R (s)	0.8 ± 0.1^{h}	43.1 ± 0.4^{g}	59.7 ± 0.3^{b}	63.2 ± 0.2^{a}	58.1 ± 0.2^{c}	56.4 ± 0.1^{e}	56.3 ± 0.2^{e}	58.4 ± 0.2^{c}	58.4 ± 0.2^{c}	57.3 ± 0.9^{c}	53.4 ± 0.5^{f}	56.2 ± 0.4^{e}
	R^2	0.998	0.998	0.998	0.998	0.997	0.997	0.997	0.998	0.999	0.999	0.997	0.997
	s (1/Pa)	0.005	0.005	0.005	0.005	0.006	0.006	0.006	0.005	0.004	0.004	0.006	0.006

[a] Data are presented as means ± standard deviation. Data value with different superscript letters in rows are significantly different, $p \le 0.05$.

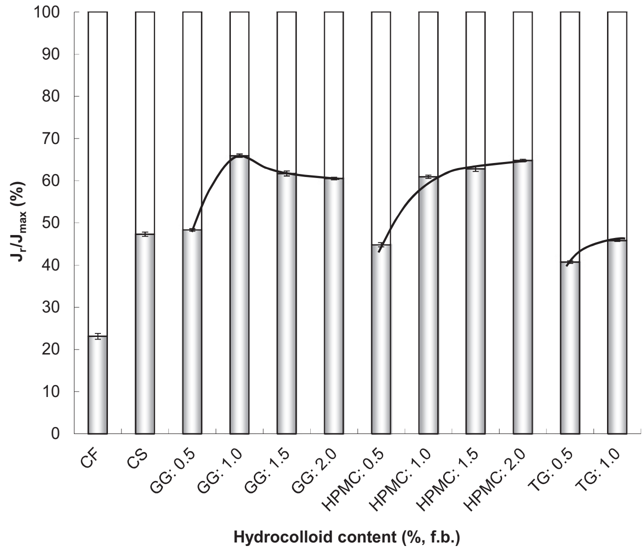

Fig. 4. Effect of the tested additives on the J_r/J_{max} during recovery phase of creep tests for chestnut flour dough without (CF) and with chia flour (CS) at 4.0 g/100 g, f.b. combined with hydrocolloids at several amounts (0.5, 1.0, 1.5, 2.0 g/100 g, f.b.): guar gum (GG), HPMC and tragacanth gum (TG).

TG increased tan δ values. The lowest elasticity values were found for this gum in creep-recovery tests.

Creep retardation time, λ_C, decreased significantly when compared with CS with tested hydrocolloids, increasing with increasing HPMC content and remained practically constant with increasing TG or GG. Likewise, the flow resistance, η_{0C}, dropped with increasing GG amount below 1.0 g/100 g, f.b. and HPMC at 2.0 g/100 g, f.b.; the opposite trend was observed in other conditions. Therefore, the viscosity parameter values followed the order of GG < HPMC < TG below 1.0 g/100 g, f.b. in similar way as it was previously found for steady-shear flow measurements.

Significant variations were found in recovery compliance values (J_{0R} and J_{mR}) with tested additives. Specifically, J_{0R} increased significantly in relation to CS with all studied hydrocolloids. J_{mR} also increased significantly when compared with CS, except for doughs with HPMC above 1.0 g/100 g, f.b. and GG at 1.0 g/100 g f.b.

The retardation times, λ_R, increased when compared with CS for all assayed additives, and increased with increasing hydrocolloid content except for CHF/GG below 1.0 g/100 g, f.b. where a threshold value was again found. High values of λ_R by the presence of additives meant that the retarded elastic recovery of dough was slower. Furthermore, CF doughs at same hydrocolloid content (1.0 g/100 g, f.b.) with larger λ_R values showed lower WA values.

J_r/J_{max} ratio gives information about the elasticity of CF dough. Low value was achieved for CF (22.3%) and it was improved significantly with the presence of tested additives in a different way depending on type and content of additive (Fig. 4). Specifically, doughs with CHF/GG (65.9% at 1.0 g/100 g, f.b.) exhibited the most pronounced elastic properties followed by CHF/HPMC (64.8% at 2.0 g/100 g, f.b.) and CHF/TG (45.8% at 1.0 g/100 g, f.b.). J_r/J_{max} increased with increasing additive content except for GG, where a threshold at 1.0 g/100 g, f.b. of hydrocolloid content was found; this result was already reported when GG was added separately (Moreira et al., 2011b). Higher J_r/J_{max} values are related to lower tan δ values. The obtained elasticity values for GG at 4.0/1.0 g/100 g, f.b. and HPMC 4.0/2.0 g/100 g, f.b. were in the same range to those reported for wheat flours that are around 65% (Wang & Sun, 2002), TG addition also involved a positive improvement on the elastic properties of CF doughs.

3.3. Thermal behaviour

Table 5 shows the values of the main characteristic parameters (C2, C3, C4, C5, α, β, γ_e) for studied doughs obtained using Mixolab® complete tests. Particularly, no significant differences were identified in C2 and C3 values with TG addition, whereas both parameters increased significantly when compared with CS with HPMC and GG addition. Conversely, C4 values decreased significantly with the presence of TG and increased with HPMC and GG when compared with CS, remaining practically constant with increasing GG and HPMC amount. The presence of GG and TG showed a slight reduction in C5 values. The reduction in C5 values with tested additives usually involved lower starch retrogradation (Rosell et al., 2007; Santos, Rosell, & Collar, 2008). Additionally, C4/C3 ratio was reduced with all studied additives (from 1.0 to 1.05) in relation to CS (1.13). Doughs with hydrocolloids showed C4/C3 values within the range previously reported for soft (1.02) and hard (1.05) wheat flours (Moreira, Chenlo, Torres & Prieto, in press-b).

Concerning proteins network weakening rate (Table 5), $-\alpha$, this slope values dropped significantly when compared with CS with hydrocolloids addition, although without significant variations with increasing GG and HPMC above 1.0 g/100 g, f.b. and TG in studied concentration range. The enzymatic activity rate, γ_e, values showed similar behaviour with increasing hydrocolloid content, except for TG where dropped significantly with increasing TG

Table 5
Thermal behaviour assessment: parameters values evaluated during complete tests for chestnut flour doughs without (CF) and with (CS) chia flour (CHF) and hydrocolloids (guar (GG), tragacanth (TG) or HPMC) on the target consistency value (C1: 1.10 ± 0.07 Nm).[a]

Additives	w/w (g/100 g, f.b.)	C2 (Nm)	C3 (Nm)	C4 (Nm)	C5 (Nm)	$-\alpha$ (Nm/min)	β (Nm/min)	γ_e (Nm/min)	T_0–T_1 (°C)
-, CF		$0.69 \pm 0.01^{a,b}$	2.01 ± 0.02^{a}	2.28 ± 0.03^{a}	2.84 ± 0.03^{a}	0.039 ± 0.002^{a}	$0.39 \pm 0.01^{c,d}$	0.044 ± 0.002^{a}	69.1^{b}–79.5^{b}
CHF (CS)	4.0	$0.64 \pm 0.02^{c,d}$	1.82 ± 0.03^{b}	1.88 ± 0.05^{c}	2.36 ± 0.01^{c}	0.044 ± 0.004^{a}	$0.41 \pm 0.02^{b,c}$	0.002 ± 0.001^{e}	71.7^{a}–84.8^{a}
CHF/GG	4.0/0.5	0.71 ± 0.01^{a}	1.96 ± 0.01^{a}	2.05 ± 0.03^{b}	2.47 ± 0.02^{b}	0.032 ± 0.001^{b}	$0.40 \pm 0.02^{c,d}$	0.015 ± 0.001^{b}	$68.8^{b,c}$–79.1^{c}
	4.0/1.0	0.71 ± 0.01^{a}	2.00 ± 0.02^{a}	2.02 ± 0.01^{b}	2.31 ± 0.01^{d}	$0.029 \pm 0.001^{b,c,d}$	0.45 ± 0.01^{a}	0.002 ± 0.000^{e}	67.7^{e}–78.5^{d}
	4.0/1.5	0.70 ± 0.01^{a}	2.01 ± 0.02^{a}	2.01 ± 0.02^{b}	2.30 ± 0.01^{d}	$0.029 \pm 0.001^{b,c,d}$	0.45 ± 0.01^{a}	0.001 ± 0.000^{e}	$67.1^{f,g}$–77.9^{c}
	4.0/2.0	$0.69 \pm 0.01^{a,b}$	2.01 ± 0.02^{a}	2.01 ± 0.01^{b}	2.30 ± 0.01^{d}	$0.028 \pm 0.001^{c,d}$	0.45 ± 0.01^{a}	0.001 ± 0.000^{e}	66.2^{h}–77.1^{f}
CHF/TG	4.0/0.5	$0.63 \pm 0.01^{c,d}$	1.84 ± 0.01^{b}	1.92 ± 0.02^{c}	$2.42 \pm 0.02^{b,c}$	$0.028 \pm 0.001^{c,d}$	$0.39 \pm 0.01^{c,d}$	0.016 ± 0.001^{b}	$68.5^{c,d}$–79.1^{c}
	4.0/1.0	0.62 ± 0.01^{d}	1.77 ± 0.02^{c}	1.81 ± 0.03^{d}	2.22 ± 0.04^{e}	0.027 ± 0.001^{d}	$0.44 \pm 0.01^{a,b}$	0.003 ± 0.001^{d}	67.6^{e}–78.5^{d}
CHF/HPMC	4.0/0.5	0.70 ± 0.01^{a}	1.97 ± 0.02^{a}	2.04 ± 0.02^{b}	$2.44 \pm 0.01^{b,c}$	0.032 ± 0.001^{b}	0.37 ± 0.01^{d}	0.012 ± 0.001^{c}	68.2^{d}–$79.0^{c,d}$
	4.0/1.0	$0.69 \pm 0.01^{a,b}$	1.99 ± 0.02^{a}	2.04 ± 0.03^{b}	2.39 ± 0.01^{c}	0.032 ± 0.001^{b}	$0.41 \pm 0.01^{b,c}$	0.006 ± 0.000^{d}	$67.4^{e,f}$–$78.2^{d,e}$
	4.0/1.5	$0.68 \pm 0.01^{a,b}$	2.00 ± 0.02^{a}	2.03 ± 0.03^{b}	2.39 ± 0.01^{c}	$0.031 \pm 0.001^{b,c}$	$0.41 \pm 0.01^{b,c}$	0.006 ± 0.001^{d}	66.8^{g}–77.3^{f}
	4.0/2.0	$0.66 \pm 0.01^{b,c}$	2.00 ± 0.01^{a}	2.03 ± 0.02^{b}	2.39 ± 0.01^{c}	$0.031 \pm 0.001^{b,c}$	$0.41 \pm 0.01^{b,c}$	0.006 ± 0.001^{d}	65.1^{i}–76.1^{g}

[a] Data are presented as means ± standard deviation. Data value with different superscript letters in columns are significantly different, $p \leq 0.05$. C2 (related to proteins weakening), C3 (related to starch gelatinization), C4 (cooking stability), C5 (related to retrogradation), α (proteins network weakening rate), β (gelatinization rate), γ_e (enzymatic activity rate), T_0–T_1 (gelatinization temperature range).

content. CS with GG, HPMC and TG at 1.0 g/100 g, f.b. exhibited γ_e values within the range to those found for soft wheat flours (Moreira et al., in press-b). The β slope value increased significantly in comparison to CS with GG above 1.0 g/100 g, f.b., remained practically constant with increasing hydrocolloid amount. The presence the TG increased the gelatinization rate when compared with CS at 1.0 g/100 g, f.b. The largest increase in the β slope magnitude was identified with GG addition. Complete tests also indicated that additives decreased the initial (T_0) and final (T_1) gelatinization temperature, achieving the largest effects with HPMC addition. Even so, analysing jointly two properties (mixing and thermal behaviour) the best effects on baking stability of CF doughs were achieved with CHF/GG at 1.0 g/100 g, f.b. and CHF/HPMC at 2.0 g/100 g, f.b.

4. Conclusions

Mixing and thermal properties of CF doughs were significantly improved with the presence of CHF combined with GG, HPMC or TG. The assayed additives increased positively the water absorption of doughs. The presence of GG and HPMC increased positively the stability of CS doughs. The apparent viscosity, storage and loss moduli dropped significantly with additives, except for TG where loss moduli increased. The studied additives also decreased the non-recoverable fraction of CS during the creep-recovery tests, being the most significant improvement observed with GG and HPMC addition. Pasting properties of CF doughs were promoted with the combined effect of CHF and hydrocolloids. The stability to baking and enzymatic activity speed for the CF doughs with CHF combined with GG, HPMC or TG at 1.0 g/100 g, f.b. showed close values to those of wheat flour. The combination of CHF at 4.0 g/100 g, f.b. with GG at 1.0 g/100 g, f.b. or HPMC at 2.0 g/100 g, f.b. provided the best results to improve the CF dough properties, since that the apparent viscosity was lower and the stability and elasticity increased.

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