Effect of sodium chloride, sucrose and chestnut starch on rheological properties of chestnut flour doughs

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Abstract

The influence of the addition of NaCl (0.6, 1.2, 1.8%, w/w), sucrose (0.6, 1.8, 3.4, 5.0%, w/w), chestnut starch (5.0, 10.0, 15.0%, w/w) and NaCl-sucrose mixtures (0.6-0.6, 1.8-1.8%, w/w) on the rheological properties of chestnut flour (CF) doughs were studied using a controlled stress rheometer. Mixing and complete tests were achieved by the Mixolab® apparatus. Shear (0.01 to 10 s^{-1}), oscillation (1 to 100 rad s^{-1}), temperature sweep (30 to 100ºC) and creep-recovery (loading of 50 Pa) measurements were performed. Steady-flow curves exhibited a Newtonian plateau at <0.1 s^{-1} that was shifted to lower shear rates with the additives. Apparent viscosities were satisfactorily fitted using Cross model. Moduli values of storage and loss decreased, at constant angular frequency, with increasing additives. Gelatinization temperatures were slightly modified. Creep-recovery data, that were fitted using Burgers model, showed that elasticity was low (23.0%) and doughs with chestnut starch presented the highest recoverable proportion (45.6%).

Keywords: Steady shear curves, viscoelasticity, gelatinization, creep, mixing, chestnut starch.

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1. Introduction

The development of new gluten-free bakery products of high quality that are suitable for people with celiac disease is necessary, since there are more intolerant people to wheat proteins (Ronda, Gómez, Caballero, Oliete, & Blanco, 2009). Chestnut flour (CF), that is gluten-free, could be employed in these special diets. CF is also a good source of essential fatty acids (Borges, Carvalho, Correia, & Silva, 2007). The main disadvantage of the CF doughs is the low protein content and the absence of proteins with viscoelastic properties like gluten. However, additives and processing procedures can modify significantly the rheological characteristics of doughs (Yu & Ngadi, 2006).

The main techniques used for measuring doughs properties can be classified as empirical or fundamental. Empirical tests are traditionally carried out by means of farinograph, rapid visco analyzer (RVA), among others, and multifunctional new apparatus like Mixolab® (Jansen, van Vliet, & Vereijken, 1996). In recent years, several fundamental rheological measurements to monitoring fundamental viscoelastic properties of dough with or without additives have been used employing rheometers. In particular, shear measurements are used to evaluate the effect of mixing and type of flour on dough properties, oscillation measurements are a powerful tool for examining the fundamental viscoelastic properties of dough and creep-recovery tests are useful to establish relations with measurements carried out by empirical techniques (Campos, Steffe, & Perry, 1997; Keentok, Newberry, Gras, Bekes, & Tanner, 2002; Salvador, Sanz, & Fiszman, 2006). Empirical and fundamental properties of wheat flour doughs with additives were studied by several authors (Maache-Rezzoug, Boouvier, Allaf, & Patras, 1998; Lynch, Dall Bello, Sheehan, Cashman, & Arendt, 2009). It is necessary to understand the functions and interactions of the ingredients on doughs, such as salt (sodium chloride) and sugar (sucrose), to improve the rheological properties and storage stability of the derived products (Sumnu, Ndife, & Baymdirh, 1999).

The presence of sodium chloride (NaCl), which is generally used at concentrations below 2% (flour basis, f.b.), plays an important role on dough properties. Salt acts as a flavour enhancer, toughens the protein and improves the dough tolerance to mixing (Butow, Gras, Haraszi, & Bekes, 2002). Some authors indicated that salt increases dough development time and its stability (Angioloni & Dalla Rosa, 2005; Miller & Hoseney, 2008). However, fundamental rheology has been recently used to describe the salt effect on dough with opposite results, founding for wheat flour a slight reduction in the viscoelastic moduli (Larsson, 2002; Wu, Beta, & Clarke, 2006; Salvador et al., 2006). This behaviour was explained by decreasing of the inter-chain hydrophobic interactions of proteins (Melander & Horváth, 1977). These differences could be caused by the different characteristics of materials, (i.e. the moisture content and flour type), mixer types and process conditions. Salts, depending on their nature and concentration, can cause either an elevation or a depression of the gelatinization temperature, and similarly, increase or decrease the retrogradation. Salt effect on gelatinization is certainly different and more complex than the one of non ionic solutes, as sucrose (Chiotelli, Pilosio, & Le Meste, 2002).

The sucrose effect is other important factor on dough behaviour (Maache-Rezzoug et al., 1998). Sugar is mainly employed in pastrymaking and optionally in breadmaking to improve nutritional, sensory and keeping quality of products (Singh, Bajaj, Singh, & Gujral, 2002). This additive affects flavour, dimensions, colour, hardness and surface finish. In excess, sugar causes a dough softening, due partially to the competition between the added sugar and the available water in the system (Gallagher, O'Brien, Scannell, & Arendt, 2003). Sugar makes the product fragile, since it tends to disperse the protein and starch molecules, thereby preventing the formation of a continuous mass (Maache-Rezzoug et al., 1998). Mizukoshi (1985) reported the existence of a threshold shear modulus value associated with the variation of sugar content (30-40%) on the dough. Sugars affect significantly the retrogradation depending on the sugar and starch types (Chang, Lim, & Yoo, 2004). Sugars delay starch gelatinization by increasing the gelatinization temperature (Mezreb, Goullieux, Ralainiria, & Queneudec, 2006). This behaviour was explained as result from the reduction of the water activity of the system due to the action of sugars as well as related to interactions among the sugars and the starch chains (Sumnu et al., 1999).

Nowadays, low sugar content in the diet is a recommendation (Singh & Mohamed, 2007). CF products are high in sucrose, so the decrease in sugar contents would facilitate the opening of new markets. Sugar content can be reduced by the addition of other components like starch. The addition of potato starch (0-7.5%) to noodles doughs showed a positive influence on its rheological properties (Yu & Ngadi, 2006). The partial substitution of rice flour by pregelatinizated corn starch also improved the quality of gluten-free cakes (Ronda et al., 2009).

The main aims of this work were to prepare CF doughs with different concentrations of sodium chloride, sucrose and chestnut starch using Mixolab® and to study their rheological properties by steady-shear, oscillatory, temperature sweep and creep-recovery tests. The influence of adding sodium chloride and sucrose mixtures on the rheological behaviour of CF doughs is also discussed. The study of the rheological properties of these systems, for which data are not available in the literature, is of industrial and scientific interest.

2. Materials and Methods

2.1. Raw materials

Commercial chestnut flour with a moisture content of 9.1 ± 0.3% (dry basis, d.b.) (ICC-Standard Methods No.110/1, 2008) was considered as control sample. Chemical composition (%, d.b.) of the main components of the CF was obtained. The starch (67.4 ± 8.8), protein (6.3 ± 0.1), fibre (3.8 ± 1.6) and fat (1.8 ± 0.1) contents were determined in triplicates following the AOAC approved methods No. 996.11, 979.09, 992.16 and 948.22, respectively (AOAC, 1995). Sugars (20.7 ± 3.4) content was also determined by triplicate using high-performance liquid chromatography (HPLC) following the method applied for chestnuts by Míguez-Bernárdez, De la Montaña-Miguélez, & García-Queijeiro (2004).

Doughs of CF with several concentrations (% f.b.) of NaCl (0.6, 1.2, 1.8), sucrose (0.6, 1.8, 3.4, 5.0) and chestnut starch (5.0, 10.0, 15.0) were prepared separately to evaluate the concentration effect of each ingredient on the rheological properties. Samples with NaCl-sucrose mixtures (0.6-0.6, 1.8-1.8) were also prepared. Table sodium chloride and sucrose were employed. However, chestnut starch was extracted from fresh chestnuts using a quantity of 300g of CF that was mixed with 600 mL of distilled water (ratio 1:2) following the method employed and described in detail by Moreira, Chenlo, Torres, & Prieto (2010a).

2.2. Empirical techniques: Mixolab® characterization

The preparation and characterization of the doughs was according to the standard method (ICC-Standard Method No. 173, 2008). Two different assays were performed by Mixolab® (Chopin Technologies, France). The first one, mixing test, consist of dough mixing at constant mixing rate during 30 min at 30 ºC and gives similar information on dough behaviour to that experiments carried out with farinograph. The second one, complete test, after a shorter (8 min) mixing step, involves a heating-cooling cycle (37 min) and gives similar information to that the experiments carried out by RVA. In both tests, CF with the corresponding additive was placed into the Mixolab® bowl, mixed at 80 rpm for sample homogenization and heated up to 30 ºC. At this moment, the apparatus adds distilled water to achieve pre-fixed hydration (f.b., corrected to 14% moisture basis). The total mass of flour and distilled water placed into bowl was 75 g. Several preliminary mixing tests were necessary to determine the optimum hydration level to reach the maximum consistency of dough (C1: 1.1 Nm) (Rosell, Collar, & Haros, 2007). Complete test has been used after determination of the optimum hydration level to characterize the dough properties as function of mixing and temperature. All assays were carried out by triplicate and the corresponding standard deviations, s, were calculated. The main parameters obtained from Mixolab® tests were previously reported (Rosell et al., 2007; Moreira, Chenlo, Torres, & Prieto, 2010b).

2.3. Fundamental techniques: Rheological characterization

Rheological measurements were determined by a controlled stress rheometer (MCR 301, Anton Paar Physica, Austria). The measurement system consisted of parallel plate geometry (50 mm diameter, 2 mm gap). Temperature was 30.00 ± 0.01ºC (Peltier system). The CF dough, previously prepared using Mixolab® up to reach C1, was placed between the plates. The rim of the sample was coated with paraffin (Panreac

Química S.A.) to prevent evaporation during the measurements. A rest time of 15 min was applied to all samples before measuring. Three replicates of each measurement were made and the corresponding standard deviations, s, were calculated.

2.3.1. Steady-shear flow tests

Shear tests were performed in controlled-stress mode over the range of shear rates from 0.01 to 10 s^{-1}. The shear rate range was limited to allow the shear measurements (≥0.01 s^{-1}) and to avoid problems of sample loss (≤10 s^{-1}). Steady-shear flow data were fitted by Cross model (Cross, 1965):

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

where η (Pa s) is the apparent viscosity; $\dot{\gamma}$ (s^{-1}) is the shear rate; 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.

2.3.2. Oscillatory shear tests

Strain sweep at standard frequency of 6.28 rad s^{-1} (1 Hz) were previously carried out to determine the linear viscoelastic zone below 1% strain, γ. Frequency sweep tests were performed from 1 to 100 rad s^{-1} at 0.1% strain value to determine the storage, G', and loss, G'', moduli (Pa). Experimental G' and G'' were fitted by the following equations:

$$\log G' = \log a' + b' \log \omega \qquad (2)$$

$$\log G'' = \log a'' + b'' \log \omega \qquad (3)$$

where ω (rad s^{-1}) is the angular frequency and a', a'', b' and b'' are the corresponding fitting parameters.

2.3.3. Creep-recovery tests

Creep-recovery tests were carried out applying on the dough a constant stress, σ (50 Pa) during 60 s out of linear viscoelastic region and allowing strain recovery in 180 s after removal of load, $\sigma = 0$ Pa. Creep data was described with creep compliance rheological parameters, J(t) (1/Pa) = γ/σ where σ is the constant stress during creep test (Steffe, 1996). Compliance curve data of CF dough systems were fitted to the Burgers model (Burgers, 1935) by the following equations for creep and recovery phase, respectively:

$$J(t) = J_0 + J_m(1 - \exp(-t/\lambda)) + t/\eta_0 \qquad (4)$$

$$J(t) = J_{max} - J_0 - J_m(1 - \exp(-t/\lambda)) \qquad (5)$$

where J_0 (1/Pa) is the instantaneous compliance, J_m (1/Pa) is the viscoelastic compliance, t (s) is the phase time, λ (s) is mean retardation time, η_o (Pa s) is the zero shear viscosity and J_{max} (1/Pa) is the maximum creep compliance. The recovery compliance, J_r (1/Pa) is calculated by the sum of J_0 and J_m corresponding to recovery phase, Eq. (5). The J_r/J_{max} ratio gives information on relative elastic part of the maximum creep compliance.

2.3.4. Temperature sweep tests

Doughs were heated from 30 to 90 ºC at constant rate of 4 ºC/min in the rheometer cell. The assays were performed at strain of 0.1% and frequency of 6.28 rad s^{-1} (1 Hz). These tests allowed to determine the gelatinization temperatures range (T_0 - T_1) and to establish a comparison with data obtained using Mixolab®. The rate of weakening of proteins (-α) and gelatinization (β) were calculated as the slope before T_0 and between T_0 and T_1, respectively.

2.4 Statistical analysis

The influence of additive concentrations on the rheological properties of CF doughs was compared. Differences among means were identified by one-factor analysis of variance (ANOVA), followed by the Duncan test ($p \leq 0.05$), (SPSS 18.0 statistical package).

3. Results and discussion

3.1. Mixolab® mixing tests

The influence of NaCl, sucrose, chestnut starch or mixtures of NaCl-sucrose addition on CF dough mixing properties at maximum torque value (C1: 1.10 ± 0.07 Nm) was determined using mixing tests at 30ºC, following the aforementioned protocol. The main mixing parameters, water absorption (WA), development time and stability, are given in Table 1. Torque in all studied doughs initially increased with mixing time until to reach C1, whose value depended on the WA. The WA of CF dough was significantly affected by addition of NaCl above 1.2%, sucrose above 3.4% and chestnut starch in all assayed contents range. The WA increased with increasing NaCl and chestnut starch concentration. This effect can be related to the high hygroscopic character of these additives. Nevertheless, it has been reported previously that the addition of NaCl on wheat flour doughs decreased WA (Hlynka, 1962), but also the presence of other salts (NaBr, NaI) gave higher WA values (Preston, 1989). Sucrose had the opposite effect, WA of CF doughs slightly decreased with increasing sugar concentration. This behaviour is restricted in this type of flour because sugar content of CF is originally high and it can inhibit the granular starch hydration and involve sucrose-starch interactions (Sacchetti, Pinnavaia, Guidolin, & Dalla Rosa, 2004).

High concentrations of NaCl (above 1.2%) increased significantly the development time and stability of CF, which is in agreement with previous studies for wheat flour (Hlynka 1962; Preston, 1989; Singh et al., 2002). Doughs with salt addition showed the highest development time and stability at the consistency of 1.1 Nm. High stability values are usually related to the strength of flours (Marco & Rosell, 2008). Development time of CF without additives were significantly reduced (from 4.7 to 2.0 min) by adding of chestnut starch, but unfortunately shorter stability times (from 12.2 to 1.6 min) were also found, indicating that this dough was less tolerant to mixing than the other assayed systems (Galal, Varriano-Marston, & Johnson, 1978). However, the development time and stability of doughs fortified with chestnut starch at different levels (5.0% to 15.0%) did not presented significantly differences. In the case of sucrose, development times and stability were only significantly different at 5.0% regarding to the obtained values for CF without additives. Both parameters decreased with increasing sugar content, indicating a softening of dough regarding to CF without additives. The WA, development time and stability of CF showed no significant differences when NaCl-sucrose mixtures were added. The original dough mixing profile (CF without additives) could be achieved by adding NaCl-sucrose mixtures with the same proportion (0.6-0.6 or 1.8-1.8). In all studied systems once the period of dough stability finished, the torque began to decrease because dough became less elastic, stickier, and lost gas holding properties (Levine & Boehmer, 1997).

3.2. Rheometer measurements

3.2.1 Steady-shear tests

All CF doughs at the maximum consistency (C1) obtained previously by Mixolab® were rheologically characterized at 30 ºC at different shear rates (0.01 to 10 s^{-1}). Fig. 1 shows the steady shear flow curves for CF doughs without additives and with the tested maximum amounts of NaCl (1.8%), sucrose (5.0%) and NaCl-sucrose mixtures (1.8-1.8%). CF doughs exhibited shear-thinning behaviour. Apparent viscosity of all assayed CF doughs decreased with increasing shear rate above certain values of shear rate as function of the type and concentration of additives. The apparent viscosity of CF doughs with sucrose showed the highest decreasing in apparent viscosity regarding to CF without additives in the whole range. NaCl and NaCl-sucrose mixtures also decreased the apparent viscosity at each shear rate regarding to CF without additives. In CF dough with maximum additives concentrations the Newtonian plateau is only observed at low shear rates (close to 0.01 s^{-1}). It may be hypothesised that the addition of the maximum amounts of all studied additives can result in higher flow ability during dough preparation and handling. The Newtonian plateau η_0 (at low shear rate < 0.1 s^{-1}) was shifted to lower shear rates by increasing of NaCl, sucrose, NaCl-sucrose mixtures (data not shown). The presence of Newtonian plateau at low shear rates (10^{-5} s^{-1}) was reported for wheat flour doughs (Rouillé, Della Vallea, Lefebvrea, & Sliwinskic, 2005) and also was previously identified for other gluten-free doughs like chickpea flour (Ravi & Bhattacharya, 2004).

Fig. 2 shows the flow curves for CF doughs without additives and with tested chestnut starch concentrations (5.0, 10.0, 15.0%). CF doughs with chestnut starch addition also exhibited shear-thinning behaviour. The influence of chestnut starch addition can be noticed above values of shear rate higher than 0.1 s^{-1} and particularly showed the highest differences regarding to CF without additives at shear rates from 1 to 10 s^{-1}. Apparent viscosity remains practically constant with chestnut starch addition below 0.1

s^{-1} shear rate and it decreased with increasing additives concentration at constant shear rate above 0.1 s^{-1}.

The flow curves for all assayed doughs were satisfactorily fitted ($R^2 > 0.987$ and $s < 0.012$ Pa s) using the Cross model, Eq. (1). Table 2 shows the Cross model parameters and statistical parameters of fitting for all assayed doughs. The values of time constant, k, of all studied systems increased significantly with increasing additives concentrations. An increase in k values with the presence of additives indicated a higher rate of breakdown of agglomerated structure (Ravi & Bhattacharya, 2004). The values of the flow index, n, increased regarding to CF with addition of NaCl, sucrose and chestnut starch. Doughs with the highest additives concentration showed higher n values, however n values did not varied significantly at high concentration of additives, meaning that the CF doughs did not varied significantly the pseudoplastic behaviour when salt (1.2 or 1.8%), sucrose (1.8, 3.4 or 5.0%) or chestnut starch (10.0 or 15.0%) was added. The values of the flow index, n, can be considered low (from 0.10 to 0.29) for all doughs indicating the strong shear-thinning character of the samples. Also, wheat flour doughs were previously fitted using Cross model and reported n values are in a similar range (from 0.03 to 0.20) (Rouillé et al., 2005). With the additives used in the present study η_0 value varied in a restricted range (204.6-253.8 10^3 Pa s). Salt and chestnut starch increased slightly the η_0 value regarding to CF dough without additives, while sucrose imparted a reverse trend above 1.8% of concentration. The η_∞ values decreased significantly with increasing additives amounts. A marked decrease in η_∞ can indicate that high shearing disrupts the agglomerated structure (Ravi & Bhattacharya, 2004). Regarding to k, n, η_0 and η_∞ values for the studied CF doughs with NaCl-sucrose mixtures showed intermediate values among flours with NaCl and sucrose added at the same level. In fact, all these parameters can be successfully evaluated with the Cross model parameters of doughs with alone NaCl or sucrose according to:

$$\left(k,n,\eta_0,\eta_\infty\right)_{\text{NaCl-sucrose mixtures}} = \sum_{i=1}^{2} x_i \varepsilon_i \qquad (6)$$

where x_i is the weight ratio between each component concentration (NaCl or sucrose) and total additive concentration (NaCl plus sucrose) on doughs and ε_i represents the k, n, η_0 and η_∞ parameters values for CF doughs with alone NaCl and sucrose. This relationship allows the estimation by Cross model of apparent viscosity of CF doughs with NaCl-sucrose mixtures between 0.6 and 1.8% from apparent viscosity values of CF doughs fortified with sucrose or sodium chloride.

3.2.2. Oscillatory tests

The effects of NaCl, sucrose and chestnut starch addition regarding to CF without additives at 30ºC on the evolution of storage or elastic (G') and loss or viscous (G'') moduli values with frequency is shown in Fig. 3, 4 and 5, respectively. All tested doughs systems, as expected, showed G' > G'' throughout the frequency range indicating a gel structure. G' and G'' values slightly increased with increasing angular frequency from 1 to 100 rad s^{-1}. The slightly increase can be attributed to the absence of binding agents like gluten in the CF dough (Sivaramakrishnan, Senge, & Chattopadhyay, 2004). Doughs with chestnut starch addition showed the highest slopes of G' with angular frequency and this behaviour could be attributed to the fact that starch is a hydrocolloid that exhibits similar characteristics to gums (Yu & Ngadi, 2006). The increasing of G' and G'' slope values with addition of hydrocolloid was previously reported for rice flour doughs (Sivaramakrishnan et al., 2004).

Both moduli for all assayed doughs decreased with increasing additives amount at constant angular frequency. The reduction of G' and G" with increasing NaCl and sucrose addition are in accordance with those reported by Salvador et al. (2006) and Angioloni & Dalla-Rosa (2004) for wheat flour doughs, while Yu & Ngadi (2006) reported that G' increases with increasing starch addition. However, slight changes were observed in the slope of both moduli with increasing frequency or the relative contribution of the both elastic and viscous components (tan δ) and consequently the viscoelastic behaviour of the systems with NaCl, sucrose and NaCl-sucrose remain practically constant. In all assayed range of frequency for these additives the tan δ values increased from 0.18±0.01 for 1 rad s^{-1} to 0.21±0.01 for 70 rad s^{-1}. These constant tan δ values mean that doughs exhibit the same degree of cross-linking and that no major structural changes take place with the addition of NaCl and sucrose. This effect was previously reported for wheat noodle dough system with salt (Wu et al., 2006). In opposite way, the addition of chestnut starch varied significantly the dependence with increasing frequency and the relative contribution of both moduli (tan δ from 0.25±0.01 for 1 rad s^{-1} to 0.18±0.01 for 70 rad s^{-1}), which showed the highest reduction in G' values at low angular frequencies.

The values of G' and G" showed a pronounced increase above 70 rad s^{-1} for some samples (doughs of CF without additives and with the lowest additives amounts). This behaviour can be related to the sample slippage on the rheometer plate at the highest frequencies. Therefore oscillation tests were modelled by Eqs. (2) and (3) in the range of angular frequency from 1 to 70 rad s^{-1}. The values of a', a", b', and b" parameters of calculated from Eqs. (2) and (3) and the coefficients of fitting ($R^2 > 0.99$ for G' and $R^2 > 0.98$ for G") for all tested preparations are given in Table 2. The values of a' and a" (corresponding to G' and G'' values at 1 rad s^{-1} of angular frequency) decreased significantly with increasing amounts of each additive. Linear relationships for decreasing of a' (elastic) and a''(viscous) with sucrose and NaCl-sucrose content and a'' with chestnut starch addition were found. Tested doughs showed practically b' constant value (0.11 ± 0.02), except for doughs with chestnut starch (b': 0.21 ± 0.01), while b'' (0.15 ± 0.03) exhibited constant values for all assayed doughs. The increase of b' with chestnut starch addition can be attributed to interactions between starch granules in high concentration systems (Lii, Shao, & Tseng, 1995).

3.2.3. Creep-recovery tests

Fig. 6 shows the influence of addition of NaCl (1.8%), sucrose (5.0%), NaCl-sucrose mixtures (1.8-1.8%) and chestnut starch (15.0%) on the creep-recovery curves of CF doughs, where recovery phase was shortened to the first 120 s in order to improve the visualization. All assayed curves exhibited viscoelastic behaviour with similar shapes and J(t) values (from 0.0005 to 0.007 1/Pa) to those reported for gluten free formulations curves (from 0.0002 to 0.005 1/Pa) (Lazaridou, Duta, Papageorgiou, Belc, & Biliaderis, 2007) and lower than those found for rice flour doughs curves (from 0.004 to 0.028 1/Pa) (Sivaramakrishnan et al., 2004). The maximum creep strains achieved by creep tests were ranged from 17 to 33% depending on the type and concentration of additive. The most pronounced variations were obtained for doughs with chestnut starch addition. CF doughs with NaCl and sucrose showed significant variations, but in a narrow range. This result is in agreement with the obtained results by oscillatory and steady-shear flow tests. In the same way, in the literature no significant differences were observed in creep and recovery tests for wheat flour doughs with NaCl (1.2 and 2.4%) and sucrose (10 and 20%) addition (Salvador et al., 2006).

The compliance curve data of all tested doughs were successfully fitted ($R^2 > 0.984$ and $s < 0.025$ Pa s) to the Burgers model, Eqs. (4) and (5), and the corresponding parameters are collected in Table 2. The analysis of the parameters for creep phase, Eq. (4), indicated that instantaneous and maximum compliance, J_0 and J_{max} (directly related to maximum strain), decreased linearly with increasing NaCl, sucrose and NaCl-sucrose mixtures concentration. J_0 also decreased significantly with chestnut starch addition, but it remained constant with increasing concentration, while J_{max} increased significantly with increasing chestnut starch amount. On the other hand, J_m decreased slightly with increasing additives concentrations, except for chestnut starch that increased and the retardation time also increased with addition of additives, especially for chestnut starch addition (from 3.8 to 8.5 s). Finally, the flow resistance (viscosity parameter, η_0) also varied in a restricted range of values (18.5-23.8 10^3 Pa s) with additives addition. This parameter increased significantly regarding to CF without additives with NaCl above 1.8%. It also increased significantly with increasing sucrose above 1.8% and NaCl-sucrose also at 1.8%. In the case of chestnut starch addition, η_0 increased significantly at 5.0% regarding to CF without additives, but no significant differences were observed above 10% concentration.

The creep-recovery curves showed qualitatively similar shape, except for chestnut starch addition, and the unrecoverable viscous proportion was larger than the recoverable elastic proportion independently on additive employed. This result is characteristic of a weak cross-linked polymer system (Moreira et al., 2010b). Recovery phase data, presented in Table 2, clearly showed with low J_r/J_{max} values the lack of elasticity of CF dough, which improves significantly with chestnut starch addition. J_m

and λ increased significantly with additives regarding to CF, especially for chestnut starch addition. The J_m parameter decreased in a restricted range (111.1 10^{-5} to 78.8 10^{-5} 1/Pa) with increasing NaCl, sucrose and its mixtures. The opposite behaviour was found for CF doughs with chestnut starch addition. The J_r/J_{max} ratio, which is a measure of dough elasticity, also varied in a restricted range (20.3 to 23.7%) with NaCl, sucrose and NaCl-sucrose mixtures addition and it must be considered low compared to these ratios for wheat flours that has been found around 65 % (Sivaramakrishnan et al, 2004). The J_r/J_{max} ratio (45.4 ± 0.2 %) improves significantly with chestnut starch addition independently of concentration.

3.2.4. Temperature sweep tests

The influence of NaCl (1.8%), sucrose (5.0%), chestnut starch (15.0%) and NaCl-sucrose mixtures (1.8-1.8%) on the evolution of the storage modulus (G') with temperature of CF doughs is presented in Fig. 7. All assayed CF dough with additives showed lower G' values than CF without additives at each studied temperature. Below 65 °C, G', for all tested CF doughs, gradually decreased as temperature increased, indicating softening of the dough. These changes are caused by heat-induced processes and protein weakening (Rosell et al., 2007). Thereafter, the storage modulus began to increase rapidly between 66.4 and 72.6ºC, reaching a peak between 80.8 and 86.2 °C, depending on type and amount of additive and then slowly decreased. The increase of storage modulus during heating has been reported to be proportional to the starch content of the dough; indicating the physicochemical changes in heated dough are essentially due to changes in the starch fraction (Angioloni & Dalla Rosa, 2005).

The specific ranges corresponding to the gelatinization temperatures (T_0 and T_1) of all assayed CF doughs are shown in Table 2. The presence of NaCl at 1.8% concentration caused a significant rise in the inflection point temperature (T_0), however no significant differences were noted below 1.2%. The temperatures (T_1) at which maximum values of G' appeared were also higher in the presence of NaCl at 1.8%. The effect of NaCl in delaying the starch gelatinization has been reported (Galal et al., 1978; Preston, 1989; Chiotelli et al., 2002) and different explanations for this phenomenon proposed. When salt is added to dough, it lowers water activity and increases the energy necessary for chemical and physical reactions involving water (Angioloni & Dalla Rosa, 2005). The presence of sucrose (above 1.8%) caused a delay in the appearance of T_0 and T_1, which would be coherent with restricted access to the available water (Salvador et al., 2006). The highest gelatinization temperatures were achieved at 3.4 and 5.0% sucrose concentrations. Understanding the delay in starch gelatinization is crucial for improving the texture and other qualities of starch based products containing higher amounts of sucrose (Sharma, Oberoi, Oberoi, Sogi, & Gill, 2009). The effect of NaCl-sucrose mixtures in gelatinization temperatures did not varied significantly regarding to each alone additive. However, a reverse trend in T_0 and T_1 was found with increasing chestnut starch concentrations. As expected, both temperatures showed the lowest values of all studied systems due to the reduction of sugar content in the doughs. This behaviour was previously reported for gluten-free doughs containing different amounts of corn starch (Mariotti, Lucisano, Pagani, & Perry, 2009).

In Table 2 additional parameters like $-\alpha$ and β calculated from temperature sweep tests (Fig. 7) are also provided. The $-\alpha$ slope no varied significantly with additives, except for chestnut starch addition, where the slope values decreased significantly regarding to

CF without additives, but no significant variations with increasing chestnut starch concentration were found. The β slope decreased regarding to CF slightly with NaCl addition and significantly with increasing sucrose concentration above 3.4%. The reduction in rate of gelatinization by addition of salt and sugar on doughs was previously reported in the literature (Salvador et al., 2006; Lynch et al., 2009). The β value for CF showed no significant differences with the rest of assayed additives.

3.3. Mixolab® complete tests

Fig. 8 shows the curves from Mixolab® complete test for CF dough fortified with NaCl (1.8%), sucrose (5.0%), chestnut starch (15.0%) and NaCl-sucrose mixtures (1.8-1.8%). Representative characteristic parameters necessary to analyze in detail the information reported in this type of figures are exposed in Fig. 8. The parameters values for all assayed systems with their standard deviations are summarized in Table 3. The C2 parameter showed no significant differences with tested additives. The values of C3, C4 and C5 decreased with increasing NaCl and sucrose amounts. The C3 and C4 reduction was more pronounced with the concentration of NaCl, since NaCl at 1.8% presented the same value of these parameters as sucrose at 5.0%. In opposite way, the C5 reduction was more pronounced with sucrose addition. In fact, sucrose at 5.0% showed the lowest C5 values of all studied systems. In contrast, the values of C3, C4 and C5 for the added amounts of chestnut starch and NaCl-sucrose mixtures exhibited no significant differences regarding to CF without additives, except for NaCl-sucrose mixtures at 1.8% where all parameters decreased significantly regarding to CF without additives. Recently, it was reported that different wheat flours with high values of C2, C3, C4 and C5 (0.79, 2.31, 2.33 and 3.49 Nm, respectively) gave low cakes volume (Kahraman, Sakiyan, Ozturk, Koksel, Sumnu, & Dubat, 2008). Taking into account these considerations, it can be established that systems with sucrose (5.0%) are more suitable to obtain cakes because presented the lowest values of these parameters. In the same way, the NaCl or sucrose addition reduced the effects of staling and crumbs firmness on breads made with this flour. Ozturk, Kahraman, Tiftik, & Koksel (2008) reported that good cookie flours should have high values of C3, C4 and C5 (2.45, 2.46, 3.38 Nm, respectively). In this case, the addition of chestnut starch or low amounts of salt or sugar to CF doughs could be adequate. Other authors previously have reported the use of corn, potato, banana and seewtsop starches as additive to improve the quality of cakes, noodles, spaghetti or frozen foods, respectively (Ronda et al., 2009; Hernández-Nava, Berrios, Pan, Osorio-Díaz, & Bello-Pérez, 2009; Yu & Ngadi, 2006; Nwokocha & Williams, 2009).

In Table 3 the parameters of $-\alpha$, β, γ and T_0-T_1 range obtained using Mixolab® are also given. The $-\alpha$ and γ slopes are not varied significantly with additives addition, except for chestnut starch addition. In this case, rate of protein weakening decreased significantly regarding to CF without additives, but did not vary significantly with increasing chestnut starch concentration, while rate of enzymatic (amylase) degradation decreased slightly. Particularly, the addition of chestnut starch at 15% modified the γ slope sign (-0.019 Nm/min), obtained similar values to data previously reported for rice flour dough (Rosell & Marco, 2008). The β slope decreased slightly with increasing NaCl and sucrose concentration and the lowest β value (0.25 Nm/min) of all studied systems was for sucrose at 5.0%. The β value for CF showed no significant differences with the rest of assayed additives. The results for α and β slopes trends obtained in rheometer were corroborated with Mixolab® tests.

Initial and final gelatinization temperatures (T_0-T_1) of chestnut starch can be also obtained using Mixolab® by the evaluation of temperature dough when C2 and C3 are achieved (Fig. 8). Nevertheless, Mixolab® obtained systematically higher T_0 (2.1 ± 0.2 ºC) and lower T_1 (0.7 ± 0.4 ºC) values comparing to those derived from temperature sweep resulting in a lower (T_0-T_1) range. The aforementioned comments about the influence of assayed additives on the trend of gelatinization temperatures obtained by rheometer were corroborated here. On the whole, it can be observed that the obtained results for CF doughs with additives in rheometer were in agreement with the obtained data by Mixolab®, except for doughs fortified with salt. In this case, contradictory results were found, since Mixolab® showed a trend to strengthen doughs with salt addition regarding to CF by increasing development time and stability values; while rheometer tests showed a reverse trend with the reduction of apparent viscosity, storage and loss moduli as well as creep-recovery curves regarding to CF. Some explanations for the occasional differences among macro (Mixolab® mixing tests) and micro (rheometer oscillatory tests) scale deformation measurements are found in the literature (Lynch et al., 2009). One explanation could be the different deformation rates and stresses used in the measurements. Empirical measurements impart high different simultaneous stresses, whereas fundamental (rheometry) only evaluates the stress in controlled measurement conditions. Nevertheless, it is generally agreed that the effect of salt depend on the quality and quantity of protein (Wu et al., 2006) and low protein dough (as chestnut flour, about 6.0%) shows decreasing elastic behaviour with increasing salt content.

4. Conclusions

The addition of chestnut starch and conventional additives like salt and sugar modified the rheological behaviour of CF dough during mixing and heating-cooling operations as obtained by the Mixolab® measurements. The influence of additives on rheological properties was also studied with steady-shear, oscillatory, temperature sweep and creep-recovery tests carried out in the rheometer. In this line, apparent viscosity, storage and loss moduli decreased with increasing additives concentration. During creep-recovery tests, only doughs with chestnut starch addition showed higher elastic properties. Temperature sweep results from rheometer and the data from Mixolab® complete tests were in accordance. Acceptable agreement between empirical and fundamental assays was found, except for CF doughs with salt addition. The analysis of the results indicated that assayed additives allow improving the weak interactions between components of the chestnut flour dough, typical gluten-free flours, and this flour is more suitable for pastrymaking. Further studies are required to investigate the influence of other additives that allow improving the elastic characteristics of CF doughs.

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Captions for Figures

Fig. 1. Experimental steady shear flow curves for CF dough without and with additives: NaCl (1.8%), sucrose (5.0%) and NaCl-sucrose mixtures (1.8-1.8%). Lines correspond to Cross model, Eq. (1).

Fig. 2. Experimental steady shear flow curves for CF dough without additives and with several chestnut starch concentrations (5.0, 10, 15.0%). Lines correspond to Cross model, Eq. (1).

Fig. 3. Experimental G' and G" data for CF dough without additives and with several NaCl concentrations (0.6, 1.2, 1.8%). Lines correspond to Eq. (2 and 3).

Fig. 4. Experimental G' and G" data for CF dough without additives and with several sucrose concentrations (0.6, 1.8, 3.4, 5.0%). Lines correspond to Eq. (2 and 3).

Fig. 5. Experimental G' and G" data for CF dough without additives and with several chestnut starch concentrations (5.0, 10, 15%). Lines correspond to Eq. (2 and 3).

Fig. 6. Creep and recovery curves for CF dough without and with additives: NaCl (1.8%), sucrose (5.0%), NaCl-sucrose mixtures (1.8-1.8%) and chestnut starch (15.0%). Lines correspond to Eqs. (4 and 5).

Fig. 7. Evolution of G' with temperature sweep for CF dough without and with additives: NaCl (1.8%), sucrose (5.0%), NaCl-sucrose mixtures (1.8-1.8%) and chestnut starch (15.0%).

Fig. 8. Mixolab® complete test curves for CF dough without and with additives: NaCl (1.8%), sucrose (5.0%) and chestnut starch (15.0%).