Linear and non-linear rheology of bread doughs made from blends of wheat (*Triticum aestivum* L.) and rye (*Secale cereale* L.) flour

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Abstract

Strain hardening of wheat flour (WF) proteins during fermentation and baking is at the basis of the excellent quality of wheat breads. Yet, there are good reasons to use rye flour (RF), such as its high content of dietary fiber and other bio-actives. However, rye proteins lack the ability to form dough with sufficient strain hardening capacity under extension, which partially explains the inferior quality of rye breads. A promising strategy to make high-quality breads with high nutritional value is the use of WF and RF blends. Despite this, the rheological behavior of WF/RF bread doughs has not yet been investigated. This study examines their rheology by non-linear uniaxial extensional and small-amplitude oscillatory shear measurements, and relates these measurements to the quality of the resulting breads. The strain hardening index (SHI), derived from extensional measurements, is expressed as the transient extensional viscosity at maximum strain [$\eta_{e0}^+(\epsilon_{max})$] relative to the linear extensional viscosity extrapolated to maximum strain [$\eta_{e0}^+(\epsilon_{max})$]. Both the SHI and bread volume decreased when the level of RF in the blend increased. As an example, replacing 60% WF by RF led to a relative decrease of the SHI and bread volume of 34% and 64%, respectively. The decrease of the SHI is correlated to an increase in $\eta_{e0}^+(\epsilon_{max})$. Comparison of the extensional curves of doughs made with blends of WF and RF and doughs made with blends of WF and wheat starch (WS) further revealed that RF components play a major role in the rheology of the doughs. In conclusion, it was found that WF/RF blends need to contain at least 60% WF to obtain bread of proper quality.

25 **Keywords:** dough rheology, wheat flour–rye flour doughs, non-linear extension, linear shear, strain hardening, bread
26 volume

1. Introduction

Over the past decade, consumer concerns regarding health issues such as malnutrition and lifestyle diseases (for instance diabetes and several cancers) have led to an increased demand for nutrient dense foods (Fardet, 2010). This in turn has initiated the growth of a new market for health-beneficial foods (Dewettinck et al., 2008). A notable staple food in Western society is bread made from wheat flour (WF). Nonetheless, straight-grade flour from most non-wheat cereals has higher dietary fiber, essential amino acid, vitamin, and mineral levels than that of wheat, which explains the growing importance and popularity of multigrain breads in the baking industry (Dewettinck et al., 2008). Indeed, Angioloni & Collar (2011) showed that replacing WF by flour derived from non-wheat cereals improved the nutritional quality of the obtained multigrain breads. Rye (*Secale cereale L.*) is the most common non-wheat cereal used in bread making (Bushuk, 2001). In addition to containing numerous bioactive compounds which affect human health (Jonsson et al., 2018), rye has one of the highest dietary fiber contents among cereals (Andersson, Fransson, Tietjen, & Aman, 2009).

Traditionally, bread making starts by mixing flour, water, salt, yeast, and optionally other ingredients such as surfactants and enzymes. Mixing and kneading these constituents hydrates the flour particles and leads to incorporation of air cells and dough formation. The gas cells then expand during dough fermentation and early baking as a result of carbon dioxide production by yeast. Proper stabilization of gas cells against coalescence and disproportionation (Ostwald ripening) during these stages of bread making is essential to obtain bread with a high loaf volume and a homogeneous crumb structure (van Vliet, 2008). In wheat bread making, gas cell stability is mainly ensured by the gluten network, which acts as a physical barrier preventing gas cells from undergoing coalescence and disproportionation. (Gan, Ellis, & Schofield, 1995; Sroan, Bean, & MacRitchie, 2009). Indeed, upon hydration and kneading wheat gluten proteins form a continuous three-dimensional network, which provides dough with its unique viscoelastic character (Delcour & Hoseney, 2010).

Wheat gluten storage proteins are typically subdivided in gliadins and glutenins, based on their extractability in aqueous alcohol and dilute acid solutions, respectively (Osborne, 1907). Gliadins are monomeric proteins and function as plasticizer for glutenins. They provide dough with viscosity while glutenins are polymeric proteins imparting elasticity on dough. The bread making performance of WF co-depends on the balance between the viscous and elastic properties of dough, which in turn depend on the relative qualities and quantities of gliadins and glutenins in WF

(Veraverbeke & Delcour, 2002). More specifically, dough made from WF with an appropriate balance between viscosity and elasticity exhibits ‘strain hardening’ upon uniaxial or biaxial extension, which is a valuable indicator of bread quality (Sroan et al., 2009; van Vliet, 2008 and references therein). Strain hardening can be defined as the super-linear increase of the stress required to deform a material with increasing extension (at a constant strain rate). Its importance during late fermentation (i.e. proofing) and particularly during oven rise in the early phase of baking can be explained by the thinning of the dough film in between neighboring gas cells as a result of their expansion (**Fig. 1**) (Dobraszczyk, Smewing, Albertini, Maesmans, & Schofield, 2003). When this thinning endures locally in between gas cells, they merge likely due to rupture of the dough film (**Fig. 1a**). If, however, the stress required to further deform the dough film increases super-linearly with the strain, local thinning of the dough film between gas cells is less pronounced and expansion likely proceeds along regions of the dough which are thicker and thus more prone to deformation (**Fig. 1b**). This implies that strain hardening of gluten proteins in dough promotes equal growth of gas cells and delays their coalescence and disproportionation during late fermentation and early baking (van Vliet, 2008).

Fig. 1 Schematic representation of the thinning of the dough film between neighboring gas cells as a result of their expansion during late fermentation and early baking. Occasionally, a region of localized strongly thinned dough film may be formed between expanding gas cells. When the dough exhibits poor or even no strain hardening, the dough film between gas cells continues to thin until it ruptures and the gas cells merge (**a**). However, when the dough exhibits strain hardening, thinning of the film between gas cells is halted, as further expansion proceeds along parts of the film which are thicker and therefore more prone to deformation (**b**)

In contrast, rye breads generally have much lower specific loaf volume and poorer crumb structure than wheat breads because rye flour (RF) proteins lack the ability to form a viscoelastic network during hydration and kneading (Beck, Jekle, Selmaier, Koehler, & Becker, 2011; Gellrich, Schieberle, & Wieser, 2003). Indeed, although there is partial homology between the structures of wheat (i.e. gliadins and glutenins) and rye (i.e. secalins) flour storage proteins (Field, Shewry, & Mifflin, 1982; Gellrich et al., 2003), the flour protein compositions are completely different. The majority of WF proteins are gliadins and glutenins (80-85% of WF proteins), with the remaining 15-20% belonging to the class of albumins and globulins (Delcour & Hoskeney, 2010). Rye flour proteins, on the other hand, contain a vast majority of albumins and globulins (37-51%), and only 26-34% of secalins and 21-30% out of unextractable proteins (Redant, Buggenhout, Brijs, & Delcour, 2017). In addition, whilst the total protein content of WF is about

10-12% (Goesaert et al., 2005), the protein content of RF is often much lower and typically ranges between 4 and 11% (Buksa, Ziobro, Nowotna, & Gambuś, 2013; Verwimp, Vandeputte, Marrant, & Delcour, 2004). Furthermore, some structural differences between the high (Kipp, Belitz, Seilmeier, & Wieser, 1996; Kohler & Wieser, 2000) and low (Gellrich, Schieberle, & Wieser, 2004) molecular weight fractions of WF glutenins and RF secalins have been identified.

In summary, WF generally has excellent bread making quality, while RF contains higher levels of dietary fiber and bioactive compounds (Angioloni & Collar, 2011). Other studies, aimed at improving the nutritional quality of wheat flour bread, already looked at the rheological behavior of wheat flour doughs blended with components such as resistant starch (Arp, Correa, & Ferrero, 2018; Sanchez et al., 2014), carob flours (Salinas, Carbas, Brites, & Puppo, 2015), grape peels (Mironeasa, Iuga, Zaharia, & Mironeasa, 2019), mesquite flour (Bigne, Romero, Ferrero, Puppo, & Guerrero, 2017) or wheat germ (Gómez, González, & Oliete, 2012). However, to the best of our knowledge, the potential of blends of WF and RF as raw material to produce nutrient dense multigrain breads has not been extensively studied. Hence, this paper is the first to study the rheological behavior of WF/RF bread doughs in-depth to aid in the development of nutritious WF/RF multigrain breads and to overcome the limited bread making potential of RF.

Recent work by our group (Meerts, Cardinaels, Oosterlinck, Courtin, & Moldenaers, 2017a, 2017b; Meerts, Van Ammel, et al., 2017) has shown the value of pure uniaxial extensional measurements for studying the rheology of wheat doughs at large deformations in the non-linear regime. Such measurements allowed distinguishing WF samples of different quality (Meerts, Cardinaels, et al., 2017b) due to the highly non-linear response of the gluten network when subjected to large deformations (Amemiya & Menjivar, 1992). Uniaxial extensional measurements were performed on a strain-controlled rheometer equipped with an extensional viscosity fixture (EVF). The major advantages of such fundamental set-up over the well-known and often-used empirical Kieffer extensibility rig are (i) the application of a well-defined extensional deformation and (ii) the absence of shear when applying the extensional deformation (Dunnewind, Sliwinski, & Grolle, 2004; Meerts, Cardinaels, et al., 2017b).

Against this background, the present work aimed at studying the rheology of doughs made from WF/RF blends in the linear and non-linear regime. Pure uniaxial extensional measurements allowed probing the non-linear strain hardening properties of dough. In addition, small-amplitude oscillatory shear (SAOS) measurements were used to study the dough microstructure in the linear regime. Extensional and SAOS measurements were also performed on doughs made

from blends of WF and wheat starch (WS) to assess the effect of diluting the gluten concentration in WF and, hence, weakening the gluten network in the absence of rye proteins and non-starch polysaccharides. The outcome of our work provides better understanding of the rheology of WF/RF bread doughs and serves as a basis for selecting multigrain dough formulations in order to produce multigrain breads of high quality.

2. Materials and methods

2.1. Materials

Bilux flour, consisting of a blend of different WF cultivars, was from Dossche Mills (Deinze, Belgium). Rye kernels (variety Dukato) were from AVEVE (Merksem, Belgium). The rye kernels were conditioned to 16.0% moisture and subsequently milled in-house using a Bühler (Uzwil, Switzerland) MLU-202 laboratory mill as in Delcour, Vanhamel, & De Geest (1989). WS (moisture content 12.2%) was from Tereos Syral (Aalst, Belgium). Sugar, salt, and fresh compressed yeast (AB Mauri, Dordrecht, Nederland) were bought in a local supermarket. β -D-Allose, L-arabinose, D-xylose, D-mannose, D-galactose, D-glucose, benzoic acid, sodium borohydride, 2-octanol, and ethyl acetate were from Sigma-Aldrich (Bornem, Belgium). Bromophenol blue, trifluoroacetic acid, 1-methylimidazole, and absolute ethanol were from Thermo Fisher Scientific (Aalst, Belgium). Ammonia, potassium hydroxide, acetic acid, acetic anhydride, and anhydride sodium sulfate were from VWR International (Oud-Heverlee, Belgium).

2.2. Flour composition

Moisture levels were determined according to AACCI Method 44-19.01 (**Table 1**). Protein content was measured with an automated Dumas protein analysis system (Vario Max Cube, Elementar, Hanau, Germany), using an adaptation of AOAC method 990.03 (AOAC International, 1995) ($N \times 5.7$) (**Table 1**). Total arabinoxylan (TOT-AX) content was calculated as 0.88 times the xylose and arabinose levels as determined in a gas chromatography procedure in which flour samples were sequentially subjected to acid hydrolysis, monosaccharides were reduced to alditols and subsequently converted to alditol peracetates (Courtin, Roelants, & Delcour, 1999) which were analyzed with an Agilent (Wilmington, DE, USA) gas chromatograph (6890 Series) equipped with an auto sampler and flame ionization detector. Separation was with a polar column (Supelco SP 2380, 30.0 m length, 0.32 mm inner diameter, 0.2 μ m film thickness, Bellefonte, PA, USA). Helium was used as a carrier gas. In the above, the arabinose levels were first corrected for the presence of arabinose originating from arabinogalactan peptide (arabinose to galactose ratio 0.7) in

wheat and rye. Water-extractable arabinoxylan (WE-AX) levels were determined using a similar procedure as for the TOT-AX content, with the only exception that hydrolysis took place on aqueous extracts (2.5 ml) in 4.0 M trifluoroacetic acid (2.5 ml). Aqueous extracts were obtained by suspending 2.0 g of flour in 20 ml of water, followed by centrifugation and filtration. WU-AX levels were calculated by subtracting the WE-AX from the TOT-AX levels (**Table 1**). The number average degree of polymerization (avDP_n) of WE-AX was calculated by dividing the level of WE-AX relative to the level of reducing end xylose residues in the aqueous extract. Reducing end xylose levels were determined in a gas chromatography procedure in which aqueous extracts of flour were sequentially subjected to reduction of the reducing ends of AX to alditols, acid hydrolysis, and conversion to alditol peracetates (Courtin, Van den Broeck, & Delcour, 2000).

Table 1 Moisture content (%), protein content on dry matter (dm) basis (% of dm), total arabinoxylan (TOT-AX) content (% of dm), water-extractable arabinoxylan (WE-AX) content (% of dm) and water-unextractable arabinoxylan (WU-AX) content (% of dm) of wheat flour (WF) and rye flour (RF). Results are presented as sample mean with standard deviation, apart from WU-AX content which was calculated as the difference between TOT-AX and WE-AX.

2.3. Bread making

Blends (all on weight basis) of WF and RF or WF and WS were mixed overnight using an end-over-end shaker. The optimal water absorption of doughs prepared with pure WF, 80% WF and 20% RF (WF80-RF20) or WS (WF80-WS20), 60% WF and 40% RF (WF60-RF40) or WS (WF60-WS40), 40% WF and 60% RF (WF40-RF60) or WS (WF40-WS60), 20% WF and 80% RF (WF20-RF80) or WS (WF20-WS80), and pure RF (RF100) was determined with a Farinograph (Brabender, Duisburg, Germany) according to AACC method 54-21.02 (AACC International, 2000) (**Table 2**). The optimal mixing time of said doughs was determined with a Mixograph according to AACC method 54-40.02 (AACC International, 2000) (**Table 2**). For bread making trials, yeasted doughs were prepared according to the straight dough method of Shogren & Finney (1984). Flour (8.6 g dm), deionized water (**Table 2**), sugar (6.0% on a flour weight basis), and salt (1.5% on a flour weight basis) were mixed in a slightly greased pin mixer (National Manufacturing). Fermentation (126 min) took place in a fermentation cabinet (National Manufacturing) at 30.0 °C and a relative humidity of 90%. Doughs were sheeted after 52, 77, and 90 min of fermentation, each time at a roll distance of 2.5 mm. After the third sheeting step, doughs were rolled into a cylinder,

placed in a slightly greased rectangular baking tin, and proofed in the fermentation cabinet for 36 min. Baking was in a rotary oven (National Manufacturing) at 232 °C for 13 min. Two hours after baking, cooled breads were weighed and their volumes measured using a Volscan Profiler (Stable Microsystems, Godalming, Surrey, UK). The specific loaf volume was calculated as volume divided by mass. Bread making trials were performed in triplicate.

Table 2 Optimal water absorptions (% w/w on flour basis) and mixing times (s) of doughs prepared from 100% wheat flour (WF), 100% rye flour (RF), 80% WF and 20% rye flour (RF) (WF80-RF20), 60% WF and 40% RF (WF60-RF40), 40% WF and 60% RF (WF40-RF60), 20% WF and 80% RF (WF20-RF80), 80% WF and 20% wheat starch (WS) (WF80-WS20), 60% WF and 40% WS (WF60-WS40), 40% WF and 60% WS (WF40-WS60), and 20% WF and 80% WS (WF20-WS80). Results for the water absorption are presented as sample mean with standard deviation.

2.4. Rheological analyses

Doughs were prepared as described above. However, no yeast was added because it would have resulted in a continuous increase in sample volume. After mixing, the doughs were pressed between two plates for one minute to obtain a uniform sample thickness of 4 mm and a diameter larger than 40 mm. Pressed dough samples were allowed to rest in a closed container for 30 minutes at room temperature in order for stresses to relax in an environment preventing moisture loss.

2.4.1 Extensional measurements

As in Meerts, Cardinaels, et al. (2017b) extensional measurements were performed at room temperature using an EVF mounted on an ARES-G2 rheometer (TA Instruments, New Castle, DE, USA). The setup of the EVF consists of two drums: one drum revolves around both a stationary one and its own axis. Dough strands of fixed dimensions (length $L_0 = 12.5$ mm, height $H_0 = 4$ mm, thickness $B_0 = 4$ mm) were prepared using a hollow stamp. The strands were attached using two clamps. Extension took place at a constant nominal rate of 0.12 s^{-1} , resulting in an effective extension rate of 0.10 s^{-1} due to slip phenomena.

The Hencky strain $\varepsilon(t)$ [-] was used to describe the strain of the dough samples:

$$\varepsilon(t) = \ln\left(\frac{L(t)}{L_0}\right) \quad (1)$$

with L_0 the initial length of the dough strand and $L(t)$ the length at a given moment t . The transient extensional viscosity $\eta_e^+(\varepsilon)$ [Pa.s] is defined as:

$$\eta_e^+(\varepsilon) = \frac{\sigma_{11}(\varepsilon)}{\dot{\varepsilon}} \quad (2)$$

with $\sigma_{11}(\varepsilon)$ [Pa] the longitudinal stress, which is determined via the transducer of the rheometer. The EVF setup used in this study was limited to a maximum strain ε_{max} of 2.89.

During extension, wheat doughs can exhibit strain hardening, a measure of which is the strain hardening index (SHI) [-], which is defined as the transient extensional viscosity at maximum strain $\eta_e^+(\varepsilon_{max})$ relative to the linear extensional viscosity extrapolated to this maximum strain $\eta_{e0}^+(\varepsilon_{max})$ (**Fig. 2**).

Fig. 2 Illustration of the definition and calculation of the strain hardening index (SHI) of bread dough. The nominator contains the transient extensional viscosity at maximum strain (2.89) $\eta_e^+(\varepsilon_{max})$, whilst the denominator is obtained by extrapolating the linear extensional viscosity to maximum strain $\eta_{e0}^+(\varepsilon_{max})$

The extensional data reported here are means of measurements on seven dough strands from each of three separate dough batches. A pooled standard deviation (s_p) was used to calculate the variability within the measurements (McNaught & Wilkinson, 1997):

$$s_p = \sqrt{\frac{(n_1 - 1) * s_1^2 + (n_2 - 1) * s_2^2 + (n_3 - 1) * s_3^2}{n_1 + n_2 + n_3 - N}} \quad (3)$$

with s_1 , s_2 and s_3 the standard deviations of the seven measurements of dough preparation batch 1, 2 and 3, respectively. n_1 , n_2 and n_3 represent the total number of measurements (*i.e.* 7) in each dough batch. N is the total number of dough batches (*i.e.* 3). Relative standard deviations were on average 10%, indicating that the measurements were reproducible.

2.4.2. Shear measurements

SAOS measurements were performed as in Meerts, Cardinaels, et al. (2017b) using a stress-controlled MCR501 rheometer (Anton Paar, Graz, Austria), equipped with a 40 mm parallel plate geometry, operating in direct strain mode

(Läuger, Wollny, & Huck, 2002). A temperature of 25 °C was generated by a Peltier heating element. A solvent trap and wet cotton wool prevented sample dehydration. Top and bottom plates were coated with sandpaper to prevent slip.

After loading the dough sample, the top plate was moved downwards to ensure full contact with the sample at a normal force not exceeding 2 N. The limit of 2 N ensured that the dough samples were not exposed to significant pre-test deformations, which could affect the rheological properties of the dough (Tanner, Qi, Uthayakumaran, & Dai, 2013). After mounting the solvent trap, samples were allowed to rest for an additional 30 minutes during which a time sweep at a fixed angular frequency of 1 rad.s⁻¹ and a strain of 0.04% (which was within the linear region as verified by strain sweep tests) was performed. Resting allowed for relaxation of the stresses resulting from mixing, shaping, and dough loading. After this time sweep, samples were subjected to a frequency sweep (in the range between 0.1 and 100 rad.s⁻¹) at a constant strain of 0.04%.

In SAOS experiments samples are exposed to a sinusoidal strain $\gamma(t)$ with strain amplitude γ_0 [-] and angular frequency ω [rad.s⁻¹]:

$$\gamma(t) = \gamma_0 \sin(\omega t) \quad (4)$$

Provided the strain is sufficiently small (i.e. that the material behaves linearly), the resulting stress response $\sigma(t)$ varies sinusoidally with a stress amplitude σ_0 at the same angular frequency ω , but with a phase lag δ [rad]:

$$\sigma(t) = \sigma_0 \sin(\omega t + \delta) \quad (5)$$

The ratio between $\sigma(t)$ and $\gamma(t)$ is used to calculate the frequency-dependent storage $G'(\omega)$ [Pa] and loss $G''(\omega)$ [Pa] moduli:

$$G' = \left(\frac{\sigma_0}{\gamma_0} \right) \cos(\delta) \quad (6)$$

$$G'' = \left(\frac{\sigma_0}{\gamma_0} \right) \sin(\delta) \quad (7)$$

While G' represents the elastic behavior and G'' the viscous behavior, both are often combined to obtain the tangent of the phase angle $\tan(\delta)$:

$$\tan(\delta) = \frac{G''}{G'} \quad (8)$$

This parameter describes the viscoelastic behavior of dough. Indeed, it clearly underpins the meaning of the phase angle in terms of energy dissipation (Steffe, 1996). The more elastic a material is, the more energy it can store, and the closer δ is to 0 °. In contrast, the more viscous it is, the more energy it can dissipate, which results in δ approaching 90 °.

SAOS data were single measurements on doughs of each of three different batches. Relative standard deviations were less than 10% for both G' and G'' , indicating good reproducibility.

2.5. Statistical analysis

Data were analyzed with the Statistics Toolbox of MATLAB (Release 2017b, The MathWorks, Natick, MA, USA). One-way analysis of variance (ANOVA) followed by Tukey's honest significant difference test to identify significant differences ($P < 0.05$) was performed. Normality and homogeneity of variance of the data were verified using Shapiro-Wilk and Bartlett tests, respectively.

3. Results and discussion

3.1. Blends of wheat flour and rye flour

3.1.1. Bread making trials

Table 3 lists the specific volumes of breads made from WF, WF80-RF20, WF60-RF40 and WF40-RF60. Interestingly, substituting 20% WF by RF did not significantly ($P < 0.05$) decrease the bread volume. The specific volume of the WF60-RF40 bread was lower than that of the breads produced either from WF or WF80-RF20, but it was mainly for the WF40-RF60 that a distinctly lower ($P < 0.05$) bread volume was observed. It thus appears that blends of WF and RF require at least 60% WF to obtain bread of acceptable quality. The aim of what follows is to relate bread volumes to possible changes in the rheology of the WF-RF doughs.

Table 3 Specific bread volumes, extrapolated linear transient extensional viscosity η_{e0}^+ at the maximum strain of 2.89, transient extensional viscosity η_e^+ at the maximum strain of 2.89, and strain hardening indices (SHI) of doughs prepared with 100% wheat flour (WF), 80% WF and 20% rye flour (RF) (WF80-RF20), 60% WF and 40% RF (WF60-

RF40), 40% WF and 60% RF (WF40-RF60), 80% WF and 20% wheat starch (WS) (WF80-WS20), 60% WF and 40% WS (WF60-WS40), and 40% WF and 60% WS (WF40-WS60). Results are presented as sample mean with standard deviation. Column values with the same lowercase letter are not significantly different ($P > 0.05$).

3.1.2. Extensional measurements

Fig. 3 shows the evolution of η_e^+ as a function of strain of the doughs made from the blends of WF and RF. Dough strands from WF20-RF80 and RF100 were brittle and ruptured before the maximum strain of 2.89 was reached. Hence, extensional data of these samples could not be obtained. When extended uniaxially, WF dough displays typical strain hardening. At the extension rate used here (0.1 s^{-1}), η_e^+ of WF dough increased proportionally with the strain up to strain values of ca. 0.5 (**Fig. 3**), which is in line with an earlier report by Meerts, Cardinaels, et al. (2017b). At higher strains (> 0.5) η_e^+ of WF dough increased super-linearly with increasing strain, which is the typical strain hardening that can be expected as a result of the presence of a strong viscoelastic gluten network (van Vliet, 2008). As discussed in section 2.4.1., we here calculated a SHI, which is expressed as the ratio of $\eta_e^+(\epsilon_{\max})$ to $\eta_{e0}^+(\epsilon_{\max})$ (**Table 3**). Although this index was originally defined for polypropylene blends (Laguna-Gutierrez, Van Hooghten, Moldenaers, & Rodriguez-Perez, 2015), Meerts, Cardinaels, et al. (2017b) extended this concept to wheat bread doughs. When bread dough exhibits poor or even no strain hardening, the dough films between expanding gas cells thin locally, the dough films collapse, and the bread quality (in terms of loaf volume and crumb structure) is likely to be poor. Provided, however, that bread dough shows strong strain hardening, it further expands along dough films that are thicker, the dough films between gas cells remain stable, and the bread quality is likely to be high.

Fig. 3 Transient extensional viscosity η_e^+ as a function of strain of dough strands prepared with 100% wheat flour (WF) (WF100), 80% WF and 20% rye flour (RF) (WF80-RF20), 60% WF and 40% RF (WF60-RF40), and 40% WF and 60% RF (WF40-RF60). Note that even the dough made with 40% WF and 60% RF exhibited strain hardening. The data represent means of seven measurements of each of three separate dough batches

A first striking observation for the different dough blends was that strain hardening was still observed when the level of RF in the blend was 60%. That strain hardening occurred in all cases suggests protein-protein interactions in all dough blends (Amemiya & Menjivar, 1992). Nonetheless, there were differences in the outcomes of the uniaxial extensional measurements of the doughs from the different blends. Indeed, the SHI of the doughs significantly ($P < 0.05$) decreased as the level of RF in the blend increased (**Table 3**). Although the SHI of dough made from WF80-

RF20 (9.9) was significantly ($P < 0.05$) lower than that of the WF dough (14.3), both blends resulted in similar bread volumes (**Table 3**). While replacing an additional 20% of WF by RF had only little impact on the SHI of the doughs (WF80-RF20 and WF60-RF40 doughs had SHI values of 9.9 and 8.4, respectively), substitution of 60% WF by RF further decreased the SHI to a low value of 4.8 (**Table 3**). This implies that the critical level of WF required to develop a substantial viscoelastic network ranges between 40 and 60%. This was also reflected in the optimum dough mixing time (**Table 2**), which strongly decreased from 165 s for WF60-RF40 to 90 s for WF40-RF60, and the specific bread volume, which was substantially lower for WF40-RF60 than for WF60-RF40.

In order to better understand the relation between uniaxial extensional measurement results of WF-RF dough blends and the properties of the resulting breads, it is of relevance to discuss the individual contributions of $\eta_{e0}^+(\epsilon_{max})$ and $\eta_e^+(\epsilon_{max})$ as parameters defining the SHI. Amemiya & Menjivar (1992) have addressed how, in extension experiments, different regions can be identified, in each of which certain interactions between dough components determine the rheology. The linear part of the present $\eta_e^+-\epsilon$ curves corresponds to the so called yield region, in which short range interactions (i.e. starch-starch and gluten-starch interactions) start to break down and gluten molecules start to gain some mobility (Meerts, 2018). Since $\eta_{e0}^+(\epsilon_{max})$ is an extrapolation of this linear region of the $\eta_e^+-\epsilon$ curves, it can be used as an indicator for the short-range interactions in the dough. A second region in the present extensional measurements is the strain hardening region. When a continuous protein phase is present, the response of dough in this region is dominated by protein-protein interactions (Amemiya & Menjivar, 1992). Therefore, $\eta_e^+(\epsilon_{max})$ is a measure for the long range gluten-gluten interactions.

Replacing 20% WF by RF had no significant effect on $\eta_e^+(\epsilon_{max})$, but significantly ($P < 0.05$) increased $\eta_{e0}^+(\epsilon_{max})$ from 3.0×10^4 Pa.s for doughs made from WF to 4.9×10^4 Pa.s for WF80-RF20 doughs (**Table 3**). While doughs made from WF60-RF40 were characterized by a further increase in the value of $\eta_{e0}^+(\epsilon_{max})$ to 6.5×10^4 Pa.s, the value of $\eta_e^+(\epsilon_{max})$ was significantly ($P < 0.05$) higher (5.5×10^5 Pa.s) than that of WF doughs (4.3×10^5 Pa.s) (**Table 3**). Replacing an additional 20% WF by RF had no noticeable effect on the value of $\eta_e^+(\epsilon_{max})$, but further increased ($P < 0.05$) the value of $\eta_{e0}^+(\epsilon_{max})$ to 11.1×10^4 Pa.s (**Table 3**). We did not expect $\eta_e^+(\epsilon_{max})$ to significantly ($P < 0.05$) increase when higher levels of RF were incorporated in the blends (**Table 3**), as RF addition decreased the total protein content in the blends, and, more importantly, the wheat gluten content. Since $\eta_e^+(\epsilon_{max})$ is mainly influenced by long-range protein interactions (Meerts, Cardinaels, et al., 2017a), a decrease of $\eta_e^+(\epsilon_{max})$ was expected for the doughs based on

WF-RF blends. The increase in $\eta_{e0}^+(\varepsilon_{max})$ with RF levels suggested short-range interactions between WF and RF constituents.

When relating the specific bread volumes to the rheological dough parameters, a relatively good linear relation ($R^2 = 0.810$) between the SHI of the different doughs and the volumes of the corresponding breads was observed (**Fig. 4c**). Other studies (Meerts, Cardinaels, et al., 2017a, 2017b; Meerts, Van Ammel, et al., 2017) already pointed to the potential use of the SHI as an indicator of bread making performance, although actual bread making trials were never conducted in these studies. While $\eta_e^+(\varepsilon_{max})$ seemed to be unrelated to bread volume (**Fig. 4b**), the latter correlated well ($R^2 = 0.936$) with $\eta_{e0}^+(\varepsilon_{max})$ (**Fig. 4a**). Thus, the strong increase in $\eta_{e0}^+(\varepsilon_{max})$ is also the reason why the SHI decreased with increasing RF levels.

Fig. 4 Linear relations between specific bread volume and $\eta_{e0}^+(\varepsilon_{max})$ (a), specific bread volume and $\eta_e^+(\varepsilon_{max})$ (b), and between specific bread volume and the strain hardening index (SHI) (c) of doughs prepared from 100% wheat flour (WF) (WF100), 80% WF – 20% rye flour (RF) (WF80-RF20), 60% WF – 40% RF (WF60-RF40), and 40% WF – 60% RF (WF40-RF60).

To conclude, both the SHI and bread volume decreased when the portion of RF in the dough recipe increased. The decrease of the SHI was related to an increase in the value of $\eta_{e0}^+(\varepsilon_{max})$. Surprisingly, $\eta_e^+(\varepsilon_{max})$, which is a measure of the strength of the network in the dough, also slightly increased when the level of RF in the dough increased. The production of multigrain WF/RF breads of acceptable quality (i.e. displaying strain hardening and reaching sufficiently large specific bread volumes) was shown to be feasible when the level of WF was at least 60%.

3.1.3. SAOS measurements

Since during the extension measurements $\eta_{e0}^+(\varepsilon_{max})$ was clearly affected by the level of RF in doughs made from WF-RF blends, short-range interactions (e.g. van der Waals forces and hydrogen bonds) between RF and WF constituents probably took place. To gain additional insights into these short-range interactions in doughs made from WF-RF blends, doughs were subjected to small-amplitude sinusoidal oscillations in shear. Such measurements allow quantifying both their elastic storage (G') and viscous loss (G'') moduli.

Fig. 5 shows G' and G'' as a function of ω for doughs made from WF100, RF100, and WF40-RF60. The G' and G'' curves of the doughs from the other blends were positioned in between those shown and are not shown for clarity

reasons. That both G' and G'' increased with RF levels may be ascribed to differences in arabinoxylan (AX), protein and/or starch contents and structures (see section 3.2.3.). In all cases G' exceeded G'' , which is characteristic for highly structured materials (Létang, Piau, & Verdier, 1999). For all dough samples G' and G'' were a weak function of ω and ran parallel in the considered frequency range, indicating they behaved as weak gels (Gabriele, De Cindio, & D'Antona, 2001).

Fig. 5 Storage (G') and loss (G'') moduli as a function of angular frequency (ω) of dough strands prepared from 100% wheat flour (WF) (WF100), 100% rye flour (RF) (RF100), and a blend of 40% WF and 60% RF (WF40-RF60). The parallel evolution and the weak dependency of G' and G'' on ω was also observed for doughs made with the blends 80% WF and 20% RF, 60% WF and 40% RF, and 20% WF and 80% RF, of which the curves were omitted here for reasons of clarity. The data represent averages of single measurements of each of three separate dough preparations

Besides G' and G'' , another parameter derived from SAOS measurements is the phase angle δ , which describes whether the response of the material is more elastic or more viscous (**Fig. 6**) (see section 2.4.2.). The increase of G'' was much less pronounced than that of G' , which was reflected in a decrease of δ with increasing RF levels (**Fig. 6**). Since δ is a measure for the molecular interactions in dough (Létang et al., 1999), the decrease in δ implies that the presence of RF results in the formation of a more structured weak gel network with a more elastic, solid-like behavior. Thus, it appears that there are a great deal of short-range interactions between RF components, which act as sources of elasticity at small shear deformations (Amemiya & Menjivar, 1992).

Fig. 6 Phase angle (δ) as a function of angular frequency (ω) of dough strands prepared with 100% wheat flour (WF) (WF100), 80% WF and 20% rye flour (RF) (WF80-RF20), 60% WF and 40% RF (WF60-RF40), 40% WF and 60% RF (WF40-RF60), 20% WF and 80% RF (WF20-RF80), and 100% RF (RF100). The data represent averages of single measurements of each of three separate dough preparations.

3.2. Rheological behavior of blends made from wheat and rye flour

Considering the remarkable values of $\eta_{e0}^+(\epsilon_{max})$ and $\eta_e^+(\epsilon_{max})$ in the uniaxial extensional measurements, and the strong increase of the dynamic moduli in the SAOS measurements, both with respect to increasing RF content of the doughs, we put forward three hypotheses which may explain the rheological response of the doughs made from WF-RF blends.

3.2.1. Influence of water content

A first factor which may influence the rheology of the WF-RF doughs is their water content. Additional extensional measurements were therefore performed with doughs made from WF and 5.0 ml of water and WF40-RF60 and 5.29 ml of water and compared to the those of doughs produced with optimal water absorption (**Fig. 7**).

Fig. 7 Transient extensional viscosity (η_e^+) as a function of strain of dough strands prepared with 100% wheat flour (WF) (WF100) and a blend of 40% WF and 60% rye flour (RF) (WF40-RF60). The water addition of 5.0 ml and 5.29 ml correspond to the optimal water absorption of WF40-RF60 and WF, respectively. Both $\eta_e^+(\epsilon_{max})$ and $\eta_e^+(\epsilon_{max})$ are influenced by small variations in water content. The data represent means of seven measurements of each of three separate dough preparations.

In the linear region, a clear influence of water content on $\eta_{e0}^+(\epsilon_{max})$ was observed. Indeed, the rheological response of dough at low strains is dominated *inter alia* by starch-starch and gluten-starch interactions. Meerts, Cardinaels, et al. (2017a) suggested that such interactions are highly sensitive to the water content of dough and managed to assess the influence of water content at low to moderate strains in uniaxial extensional measurements via a simple scaling law. In this study, however, we used a value extrapolated to maximum strain [$\eta_{e0}^+(\epsilon_{max})$] instead of the region at low to moderate strains itself, to obtain an indication of the short-range interactions. This extrapolated value has the additional advantage of also taking into account the slope of the straight part of the $\eta_e^+-\epsilon$ curve. While our results show a strong influence of water content on $\eta_{e0}^+(\epsilon_{max})$, they also show that the pronounced difference in $\eta_{e0}^+(\epsilon_{max})$ between WF and WF40-RF60 dough is not solely the result of a variation in water content, but most likely involves a contribution of RF constituents as well.

The value of $\eta_e^+(\epsilon_{max})$ appears to be slightly influenced by water content. Even though the effect is very limited (Meerts, Cardinaels, et al., 2017a), it probably explains why a higher $\eta_e^+(\epsilon_{max})$ was observed for WF40-RF60 than for WF dough (**Table 3**).

Additional SAOS measurements on RF100 doughs with different water levels close to the optimal value confirmed that the dough water content impacts both on G' and G'' (data not shown). For WF doughs this has been shown to be the case as well (Létang et al., 1999; Meerts, Cardinaels, et al., 2017a). However, the effect of the dough water content on the evolution of G' and G'' was much less pronounced than that of the level of RF. Thus, RF constituents rather

than the dough water content are responsible for the increase in G' and G'' when higher RF levels are incorporated in dough.

In conclusion, the water content has an impact on the rheology of the WF-RF doughs at small strains, with lower water levels resulting in a more stiff behavior as evidenced by an increase of $\eta_{e0}^+(\varepsilon_{max})$ and the dynamic moduli. Besides water, RF constituents also appear to play a role in the more stiff behavior of dough made from blends of WF and RF.

3.2.2. Influence of gluten dilution

To elucidate the effect of wheat gluten dilution on the rheology of doughs from WF-RF blends, bread making trials and uniaxial extensional measurements were performed with doughs made from WF-WS blends. **Table 3** lists the specific volumes of the resultant breads. The volume of bread made from the WF80-WS20 blend was not significantly ($P > 0.05$) lower than that of bread made from WF. A similar observation was made for WF80-RF20, indicating that, with the flour used, wheat gluten can be diluted down to 80% of its original level in WF without loss of bread making performance. In contrast, breads made from WF60-WS40 and WF40-WS60 had significantly lower ($P < 0.05$) specific volumes than those made from the WF. However, no additional decrease in bread volume took place when even more starch was used (WF60-WS40 vs. WF40-WS60), while such decrease was observed when an additional 20% of WF was replaced by RF (WF60-RF40 vs. WF40-RF60).

Fig. 8 shows the evolution of η_e^+ as a function of strain for doughs made from WF, WF80-WS20, WF60-WS40 and WF40-WS60 doughs. The $\eta_{e0}^+(\varepsilon_{max})$, $\eta_e^+(\varepsilon_{max})$, and SHI data are summarized in **Table 3**.

Fig. 8 Transient extensional viscosity η_e^+ as a function of strain of dough strands prepared from 100% wheat flour (WF) (WF100), 80% WF and 20% wheat starch (WS) (WF80-WS20), 60% WF and 40% WS (WF60-WS40), and 40% WF and 60% WS (WF40-WS60). Substituting 40% of WF by WS resulted in a global downward shift of the extension curves. The data represent means of seven measurements of each of three separate dough preparations.

Extensional measurements could not be performed on doughs made from WF20-WS80. Strain hardening was observed for doughs made with each of the other blends (**Fig. 8**). Substituting 20% WF by WS had no significant ($P > 0.05$) effect on the SHI of the resultant dough (**Table 3**). Surprisingly, the SHI significantly ($P < 0.05$) increased for WF doughs when 40% WF was substituted by WS (**Table 3**). When 60% WF was substituted by WS, the SHI significantly ($P < 0.05$) decreased. That the SHI strongly decreased when 60% WF was replaced by WS implies that

the concentration of wheat gluten became too low to develop a viscoelastic network. This is in line with the strong decrease of the optimum dough mixing time from 150 s for doughs made with 60% WF and 40% WS to only 105 s for doughs made with 40% WF and 60% WS (**Table 2**). Nevertheless, it is remarkable that, in comparison to what was observed for WF-RF blends, relatively high SHI values were obtained for the WF-WS blends. It thus seems important to investigate the relative contributions of $\eta_{e0}^+(\epsilon_{max})$ and $\eta_e^+(\epsilon_{max})$ to the SHI. Substituting 20% WF by WS had a significant ($P < 0.05$) effect neither on $\eta_{e0}^+(\epsilon_{max})$ nor on $\eta_e^+(\epsilon_{max})$ (**Table 3**). This means that diluting wheat gluten to 80% of its original level had no impact on the rheology of the resulting dough in uniaxial extension. As expected, the gluten network was weakened when 40% WF was substituted by WS. Indeed, $\eta_e^+(\epsilon_{max})$ significantly ($P < 0.05$) decreased (**Table 3**). Substituting 60% WF by WS of course further weakened the gluten network as reflected in a decreased $\eta_e^+(\epsilon_{max})$. For both WF60-WS40 and WF40-WS60 dough a decreased $\eta_{e0}^+(\epsilon_{max})$ was also noted.

There was no correlation between SHI values of doughs from blends of WF and WS and the specific volumes of the breads made from these doughs (**Fig. 9c**). For instance, while the SHI of pure wheat doughs was significantly ($P < 0.05$) lower than that of those made with 60% WF and 40% WS, the bread volume of the former (4.4 cm³/g) was significantly ($P < 0.05$) higher than that of the latter (3.6 cm³/g). We did however find strong linear relations between bread volume and $\eta_{e0}^+(\epsilon_{max})$ ($R^2 = 0.939$) (**Fig. 9a**) as well as between bread volume and $\eta_e^+(\epsilon_{max})$ ($R^2 = 0.966$) (**Fig. 9b**). This arguably implies that the individual values of $\eta_e^+(\epsilon_{max})$ and $\eta_{e0}^+(\epsilon_{max})$ of dough rather than the SHI are related to the quality of breads made from blends of WF and WS.

Fig. 9 Linear correlation between specific bread volume and $\eta_{e0}^+(\epsilon_{max})$ (**a**), specific bread volume and $\eta_e^+(\epsilon_{max})$ (**b**), and between specific bread volume and the strain hardening index (SHI) (**c**) of doughs prepared with 100% wheat flour (WF) (WF100), 80% WF – 20% wheat starch (WS) (WF80-WS20), 60% WF – 40% WS (WF60-WS40), and 40% WF – 60% WS (WF40-WS60).

To sum up, doughs made with blends of WF and WS had a weakened gluten network when the portion of WS in the blend increased, as evidenced by a decrease in the specific bread volume and lower $\eta_e^+(\epsilon_{max})$ readings. In contrast, for the doughs made from blends of WF and RF, for which a similar wheat gluten dilution took place, the value of $\eta_e^+(\epsilon_{max})$ did not decrease. Thus, it appears that the observed changes in the bread making performance and rheology of the WF-RF doughs are not solely related to changes in the wheat gluten content, but also to an influence of the RF

components. The extensional data even suggests that RF constituents, when combined with WF proteins, developed a network similar to that in WF dough, as evidenced by $\eta_e^+(\epsilon_{max})$.

3.2.3. Influence of rye flour components

Considering that neither changes in water content nor gluten dilution were capable of fully explaining the rheology of WF-RF doughs, it is very likely that WF and RF constituents interact and that their interactions affect dough rheology.

First of all, although RF secalins do not form a viscoelastic network the way wheat gluten proteins do, they may be incorporated in the network to some extent by interacting with gluten proteins. Especially considering their high concentration in RF, not only RF secalins, but also albumins and globulins (37 – 51% w/w on RF protein basis) (Redant et al., 2017) may contribute to a network structure.

Secondly, RF AX may also affect dough rheology. In line with values reported in literature (Vinkx & Delcour, 1996), RF had a higher level of TOT-AX (3.1% of dm) than WF (2.5% of dm). Incorporating higher levels of RF in doughs made with blends of WF and RF thus increased the level of AX. The difference in AX concentration between WF and RF primarily originated from a higher level of water-extractable AX (WE-AX) in RF than in WF (**Table 1**). In addition, the populations of wheat and rye WE-AX had different structures. Indeed, the $avDP_n$ (159 ± 13) and arabinose over xylose ratio (0.47 ± 0.01) of WE-AX in wheat dough were significantly ($P < 0.05$) lower than those of WE-AX in rye dough ($avDP_n$ of 288 ± 43 and arabinose over xylose ratio of 0.58 ± 0.01). Interestingly, a remarkably strong linear relation ($R^2 = 0.933$) was observed between $\eta_{e0}^+(\epsilon_{max})$ and the TOT-AX level in dough. It thus seems likely that RF WE-AX is (at least partially) responsible for the increase in $\eta_{e0}^+(\epsilon_{max})$ and, thus, also for the decrease in the SHI of the WF-RF doughs.

AX may affect the strength of the network [i.e. $\eta_e^+(\epsilon_{max})$] in dough via three mechanisms. First, it may impair the hydration and, hence, the network formation of flour proteins due to its high water-holding capacity. Due to its strong water binding capacity (Courtin & Delcour, 2002), the higher level of AX in RF could also, at least partially, explain the increase in G' and G'' (**Fig. 5**) when dough contains more RF. Second, AX may interact with flour proteins thereby interfering with protein-protein interactions. Third, AX may be able to form a network on its own which then may well reinforce the protein network (Courtin & Delcour, 2002). However, the first two mechanisms can reasonably be expected to result in network weakening and thus seem unlikely. In contrast, RF constituents strengthened the network, which suggests that the effect of AX on $\eta_e^+(\epsilon_{max})$ may indeed be related to a network formed by AX.

Thirdly, differences between RF and WF starches may also significantly have affected the rheology of WF-RF doughs. Rye starch granules have a bimodal size distribution. They contain a large fraction (on weight basis) of large-sized A-type granules (85%) and a minor fraction of smaller B-type granules (15%) (Tiny Verwimp, 2007). Besides WF containing a larger portion of the small B-type granules (20-22% on weight basis) (Park, Wilson, Chung, & Seib, 2004; Verwimp et al., 2004), the average diameter of (A-type) rye starch granules ($\pm 31\mu\text{m}$) is slightly larger than that of (A-type) wheat starch granules ($\pm 26\mu\text{m}$) (Gomand, Verwimp, Goesaert, & Delcour, 2011; Verwimp et al., 2004). Singh & Singh (2001) showed that aqueous suspensions of large potato starch granules are characterized by higher G' and G'' and lower δ values than aqueous suspensions of smaller such granules. This illustrates the importance of the size of starch granules for their rheology in aqueous suspensions. It should thus be clear that starch granule dimension can have a profound effect on the response of dough in rheological analyses, which could contribute to the significant increase of the dynamic moduli that was observed, as well as to the increase of $\eta_{e0}^+(\epsilon_{max})$.

All this implies that RF constituents participate in the overall rheology of and network formation in doughs made from blends of WF and RF. More research is however needed to identify such interactions taking place between WF and RF constituents.

4. Conclusions

The rheology of doughs made from blends of WF and RF was studied using non-linear uniaxial extensional and linear SAOS measurements. The former measurements allowed a SHI, which is linearly dependent on the bread volume, to be defined. Both the SHI and bread volume decreased when the level of RF in the dough increased, which is shown to be related to an increase in $\eta_{e0}^+(\epsilon_{max})$. We suggest that not only the SHI can be used as a predictor for bread quality, but rather the interplay between SHI, $\eta_e^+(\epsilon_{max})$ and $\eta_{e0}^+(\epsilon_{max})$. Surprisingly, a substitution of WF by RF did not weaken the network in the mixed grain doughs. Indeed, $\eta_e^+(\epsilon_{max})$, which is a measure of the strength of the network in the dough, for the WF40-RF60 blend was equal to that of WF dough when the influence of water content was taken into account. SAOS measurements showed a pronounced increase in the dynamic moduli with increasing RF levels. Three possible hypotheses were put forward to explain the observed rheological response of the WF-RF doughs. Two of these, namely the influence of water content and the influence of gluten dilution, could not fully explain the rheology of the WF-RF doughs. Instead, it was suggested that RF constituents, and their interaction with WF constituents,

played a major role in the rheology and network formation of the WF-RF doughs. More research is needed to establish the role of certain RF constituent(s) in such network formation. Even so, blends of WF and RF were shown to produce high quality nutrient dense breads provided the level of WF in the blend is at least 60%.

The present, in-depth study on the linear and non-linear rheology of doughs made with blends of WF and RF has improved our understanding of strain hardening in such doughs. It can, thus, serve as basis for modifying dough constituents such as AX or rye proteins to optimize multigrain dough rheology and bread quality.

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641 Figure 1:

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643 Figure 2:

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645 Figure 3:

Figure 4:

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659 Table 1:

<i>Type of flour</i>	<i>Moisture</i> [%]	<i>Protein</i> [% of dm]	<i>TOT-AX</i> [% of dm]	<i>WE-AX</i> [% of dm]	<i>WU-AX</i> [% of dm]
WF	14.4 ± 0.14	14.3 ± 0.02	2.51 ± 0.22	0.54 ± 0.03	1.97
RF	13.3 ± 0.01	4.0 ± 0.01	3.07 ± 0.18	0.96 ± 0.08	2.11

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661 Table 2:

<i>Sample</i>	<i>Water absorption</i> [% w/w on flour basis]	<i>Mixing time</i> [s]
WF	59.5 ± 0.53	180
RF	55.0 ± 0.23	90
WF80 – RF20	57.5 ± 0.12	165
WF60 – RF40	57.0 ± 0.42	165
WF40 – RF60	56.6 ± 0.21	90
WF20 – RF80	56.0 ± 0.35	90
WF80 – WS20	57.5 ± 0.06	150

<i>WF60 – WS40</i>	56.5 ± 0.57	150
<i>WF40 – WS60</i>	56.5 ± 0.60	105
<i>WF20 – WS80</i>	57.5 ± 0.21	90

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663 Table 3:

Sample	Specific bread volume [cm³/g]	$\eta_{e0^+}(\epsilon_{\max})$ [10⁴ Pa.s]	$\eta_{e^+}(\epsilon_{\max})$ [10⁵ Pa.s]	SHI [-]
<i>WF</i>	4.4 ± 0.1^a	3.0 ± 0.2^a	4.3 ± 0.4^{ab}	14.3 ± 0.8^a
<i>WF80 - RF20</i>	4.4 ± 0.1^a	4.9 ± 0.4^b	4.8 ± 0.4^{ac}	9.9 ± 0.6^b
<i>WF60 - RF40</i>	3.6 ± 0.1^b	6.5 ± 0.3^c	5.5 ± 0.4^c	8.4 ± 0.6^b
<i>WF40 - RF60</i>	2.8 ± 0.4^c	11.1 ± 2.1^d	5.2 ± 0.5^c	4.8 ± 0.7^c
<i>WF80 - WS20</i>	4.3 ± 0.3^a	2.7 ± 0.3^{ae}	4.1 ± 0.4^b	15.3 ± 1.1^{ad}
<i>WF60 - WS40</i>	3.6 ± 0.1^b	2.0 ± 0.2^e	3.2 ± 0.3^d	16.2 ± 1.6^d
<i>WF40 - WS60</i>	3.4 ± 0.1^b	2.0 ± 0.3^e	2.5 ± 0.2^e	12.6 ± 1.4^e

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