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Ultrasonic investigation of the effects of composition on the volume fraction of bubbles and changes in their relative sizes in non-yeasted gluten-starch blend doughs

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ABSTRACT

Interactions between water, gluten and starch during dough mixing alter the aeration properties of dough. Effects of composition on dough gas volume fraction and relative changes in bubble sizes of non-yeasted gluten-starch (G-S) blend doughs were investigated using density measurements and an ultrasonic transmission technique, respectively. At fixed water content, greater gluten content increased the air volume fraction, while frequency-dependent ultrasonic attenuation coefficient and phase velocity measurements indicated that the bubble sizes in the G-S doughs were larger. The latter outcome may be due to mixing to optimal conditions such that shorter mixing times for doughs of high gluten content lessened the number of bubble subdivision events during mixing. The effect of increased water content on the attenuation coefficient implied a decrease in mean bubble radius as elucidated using an ultrasonic model. Time evolutions of attenuation coefficient and phase velocity for G-S blend doughs had a similar trend to those of non-yeasted wheat flour doughs. However, the shifts in the frequency of the peaks observed in the ultrasonic parameters were noticeably slower for G-S blend doughs, implying that G-S blend doughs were more stable against disproportionation.

1. Introduction

There is a significant relationship between dough aeration during mixing and the cellular structure of the baked bread (Campbell et al., 2001, 1998). It has been shown that dough aeration is influenced by mixer type (Peighambardoust et al., 2010; Whitworth and Alava, 1999), mixing headspace pressure (Chin et al., 2004; Elmehdi et al., 2004), mixing time (Campbell et al., 1998; Mehta et al., 2009), water content (Chin et al., 2005; Peighambardoust et al., 2010) and various other dough ingredients (Chin et al., 2005; Mehta et al., 2009). Resolving how dough properties are affected by changes in ingredients and mixing process parameters is not a trivial task (Koksel and Scanlon, 2012), so that understanding the mechanisms governing the changes in dough aeration is a longstanding research challenge (Baker and Mize, 1941).

Working with model gluten-starch (G-S) blend doughs enables the role of gluten and starch in dough systems to be probed in a simple way (Uthayakumaran and Lukow, 2003; Watanabe et al., 2002; Yang et al., 2011). The complexity of interactions of protein and starch with other constituents (*e.g.*, pentosans, damaged starch, endogenous lipids and enzymes) is minimized (Petrofsky and Hoseney, 1995; Uthayakumaran and Lukow, 2003), while the use of gluten from one source eliminates variations that arise from proteins of different characteristics. Moreover, non-yeasted G-S blend doughs are relatively stable systems that do not allow bubbles to cream out so that changes in the concentration and sizes of bubbles can be studied as a function of time. Despite the simplifications afforded by G-S blends, it is still experimentally very challenging to study bubbles and their evolution since all doughs lack optical transparency, bubbles change rapidly and they are very fragile (Bellido et al., 2006; Shimiya and Nakamura, 1997; Strybulevych et al., 2012).

Investigations of bubble size distributions (BSDs) in dough have been conducted with several methods, including light microscopy (Carlson and Bohlin, 1978), conventional bench-top X-ray microtomography (Bellido et al., 2006), synchrotron X-ray microtomography (Koksel et al., 2016; Turbin-Orger et al., 2012), magnetic resonance imaging (De Guio et al., 2009), and confocal

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laser scanning microscopy (Upadhyay et al., 2012). Low-intensity ultrasound has also been used to characterize dough aeration (Elmehdi et al., 2004, 2005), because its rapid and non-destructive nature makes it well suited for studying these optically opaque systems (Koksel et al., 2014; Létang et al., 2001; Ross et al., 2004; Scanlon et al., 2008; Strybulevych et al., 2012). Of particular interest in determination of bubble sizes in dough, a broad band of appropriate frequencies can be used to ascertain bubble sizes from the measured ultrasonic parameters, *i.e.*, from the phase velocity and attenuation coefficient (Leroy et al., 2008; Scanlon and Page, 2015). Precise ultrasonic determinations of the bubble size distribution (BSD) in bread dough is still being established (Leroy et al., 2008; Scanlon and Page, 2015), but changes in the distribution are readily accessible from changes in the bubbles' acoustic signature (Koksel et al., 2014; Strybulevych et al., 2012).

To better understand how the various components of the dough matrix interact to alter dough aeration properties, the first objective of this study was to use the bubbles' acoustic signature to investigate how changes in the volume fraction of starch granules and the hydration of the gluten affect the amount of gas occluded into the dough during mixing. The second objective was to investigate the rate of relative change in the BSD in these different "dough" systems based on time-dependent changes in the acoustic signature.

2. Materials and methods

2.1. Sample preparation

Dough ingredient specifications (Koksel and Scanlon, 2012) and sample preparation for ultrasonic measurements (Koksel et al., 2014) are in accordance with previous descriptions. Gluten-starch (G-S) blend doughs of varying composition were prepared by addition of saline solution (3.2% w/w) at 90, 95 and 100% (total G-S blend weight basis). Neither yeast nor leavening agents were used in the G-S blend dough formulation. Therefore changes in bubbles will arise only from disproportionation (Ettelaie and Murray, 2014; van Vliet, 1999). G-S doughs were prepared either by varying gluten content or water content based on weights of gluten and starch, as determined on a 14% m.b. (Table 1). For doughs with varying gluten content, water content was kept constant at 90% (total blend weight basis).

G-S blend doughs at each formulation were prepared using a pin mixer with a 200 g mixing bowl (National MFG. Co., Lincoln, NE, USA). Each G-S blend was mixed (116 rpm) for 1 min prior to water addition and then mixed until its peak time (Table 1) as determined from the mixing curves produced by the pin mixer. Dough temperature at the end of mixing (23 ± 0.5 °C) was controlled by a water circulation unit (Haake C, Berlin, Germany) connected to the mixing bowl.

2.2. Experimental methods

The experimental set-up for testing of doughs was comprised of an ultrasonic pulse generator/receiver (Panametrics, Olympus NDT Waltham, MA, USA), a pair of transducers (central frequency: 2.25 MHz, Olympus NDT Waltham, MA, USA), and a digital oscilloscope (Tektronix Digital Oscilloscope, TDS5032B, Tektronix Inc., Beaverton, OR, USA). A dough subsample was placed between a pair of acrylic delay lines situated between the generating and receiving transducers. The ultrasonic pulse that left the generating transducer was transmitted through the first delay line, the dough subsample, the second delay line and then it was detected by the receiving transducer. To create the reference signal, a signal was acquired with the delay lines in direct contact (Koksel et al., 2014).

The first ultrasonic signal was recorded 15 min after the end of mixing, and then every 15 min for 2 h so that changes in the signal could be followed as a function of time. All ultrasonic experiments were performed inside a temperature (23 ± 0.1 °C) and humidity (85 ± 1.0% relative humidity) controlled cabinet (Caron Products and Services Inc., Model: Caron 6010, Marietta, OH, USA).

The ultrasonic attenuation coefficient (α) and phase velocity (v) depend on the magnitudes and phases of the Fourier transforms, respectively, and were calculated according to Koksel et al. (2014). The acquired signals were corrected in order to account for the acoustic impedance mismatch at the dough-acrylic delay line interfaces (Fan et al., 2013).

Dough density (ρ) measurements were performed in a specific gravity bottle by water displacement (Koksel and Scanlon, 2012). Dough matrix density (ρ_M) was estimated by applying the rule of mixtures, considering the density and mass of gluten, starch, salt (NaCl) and water. Using a pycnometer, the densities of gluten and starch were measured as 1285 kg/m^3 and 1469 kg/m^3, respectively (Koksel and Scanlon, 2012). Air volume fraction (Φ) was calculated from dough density and matrix density [$\Phi = (1 - \rho/\rho_M) \times 100$ when expressed as a percentage].

3. Results and discussion

3.1. Effects of gluten, starch and water on dough density

The effects of composition on dough density, dough matrix density and air volume fraction are shown in Table 2. At a given water content, dough density decreased as gluten content increased, which resulted in a greater air volume fraction since the calculated dough matrix density decreased only slowly with increasing gluten. This result accords with the results of Koksel and Scanlon (2012), who reported that when doughs are mixed for a fixed period of time, dough density decreases as gluten content increases. Thus, even though longer mixing times promote air entrainment in dough (Mehta et al., 2009), these results indicate that gluten content has a pronounced effect on air entrainment since optimal development for the higher gluten content samples required shorter mix times (Table 1).

An increase in water content did not substantially affect dough density (Table 2). It has previously been reported that lowering water content (from optimum farinograph absorption to 5% below optimum) depresses the density of wheat flour doughs (Peighambardoust et al., 2010) and G-S blend doughs mixed for a fixed time (Koksel and Scanlon, 2012). The difference between the results of our study and those reported by Peighambardoust et al. (2010) and by Koksel and Scanlon (2012) can be partially attributed to the high water contents in our G-S blend doughs and the mixing protocol used for the G-S blend doughs in our study, which were mixed to their peak time. If a fixed mixing time (longer than the peak time) had been chosen, the enhanced air entrainment effect of long mixing time (Campbell et al., 1998; Mehta et al., 2009) would be expected to dominate over the hydration effects occurring at shorter mixing times (Koksel and Scanlon, 2012), so that void fractions would be larger for drier G-S blend doughs with lower peak times. Since each G-S blend dough formulation is mixed until its peak time, continuous air occlusion during overmixing was not an issue for the dough samples in this study. The cohesion of starch granules and protein in G-S blend doughs during mixing differs from that in wheat flour doughs (Koksel and Scanlon, 2012). Accordingly, there is a significant interaction of water content and mixing time for this atypical dough system that influences the aeration of G-S blend doughs.

Table 1
Composition and mixing peak times of Gluten-Starch (G-S) blend doughs.

Gluten-Starch Blend		Water (% TBWB[a])	Peak time (min)
15% Gluten - 85% Starch	(15G-85S)	90	9
20% Gluten - 80% Starch	(20G-80S)	90	7.7
25% Gluten - 75% Starch	(25G-75S)	90	7
25% Gluten - 75% Starch	(25G-75S)	95	9.2
25% Gluten - 75% Starch	(25G-75S)	100	13.7

[a] TBWB: Total blend weight basis.

Table 2
Composition and dough matrix densities of Gluten-Starch (G-S) blend doughs.

G-S blend	Water (% TBWB[a])	Density (kg/m^3) ± sd[b]	Matrix density (kg/m^3) ± sd[c]	Air volume fraction (%) ± sd[c]
15G-85S	90	1148 ± 5	1247 ± 4	7.92 ± 0.04
20G-80S	90	1133 ± 4	1242 ± 4	8.74 ± 0.04
25G-75S	90	1127 ± 4	1237 ± 4	8.90 ± 0.04
25G-75S	95	1121 ± 4	1232 ± 4	8.97 ± 0.04
25G-75S	100	1122 ± 6	1227 ± 4	8.57 ± 0.05

[a] TBWB: Total blend weight basis.
[b] sd = Standard deviation; n = 6.
[c] sd = Standard deviation as propagated errors.

3.2. *Effect of gluten on attenuation coefficient and phase velocity at 30 min after mixing*

The effects of gluten content on the attenuation coefficient (α) and phase velocity (v) of G-S blend doughs at constant water content (90% on total blend weight basis) are displayed in Fig. 1a and b, respectively. There is a gap between ~4 and 6.5 MHz in the frequency dependence of the measured ultrasonic parameters. The high frequency results are accessible because, although the central frequency of the transducers is 2.25 MHz, the transducer can also be operated at odd harmonics of its resonance frequency (third harmonic in our case). Regardless of this gap, the velocity and attenuation coefficient values interpolate well between the two regions, so that the frequency-dependence of α and v in highly hydrated G-S blend doughs can be seen to be very similar to that of bubbly media (Leroy et al., 2011) and wheat flour doughs (Leroy et al., 2008; Strybulevych et al., 2012).

Both α and v were sensitive to gluten content. For α, both the frequency at which the peak occurred ($f_{\max}$) and the magnitude of this peak were quite strongly influenced by gluten content: as gluten content increased, $f_{\max}$ shifted to lower frequencies (Fig. 1a). The advantage of identifying $f_{\max}$ as an appropriate single parameter to characterize the changes in α is that $f_{\max}$ can be linked to the resonant frequency, f_0, of the bubbles, as is explained in the following paragraph. This connection is useful since the bubble resonant frequency is directly related to bubble size in the dough and to dough matrix properties, as can be seen from the expression for the resonant frequency of bubbles of radius R_0 (Leroy et al., 2011; Strybulevych et al., 2012):

$$(2\pi f_0)^2 = \frac{3\kappa p_0 + 4G'}{\rho_M R_0^2} \tag{1}$$

Here κ is the polytropic index for the gas (air) in the bubble ($\kappa = 1.4$ for air), p_0 is the static pressure of the gas in the bubble, ρ_M is the density of the dough matrix, and G' is the real part of the complex shear modulus of the dough matrix (Leroy et al., 2011; Strybulevych et al., 2012).

The relationship between f_0 and $f_{\max}$ is particularly simple in a low viscosity fluid-like medium containing a monodisperse distribution of bubbles; then f_0 and $f_{\max}$ are equal (Leroy et al., 2011). If the distribution of bubbles in the medium is polydisperse, $f_{\max}$ corresponds to the resonance frequency of bubbles near the peak in the distribution of radii. For the frequently encountered case of a lognormal bubble size distribution (BSD), this condition holds so long as the width of the distribution, ε (logarithmic standard deviation), or polydispersity factor, is less than ~0.5. Hence, only for rather weak polydispersity ($\varepsilon < 0.1$) does $f_{\max}$ correspond to bubbles with the median radius of a lognormal distribution. When the bubble size distribution becomes more polydisperse, and/or when bubbles reside in a high viscosity matrix (as in the case for wheat flour and G-S blend doughs), the peak in the attenuation becomes broader and $f_{\max}$ shifts to higher frequencies. As a result, the bubble radius obtained from $f_{\max}$ using equation (1) is close to the radius of the small bubbles in the distribution (Leroy et al., 2011). This means that the R_0 obtained from $f_{\max}$ will be an underestimation of the median of the bubbles' lognormal distribution. Accordingly, the discussion on how G-S blend dough formulation affects the bubble sizes estimated from $f_{\max}$ is presented in relative, rather than absolute, terms.

It has been reported for different types of flour (10.3–17.5% protein content on a dry basis) that an increase in flour protein content leads to an increase in G' (Navickis et al., 1982). The same trend, an increase in G' with an increase in gluten content, was also observed for G-S blend doughs at constant water content (Hibberd, 1970). Correspondingly, for our G-S blend doughs, an increase in gluten content would be expected to shift $f_{\max}$ to higher values based on the effect of the shear modulus of the matrix on resonant frequency [equation (1)]. An increase in gluten content leads to a decrease in ρ_M (Table 2), which would also be expected to shift $f_{\max}$ to higher values. Therefore, one would expect, considering how ρ_M and G' are affected by gluten content, that $f_{\max}$ should increase as gluten content increases. Our results point to the opposite. In order for $f_{\max}$ to decrease as gluten content increases, two conditions need to be satisfied: (1) bubble radii must increase as gluten content increases so that $f_{\max}$ shifts to lower frequencies; (2) the effect of bubble radius on $f_{\max}$ has to be more pronounced than the sum of the effects of G' and ρ_M that tend to increase $f_{\max}$.

The creation of larger bubbles with a greater amount of gluten is a likely outcome of mixing time differences. The number of bubbles broken up per unit dough volume is expected to increase as mixing time increases, since the number of mixer revolutions, and thus dough deformation events, increase with increasing mixing time. For mechanically developed non-yeasted wheat flour doughs, a decrease in mean bubble size with increasing mixing time has been previously reported using bench-top X-ray microtomography (Trinh et al., 2013). Accordingly, a decrease in R_0 for lower gluten content blends for which optimum development took relatively longer (Table 1) is expected, as shown by the ultrasonic experiments.

The shift in the position of the peaks in α to lower frequencies as gluten concentration increases is consistent with a similar effect on the peak associated with the rapid changes in velocity (Fig. 1b) due to bubble resonance (Povey, 1997). For phase velocity, the peak associated with bubble resonance occurs at a higher frequency than that observed for the attenuation coefficient (Koksel et al., 2014; Leroy et al., 2008; Strybulevych et al., 2012). Peaks in the phase velocity are centered around ~3.5 MHz and ~4 MHz for G-S blend formulations containing 25 and 20% gluten, respectively (Fig. 1b). An extrapolation of the phase velocity for the blend containing 15% gluten indicates a peak in v at ~5 MHz. Therefore, two different measurements - attenuation coefficient and ultrasonic velocity - indicate that bubble size in the G-S blend doughs is reduced at lower gluten content due to the enhanced bubble subdivision that is brought about by longer mixing times.

At frequencies higher than the resonance frequency of the

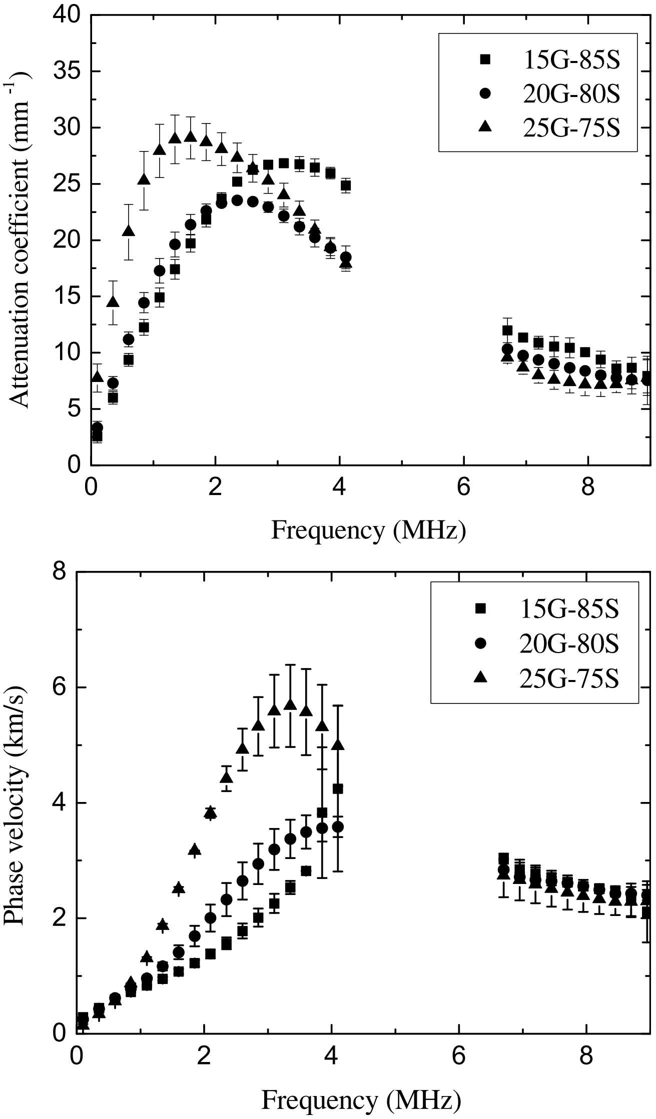

Fig. 1. Frequency dependence of (a) attenuation coefficient and (b) phase velocity of Gluten-Starch (G-S) blend doughs of different gluten contents.

bubbles, the ultrasonic velocity is expected to approach the velocity of sound propagating in the dough matrix (v_M) (Leroy et al., 2011, 2008). However, our phase velocity values had not leveled out at the high frequency end of our transducer bandwidth. The highest frequency attainable with the present ultrasonic technique was ~9 MHz, and at this frequency, phase velocity values were still declining, indicating that the bubble resonance signature was still evident. For aerated wheat flour doughs, it has been reported that v of ultrasound at frequencies higher than the resonance frequency of bubbles reached approximately 1.9 km/s (Leroy et al., 2008), whereas for G-S blend doughs we would expect from these results that v would asymptote to a higher value, approximately 2.5 km/s (Fig. 1b), pointing to a difference in matrix properties between doughs prepared from wheat flour (Leroy et al., 2011, 2008) and gluten-starch blends.

3.3. *Effect of water on phase velocity and attenuation coefficient at 30 min after mixing*

The effect of water content on α and v of G-S blend doughs at constant gluten content (25% on a 14% m.b.) are displayed in Fig. 2a and b, respectively. The overall frequency-dependences of α and v were again similar to what one would expect for aerated wheat flour doughs (Koksel et al., 2014; Leroy et al., 2008; Scanlon and Page, 2015; Strybulevych et al., 2012), regardless of water content.

Both α and v were sensitive to water content. For α, the magnitude of the peak was dependent on the water content, an effect that was also noted in measurements at a frequency of 4.5 MHz by Létang et al. (2001), who investigated the physical properties of wheat flour-water systems using ultrasound and found that the acoustic properties of doughs were sensitive to water content and mixing time. In contrast to the effect of gluten content, neither the $f_{\max}$ for attenuation nor the position of the peak in v were substantially affected by the changes in water content.

In order to explain the behavior observed for the water content with respect to $f_{\max}$, the contributions of G', ρ_M and R_0 need to be considered. Water content strongly affects the viscoelastic behavior of dough. A decrease in G' with an increase in water content has been reported previously for wheat flour doughs (Hibberd and Wallace, 1966; Létang et al., 1999; Mastromatteo et al., 2013; Song and Zheng, 2007; Upadhyay et al., 2012) and for G-S blend doughs at constant gluten content (Hibberd, 1970). When the water content of dough was increased by 15% on a flour weight basis, G' decreased by more than 20-fold (Masi et al., 1998). An increase in water content, and thus a decrease in G', would be expected to shift $f_{\max}$ towards lower frequencies [based on equation (1)]. This was not observed. According to Table 2, an increase in the water content resulted in a decrease in ρ_M which should shift $f_{\max}$ towards higher frequencies, again not observed in these experiments.

Given that $f_{\max}$ remained almost constant with changes in water content (Fig. 2a), our results imply that the decrease in G' with increasing water content is balanced by the decrease in ρ_M together with a decrease in R_0 as water content increases. Decreased bubble size with greater dough water content is expected because water content affects dough development time, *i.e.*, higher water content leads to longer development times and thus a higher number of mixer revolutions. Even though larger bubble sizes were reported with increasing water content, and with increasing water content and reduced salt concentration, respectively, from confocal laser scanning microscopy (Upadhyay et al., 2012) and X-ray microtomography experiments (Bellido et al., 2006), one must keep in mind that in those studies, a fixed mixing time was chosen.

The position of the peak in ultrasonic velocity did not exhibit a pronounced dependence on water content (Fig. 2b), in contrast to its dependence on gluten content (Fig. 1b). Therefore, the lack of a water effect on the position of the velocity peak concurs with the attenuation coefficient results. Towards the high frequency limit of our ultrasonic tests (6.5–9 MHz), v for doughs of different water contents approached one another. A high frequency value for v_M cannot be reported for G-S blend doughs with varying water contents due to the persisting confounding effect of bubbles at the highest frequency attainable, as for the results of the varying gluten content experiments.

3.4. *Time evolutions of ultrasonic phase velocity and attenuation coefficient*

The time evolutions of α and v for the 25G-75S blend at 100% water content are presented in Fig. 3a and b, respectively. The results for the 25G-75S blend at 100% water content were typical of results for all the G-S blend dough formulations. The position of the peak in α for G-S blend doughs had a tendency to slightly shift to a lower frequency by 2 h (from 1.60 MHz at 30 min, to 1.45 MHz at 1 h, and then to 1.40 MHz at 2 h after the end of mixing, Fig. 3a).

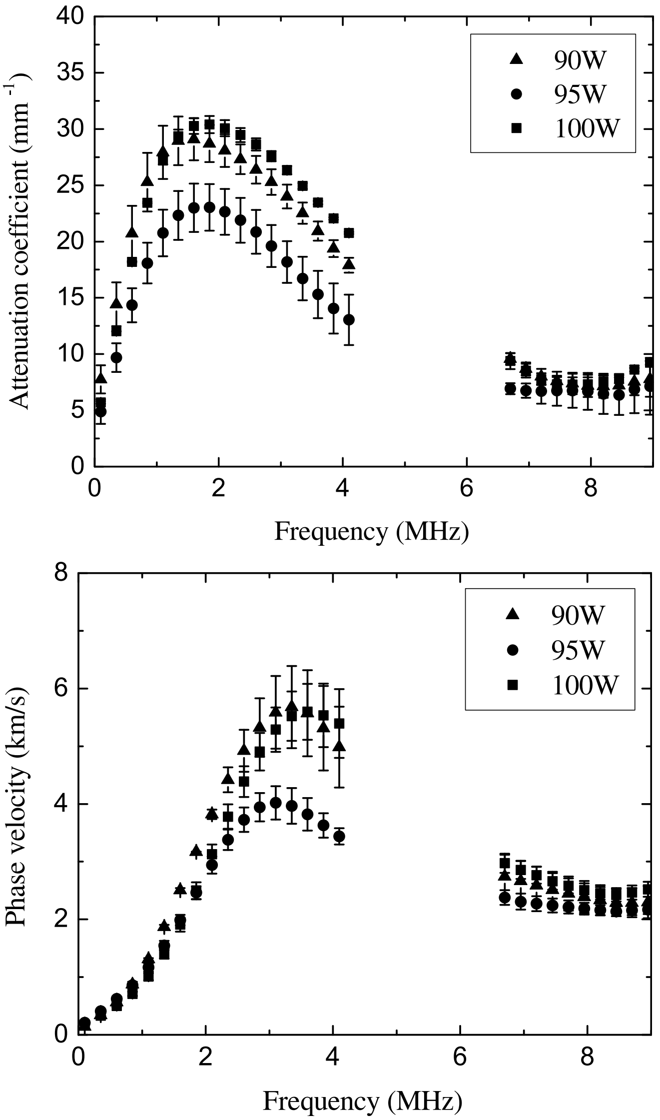

Fig. 2. Frequency dependence of (a) attenuation coefficient and (b) phase velocity of 25% Gluten-75% Starch (25G-75S) blend doughs as a function of water (W) content, expressed on a total blend weight basis.

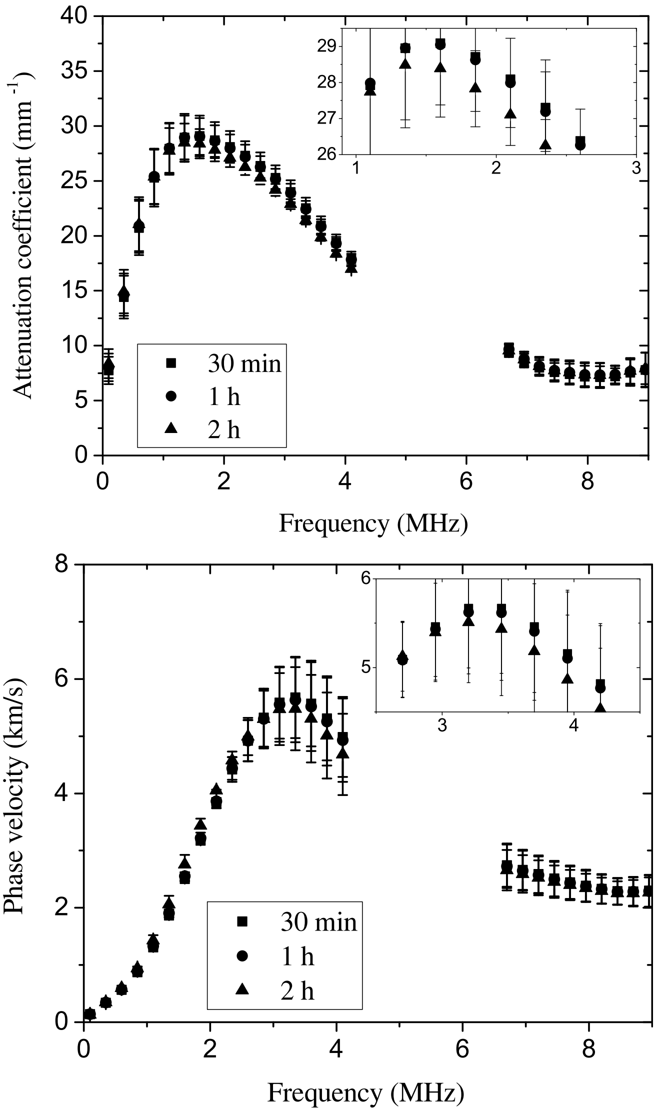

Fig. 3. Time evolutions of (a) attenuation coefficient and (b) phase velocity of 25% Gluten-75% Starch (25G-75S) blend dough at 90% water (total blend weight basis). Insets: expanded scales for the peaks of (a) attenuation coefficient and (b) phase velocity.

This trend in peak position has been previously reported for the time evolution of non-yeasted wheat flour doughs (Leroy et al., 2008), indicative of disproportionation (bubbles growing in size with time) (Kokelaar and Prins, 1995; Shimiya and Nakamura, 1997; Shimiya and Yano, 1988; van Vliet, 1999). However, the change in α for G-S blend doughs was markedly slower compared to that observed for non-yeasted wheat flour doughs (Leroy et al., 2008). Thus, G-S blend doughs exhibit slower rates of disproportionation.

Since the same mixer headspace gas composition (air) was used for G-S blend formulations and the non-yeasted wheat flour doughs of Leroy et al. (2008), the slow disproportionation rate for G-S blend doughs needs to be related to one or more of the following factors: the surface rheological properties of the adsorbed layer at the bubble interfaces (Blijdenstein et al., 2010; Murray et al., 2005), the bulk rheological properties of G-S blend doughs (Kloek et al., 2001), air volume fraction, and parameters describing the BSD, such as the mean distance between bubbles (Magrabi et al., 1999; van Vliet, 1999).

The importance of interfacial properties in determining the rate of disproportionation of air bubbles stabilized by proteins has previously been reported (Meinders et al., 2003). Ronteltap and Prins (1990) studied the stability of beer foams, and concluded that beer types with a higher interfacial dilational modulus (ratio of the change in interfacial tension to the relative change in surface area) had slower disproportionation rates. Similarly, in a study of disproportionation rates in oil-in-water emulsions where the elastic modulus of the interface was enhanced by coating the surface of oil droplets, mechanical resistance at the interface altered rates of shrinkage or growth of the oil droplets (Mun and McClements, 2006). A slower disproportionation rate in G-S blend doughs is therefore potentially attributed to their higher interfacial dilational modulus compared to that of wheat flour dough or a larger interfacial elastic modulus because of their higher gluten content.

Bubbles can also be stabilized by insoluble small particles (Murray et al., 2005). These particles arrange themselves by adsorbing onto the surface of bubbles as inflexible monolayer networks (Yusoff and Murray, 2011). The energy required to displace particle stabilizers from the surface of a shrinking bubble counterweighs the free energy reduction associated with disproportionation, so that particles act as a barrier to inter-bubble gas diffusion that is driven by Laplace pressure differences (Ettelaie and Murray, 2014). The binding of starch and protein during mixing differs between wheat flour doughs and G-S blend doughs (Koksel and Scanlon, 2012); the loss of free starch granules from the dough mass upon handling such G-S blend doughs was a notable feature. As a result, the starch granules in G-S blends may form monolayer networks around the bubbles in a way that that they do not in a conventional dough. The slower disproportionation rate observed for G-S blends doughs may therefore also be attributed to the stabilizing effect of free starch granules at the bubble interfaces.

Alternatively, bulk rheological properties of dough could also be considered. In an analysis of disproportionation rates in air bubbles injected into water that were stabilized by various food proteins (*e.g.*, gelatin, whey protein isolate, etc.), it was observed that interfacial rheological properties had only limited effects (Dickinson et al., 2002). According to Kloek et al. (2001), the effect of shear elasticity (G') dominates over other rheological parameters for slowing down the shrinkage of bubbles or for stabilizing them. Although a direct comparison cannot be made between the G-S blends used in the current study and those in Hibberd (1970), higher values of G' in G-S blend doughs (Hibberd, 1970) compared to non-yeasted wheat flour doughs are another potential mechanism to explain the slow disproportionation rate in G-S blend doughs.

4. Conclusion

An ultrasonic transmission technique has been used for monitoring the relative changes in bubble sizes and their time evolution as a function of gluten, starch and water content in non-yeasted G-S blend doughs. Frequency-dependent peaks in attenuation coefficient and phase velocity, characteristic of a low frequency bubble resonance, were seen for all G-S blends. Based on interpretation of ultrasonic results, gluten content affected the mean bubble radius entrained into the G-S blend doughs during mixing. The effect of water content on the bubble size distribution was partly offset by changes in dough rheology as a function of water content, and thus no substantial change in the peak position in attenuation coefficient was observed. Slower disproportionation rates were observed for G-S blend doughs compared to wheat flour doughs, an effect likely due to the larger interfacial elasticity of G-S blend doughs of high gluten content, a stabilizing effect of loose starch granules, or a higher shear elasticity for G-S blend doughs.

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