Using Low Frequency Ultrasound to Evaluate the Properties of Wheat Flour Doughs

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ABSTRACT

As a result of an NSERC-funded Strategic grant program, we have undertaken a thorough examination of the physical properties of wheat flour doughs using low intensity ultrasound. Because ultrasound is particularly sensitive to bubbles contained within the dough's viscoelastic matrix, measurements of ultrasonic velocity and attenuation over a wide range of frequencies have allowed us to identify three distinct regions that are associated with the mechanical response of the dough matrix and the bubbles. In this paper we summarize only the new information on dough properties derived from ultrasonic measurements at low frequencies; in this region the properties of the dough as a whole (matrix and bubbles) are investigated. We investigate how the properties of doughs are affected by surface-active bakery ingredients, arising either from altered dough matrix properties or from altered bubble entrainment capacity during the mixing process. Ultrasound techniques can also be combined with large strain techniques. By subjecting samples of dough to uniaxial compression and monitoring their relaxation with ultrasound, bubbles are seen to substantially affect the short-time relaxation behaviour of air-mixed dough samples. Although ultrasound is a low strain technique, ultrasonic measurements of doughs made from flours with a range of breadmaking quality correlate well with parameters acquired from conventional large strain techniques such as the alveograph and farinograph. In conclusion, ultrasound is an emergent technique with the potential to provide interesting new information on dough properties.

INTRODUCTION

The propagation of sound at low intensity and at high frequencies (>18 kHz) is a useful materials' characterization technique that has been used to investigate the physical properties and structure of materials. Many foods have been analyzed with ultrasound including wheat flour doughs (Kidmose et al 2001; Létang et al 2001;

Elmehdi et al 2004; Skaf et al 2009). The emphasis on low intensity is to distinguish ultrasound as a materials characterization tool from high intensity ultrasound (sonication) that has been routinely used to solubilize high molecular weight gluten proteins (Stevenson and Preston 1996; Ammar et al 2000; Singh and MacRitchie 2001). Longitudinal ultrasonic pulses with wavelengths larger than the mean gas bubble size would appear to be promising analytical techniques for evaluation of the quality of aerated wheat products (Campbell et al 1998) since bubbles profoundly affect product quality (Shah et al 1998; Cauvain et al 1999; Babin et al 2006). The sensitivity of ultrasound to bubbles arises from the big difference in compressibility of the dough matrix and the gas in the bubbles, and the big difference in density between condensed phases and gases (Elmehdi et al 2004; Leroy et al 2008a). Nevertheless, changes in dough matrix properties (brought about, for example, by changes in ingredients or processing) will also affect the measured ultrasonic properties.

After longitudinally-polarized ultrasonic pulses have propagated through a dough sample, we are able to derive information on the structure and rheology of the dough from two of the pulses' propagation characteristics - the velocity and the attenuation coefficient (Létang et al 2001; Elmehdi et al 2004). Because dough is a viscoelastic material, the velocity of propagation of ultrasound at a specific frequency is normally expressed in complex notation so that ultrasonic measurements can be related to rheological parameters such as a complex modulus. Where elastic properties of the dough dominate, independent measurements of density (ρ) and velocity (v) allow the longitudinal elastic modulus to be determined:

$$\beta = v^2 \rho \qquad (1)$$

In turn, the longitudinal modulus is related to the bulk (K) and shear (G) modulus of the dough, and in the elastic case it can be expressed as:

$$\beta = K + \frac{4}{3} G \qquad (2)$$

In a soft viscoelastic material such as dough, the bulk modulus is very much greater than the shear modulus, and so the dilatational resistance of the dough dominates in measurements of ultrasonic velocity. In a liquid, the shear modulus is zero so that the longitudinal modulus is equivalent to the bulk modulus and inversely related to the compressibility (κ).

Additional information on the material properties and the structure of heterogeneous systems such as dough is provided by the attenuation coefficient (α). As the pulse propagates, some of the acoustic energy is absorbed (α_a), with extra dissipation occurring at the interface of inclusions and matrix in heterogeneous media such as dough. Scattering of sound also contributes to attenuation (α_s), so that the total attenuation coefficient is the sum of that due to both absorption and scattering:

$$\alpha = \alpha_a + \alpha_s \qquad (3)$$

The goal of this paper is show that low-intensity ultrasound can be used to investigate how the gas bubbles and the dough matrix affect the rheological properties of viscoelastic bread doughs, and more specifically to attempt to answer the question, what technologically useful information on dough properties can we obtain from measurements of ultrasonic velocity and attenuation at low frequencies?

THE MECHANICAL SPECTRUM OF DOUGH

The amount of air entrained into a dough during mixing depends on a number of factors, such as the viscosity of the dough, which in turn is dependent on flour strength (Campbell et al 1993) and dough composition (Bellido et al 2006), especially its water content, the type of mixer (Cauvain et al 1999), the duration of mixing (Mehta et al 2009) and the headspace pressure above the dough in the mixing bowl (Campbell et al 1998; Elmehdi et al 2004). A typical gas content figure is about 10% by volume at optimum mixing time when mixed at atmospheric pressure, which translates into the miniscule value of about 0.01% by mass. Despite being seemingly inconsequential as an ingredient, air has an astonishing effect on the mechanical spectrum of dough as evaluated by the propagation of longitudinal ultrasonic pulses. In fact, the mechanical spectrum of dough, from the audible region right up to ~10 MHz, is dominated by the presence of bubbles within the dough.

In Fig. 1, the ultrasonic velocity and attenuation coefficient of dough made without yeast are shown as a function of frequency. The defining feature of Fig. 1 is the pronounced change in velocity and the peak in attenuation that occurs in the low MHz region of the spectrum which demarcates the spectrum into three distinct regions.

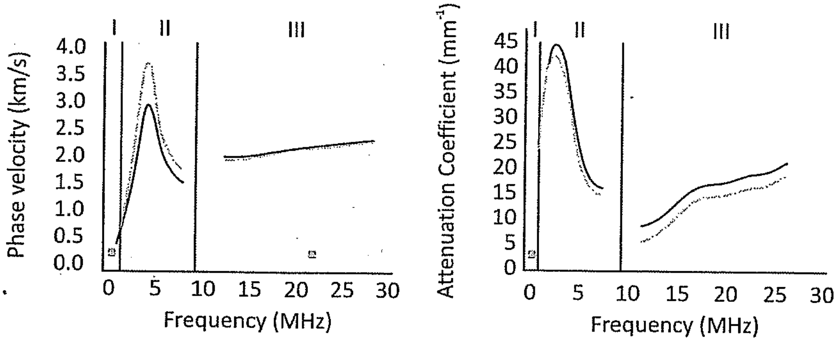

Fig. 1. The three regions of the mechanical spectrum of dough from phase velocity (left) and attenuation coefficient (right) measurements taken 2 min (solid lines) and 20 min (dashed lines) after sample preparation.

In region I, at low frequencies (long wavelengths), the dough behaves as an effective medium with ultrasound sensitive to the composite properties of both dough matrix and the bubbles it contains. Ultrasonic pulses propagate with very low velocity (cf., the velocity of sound in air and water, which are 330 and 1500 respectively) and the amplitude of the pulse is only moderately attenuated (Elmehdi et al 2004).

In region II, the bubbles respond in phase opposition to the acoustic energy of the incoming wave. It is in this region that the ultrasonic frequency matches the resonance frequency of the bubbles (Leroy et al 2008b). As a result of this bubble resonance, the phase velocity and the attenuation coefficient undergo substantial changes as a function of frequency. One outcome from the strong interaction of sound of a specific wavelength with bubbles of a specific size is the potential to use the frequency dependence of the phase velocity and attenuation coefficient in this bubble resonance region to determine the mean size and distribution of bubbles within the dough (Strybulevych et al 2007; Leroy et al 2008a,b, 2009).

In region III, the short wavelength ultrasound no longer "sees" the bubbles within the dough and the phase velocity approaches the velocity of sound in the dough matrix, while the attenuation coefficient attains much lower values than at resonance (although still considerably larger than in Region I and rising with the square of frequency (Litovitz and Davis 1965)).

It can be shown that the bubbles in the dough are truly responsible for the landscape of the mechanical spectrum by mixing dough under high vacuum so that the attenuation peak disappears and the low velocity region (I) is non-existent (Elmehdi et al 2005; Scanlon et al 2008). The rest of this chapter is focused on measurements made in region I, where the dough can be viewed as a "composite" material of bubbles embedded within a dough matrix. In addition, because the attenuation coefficient is low in region I, it is experimentally easier to acquire information on dough properties.

EXPERIMENTAL ANALYSES

All ultrasonic measurements were performed in transmission using longitudinally polarized ultrasonic pulses using pairs of 50 kHz transducers. Full experimental details have been provided by Elmehdi et al (2004), Fan (2007) and Mehta et al (2009). After mixing, sub-samples were excised from the dough piece and placed between the transducers and compressed to various pre-defined thicknesses. From plots of pulse transit time versus sample thickness, ultrasonic velocity was determined. Similarly, from plots of the exponential decay of signal amplitude as a function of sample thickness, the ultrasonic attenuation coefficient was determined. These two parameters, ultrasonic velocity and attenuation coefficient were used to characterize the properties of the dough.

The density of dough (ρ) was measured separately based on Archimedes principle. By mixing the dough under vacuum, few bubbles are entrained, and so the gas-free dough density (ρ_m) can be evaluated (Baker and Mize 1941; Campbell et al 1993, Elmehdi et al 2004). From the densities the volume fraction of bubbles can be determined:

$$\phi = 1 - \frac{\rho}{\rho_m} \qquad \text{.......} (4)$$

BUBBLE EFFECTS – MIXING UNDER PARTIAL VACUUM

One way of examining the effects of bubbles on the ultrasonic parameters is to mix the dough under different partial pressures. By mixing dough at a series of decreasing partial pressures, successively fewer bubbles are entrained (Campbell et al 1998) and so it is possible to evaluate dough compressibility as a function of the volume fraction (ϕ) of bubbles in the dough. The plot of velocity against bubble volume fraction (Fig. 2) changes little as pressure is lowered until at approximately 0.25 atm, when bubble volume fraction is less than 0.02, the velocity begins to rise at a rapid rate as less air is entrained. This rapid increase can be understood on the basis of the dough as a two-phase material with a highly compressible phase (air) and an essentially incompressible phase (dough matrix). The compressibility of the dough as a whole depends on these two compressibilities weighted according to their respective volume fraction:

$$\kappa_{dough} = \kappa_{air}\phi + \kappa_{doughmatrix}(1-\phi) \quad \text{.......................................} (5)$$

The curve denoted as Wood's approximation in Fig. 2 shows similar behaviour to that of dough indicating that dough behaves like other two-phase systems such as bubbles in water (Povey 1997). However, Wood's approximation underestimates the velocity at all volume fractions because the model neglects the shear modulus of the dough matrix (i.e., the dough's viscoelastic nature contributes to its velocity (Elmehdi et al 2004)).

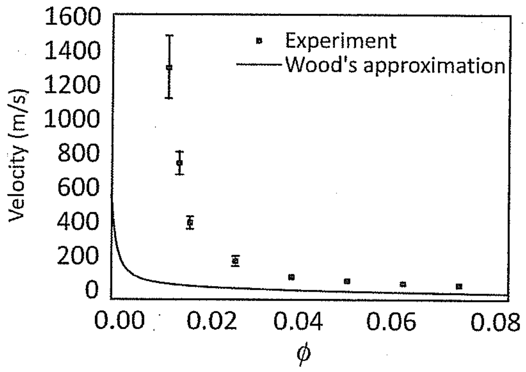

Fig. 2. Change in velocity against variation in bubble volume fraction induced by mixing under different partial pressures.

BUBBLE EFFECTS – MIXING FOR VARIOUS TIMES

Doughs mixed for longer times are less dense since more bubbles are entrained (Campbell et al 1993). This is illustrated by comparing the density of hard red spring wheat flour dough prepared by mixing for different times under air or under vacuum (Fig. 3). Little change in dough density is apparent regardless of how long the dough is mixed under vacuum, but density almost steadily decreases in the doughs that are mirrored by the decrease in velocity with increasing mixing time (Fig. 3, left hand axis). The exception occurs at the optimum mixing time of 5.6 min, where a discernible shoulder in the velocity drop occurs. The presence of the shoulder may be due to an increase in velocity brought about by a maximal alignment of glutenin polymers (Bloksma 1990) that causes the dough matrix to stiffen, and this offsets the drop in ultrasonic velocity brought about by increasing numbers of bubbles.

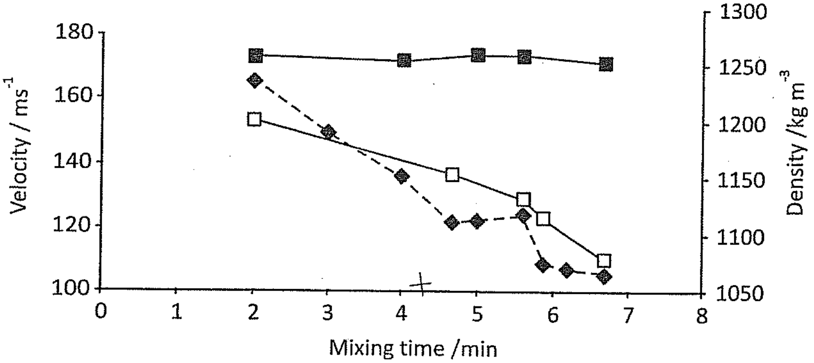

Fig. 3. Change in velocity (left axis, closed diamonds) and density (right axis, mixed in air (open squares) or vacuum (closed squares)) as a function of mixing time.

INGREDIENT EFFECTS – MIXING FOR VARIOUS TIMES

Although there is a substantial effect of bubbles on the ultrasonic velocity, the presence of the shoulder in Fig. 3 intimates that ultrasonic measurements are sensitive to changes in the material properties of the dough matrix. Because water has a profound effect on the conventional rheological parameters of dough (Dreese et al 1988), water is expected to also influence the ultrasonic properties of dough. This is seen to be the case for a red winter wheat flour (CDC Falcon) made into doughs with different amounts of water and mixed for various times (Fig. 4). The drier doughs have larger velocities at a given mix time, consistent with the dough being less compressible with less water (Kidmose et al 2001; Létang et al 2001). As before, air bubble content strongly influences the ultrasonic velocity (more bubbles with longer mixing time lowering velocity), but the effect is amplified when the dough is drier. Although speculative without performing controlled experiments, it is conceivable that the changes in velocity with mixing time are not exclusively due to bubbles since sensitivity of ultrasonic velocity to work input has been observed in extruded doughs of lower water content (Owolabi et al 2008).

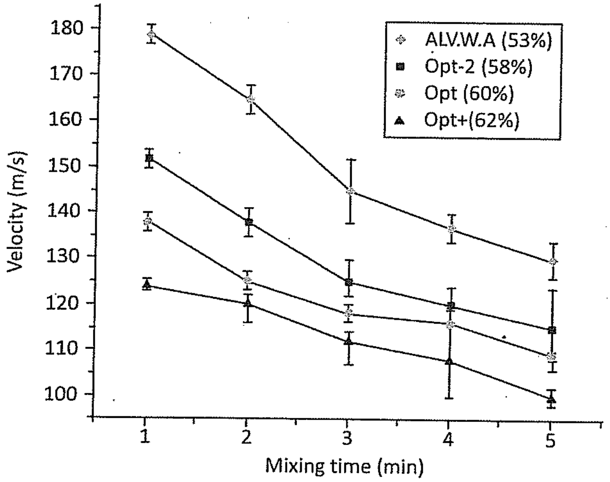

Fig. 4. Change in velocity with mixing time for doughs made with different water content.

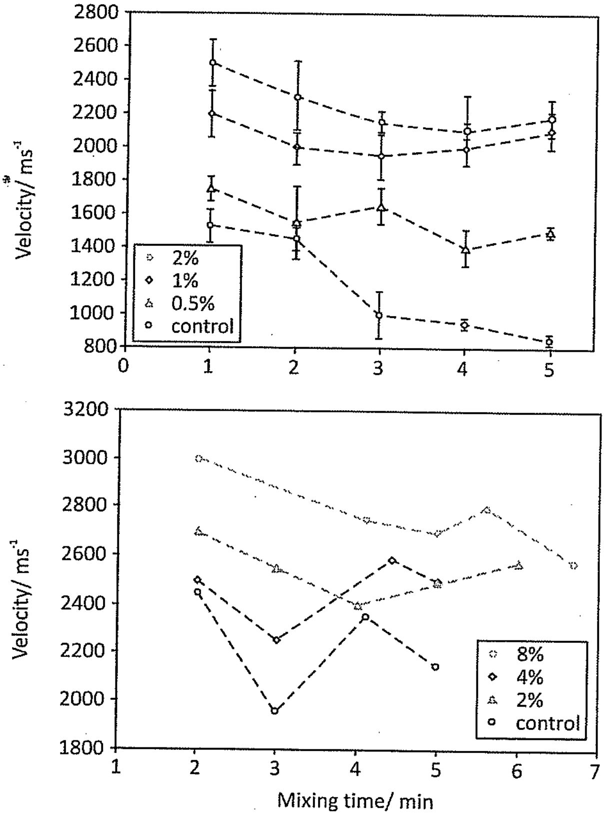

Fig. 5. The contrasting effects of distilled monoglycerides (top) and shortening (bottom) on dough matrix properties based on ultrasonic velocity measurements.

Bakery surfactants are another set of ingredients that strongly influence dough consistency (Kamel and Ponte 1993). As shown in Scanlon et al (2011b), ultrasound is sensitive to how these ingredients affect the bubbles that are entrained into the dough during mixing and to the effect that these ingredients exert on the properties of the dough matrix. By mixing under vacuum, ingredient effects can be monitored independent of bubble effects and the contrasting effect of two surface-active ingredients on the ultrasonic velocity is evident (Fig. 5); velocity increases as the concentration of distilled monoglycerides is increased and velocity decreases as shortening concentration is increased. Shear rheology measurements have shown that the shortening interacts with the hydrated proteins of the dough matrix (Fu et al 1997) to weaken the matrix, an effect that is evident in the enhanced compressibility (associated with lower velocity). The lower compressibility of doughs made with increasing amounts of distilled monoglycerides is likely attributable to the unusual structuring of free water in the dough by these bakery surfactants (Krog 1981).

RELAXATION EFFECTS – THE ROLE OF BUBBLES

Dough is a rheologically complex material, and this complexity is problematic when seeking unambiguous answers to questions such as "How does this ingredient affect dough properties?", or "What process adjustments are needed to deal with the changeover to new crop wheat flour?" Uncertainty in answering these questions occurs because the method of sampling and testing of the dough adds to its strain history, thereby potentially altering its measured properties. When stress relaxation following compression is used to study dough properties, the focus is usually on understanding dough's constitutive properties as a single phase material. However, as noted by Wang et al (2006), the bubbles in dough represent a significant source of compressibility that can influence the stress relaxation of the dough. Since bubbles are much more compressible than the dough matrix, it is conceivable that variation in the way in which samples are prepared for testing will have different effects on the bubbles and influence the subsequent stress relaxation. The evidence for bubble effects on relaxation of dough subsamples is given in (Scanlon et al 2011a).

In this analysis, subsamples of different mass were compressed to various precisely measured thicknesses. Thus, strain in the subsamples was adjusted to equivalent levels. Ultrasonic signals were measured at various times following a given deformation. To define the relaxation response to compression, the change of velocity (δv) was defined as the difference between the initial value (2 minutes after compression) and a minimum value prior to an increase in velocity. The change of attenuation (δα) was defined as the difference between the attenuation value 2 minutes after compression and the value 32 minutes after compression. In Fig. 6, the effect of strain in the subsample is shown to affect the degree of relaxation as assessed by changes in both ultrasonic parameters. These strain-induced effects are most likely due to relaxation of the bubbles in the dough rather than being exclusively attributable to the relaxation of the gluten polymers.

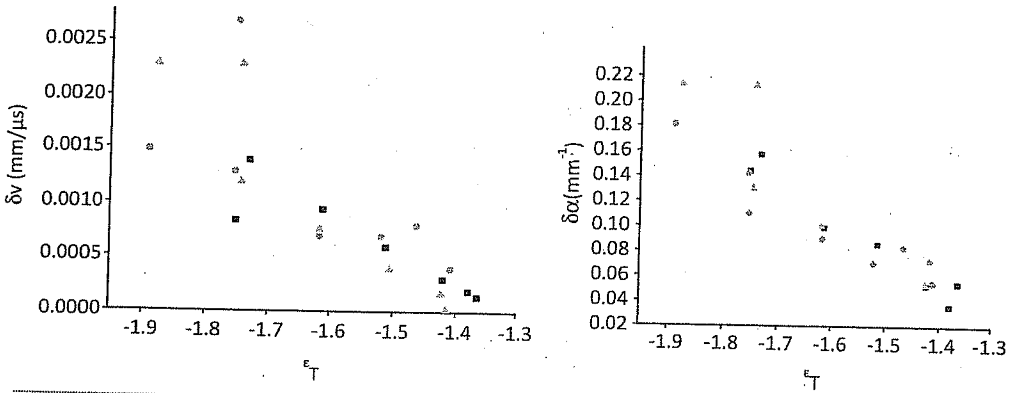

Fig. 6. Short term change in velocity (left) and attenuation (right) as a function of true compressive strain (increasing strain from right to left).

RELATIONSHIP TO OTHER RHEOLOGICAL PARAMETERS

Because ultrasound is a small strain technique, an absolute relationship between ultrasonic parameters and parameters derived from large strain techniques, such as the alveograph and farinograph, is not expected. Nevertheless, as pointed out by Kim et al (2008), the underlying constitutive properties of dough that are probed by small strain techniques will have a bearing on the way that a material deforms when subject to large strain. Therefore, we were interested in the extent to which ultrasonic velocity or attenuation were related to parameters measured by conventional cereal science techniques for doughs made from flours with a wide range in breadmaking potential. Two examples for ultrasonic velocity are shown in Fig. 7. It can be seen that correlations are reasonably strong, certainly comparable to correlations between parameters from two different conventional cereal science tests. The result in Fig. 7A is especially noteworthy in light of the results in Fig. 5, because it further supports the idea that ultrasound is sensitive to the structuring of water within the dough.

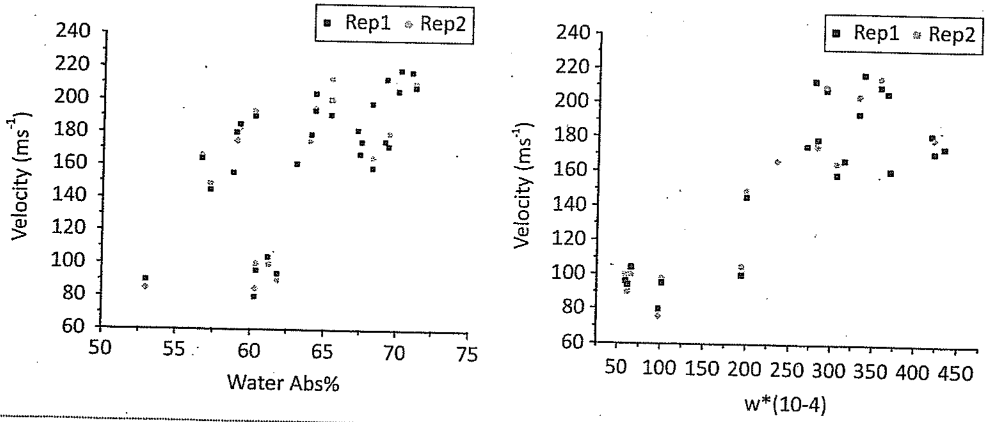

Fig. 7. Relationships between ultrasonic velocity and farinograph water absorption (A) and alveograph *W* parameter (B) for doughs made from flours with a range in breadmaking quality.

CONCLUSIONS

Ultrasound has the potential to provide useful wheat quality information, especially since both ultrasonic velocity and attenuation are sensitive probes of the gas cell structures created during processing of bread wheat doughs. Indeed, gas bubbles markedly affect the ultrasonic behaviour of dough, defining three distinct regions in its mechanical spectrum. In the low frequency regime, ultrasound can be used to probe changes in the viscoelastic properties of the dough matrix brought about by gas bubbles and bakery ingredients. An interesting and novel observation from low frequency measurements is that compressive relaxation effects are partly attributable to bubbles in the dough relaxing back to sphericity. In addition to novel insights that the technique provides, ultrasonic velocity and attenuation correlate reasonably well with some conventional dough rheology quality indices.

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