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The use of ultrasound and shear oscillatory tests to characterize the effect of mixing time on the rheological properties of dough

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Abstract

This work examined the effect of mixing time on three different flour dough systems: bread-flour wheat dough, all-purpose flour wheat dough, and cake flour wheat dough. Both ultrasound and conventional rheology techniques were used to examine the effect of mixing on these dough systems. Fundamental ultrasound results were obtained at 3.5 MHz; velocity and attenuation showed peak values at the optimum mixing time. Similar results were observed by using conventional rheology, which showed peaks in both storage and loss shear moduli at the optimum mixing time. Thus, there was an agreement between the results obtained by conventional rheology and ultrasound measurements, which shows the potential of ultrasound as an on-line quality control technique for dough-based products. The results of this work were explained with respect to molecular changes in the dough system as the mixing process proceeded; particular emphasis was placed on the presence of free water and bound water.

1. Introduction

1.1. Dough based systems-importance of characterization

Wheat flour and water mixtures, doughs, are used in the manufacture of many different food products. A wheat flour and water mixture when subjected to input of mechanical energy such as mixing will allow for the formation of dough. Even a simple wheat flour and water based dough is a complex system. Thus, the complexity of dough is not restricted to its chemical composition, but also includes physical properties (Hoseney, 1998). The rheological properties of dough reflect its machining properties during processing and the quality of the final product (Mani, Tragardh, Eliason, & Lindahl, 1992). Effective quality control of dough based products should therefore include its characterization during all stages of processing (Maache-Rezzoug, Bouvier, Allaf, & Patras, 1998; Zheng, Morgenstern, Campanella, & Larsen, 2000). Additionally, it has been reported that the rheological properties of dough at many stages in processing can be indicative of the quality of the finished product (Amemiya & Menjivar, 1992). Thus, knowledge or characterization of the rheological properties of dough can be effective in predicting its behavior during processing and controlling its quality.

1.2. Mixing-key processing step during the production of dough based foods

Mixing is a key step during the production of dough based products. The mixing step allows for the flour, water, and if present, other ingredients such as salt, chemical leavening agents, and/or yeast to be assimilated thereby forming a coherent mass. For completeness, it should be explicitly stated that air is also an important ingredient incorporated during mixing as it often goes unmentioned as an ingredient (Campbell, Rielly, Fryer, & Sadd, 1998; Scanlon & Zghal, 2001). Moreover, air bubbles affect the material properties of dough during

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processing and ultimately the textural properties of the final product. It should also be noted that Elmehdi (2001) and Scanlon, Elmehdi, and Page (2002) have employed ultrasound to study the effect of air bubbles on the material properties of bread dough and bread crumb.

In the mixing process, mechanical energy is applied to the dough (Maache-Rezzoug et al., 1998; Zheng et al., 2000). This mechanical energy permits the establishment of different conformational arrangements of the key biopolymers (particularly gluten proteins) present in the system and promotes numerous interactions between the constituents (proteins, starch, and water) of the dough (Maache-Rezzoug et al., 1998; Macritchie, 1985, Chap. 10). Considerable work has been performed with the aim of studying the components of wheat flour and their influence on the rheological properties of wheat flour-water doughs (Mani et al., 1992).

1.3. Characterization of the mechanical behavior of wheat flour dough

1.3.1. Conventional rheological methods

The mixograph has been noted in the literature as an instrument that has been developed and utilized for empirically characterizing the material properties of dough (Baltsavias, Jurgens, & Van Vliet, 1997). The mixograph provides important information on the reaction of the input materials being utilized in the formulation of the dough based product and the state of the mixing process through the characteristics deduced from the mixograms. Nevertheless, the mixograph is empirical in nature and the parameters measured by the mixograph (and other empirical tests for that matter) are poorly defined (Bourne, 1994). It follows that researchers studying dough rheology have developed and used fundamental tests that can provide results in absolute physical units (Letang, Piau, & Verdier, 1999).

1.3.2. Conventional rheological methods

The rheological properties of a material come from the relationship between stress (force), strain (deformation), and time (Letang et al., 1999). Part of the literature concerned with characterizing the rheological properties of doughs is related to the use of small deformation dynamic oscillatory measurements (Letang et al., 1999). The main reason for the wide use of these types of tests is by virtue of the use of small amplitude oscillatory strains and stresses. This allows for the deformation in the sample to be kept very small so the structure of the material is not irreversibly altered during measurements (Baltsavias et al., 1997). It follows that small deformation oscillatory tests may provide both fundamental rheological properties and information on the structure of the material.

1.3.3. Low-intensity ultrasound measurements

Although small deformation dynamic oscillatory tests can be used to characterize the rheological properties of dough, there is also a need to develop new rapid techniques that can perform precise evaluations of the properties and quality of dough (Letang, Piau, Verdier, & Lefebvre, 2001). This is in regard to the fact that the manufacture of food products is a highly dynamic and competitive industry. McClements (1997) noted that food processors must be able to rapidly respond to problems affecting the quality of products during processing and indicated that a way to achieve this goal is to develop on-line sensors capable of monitoring the food product during processing. Low-intensity ultrasound measurements have been reported in the literature to characterize food products since the velocity of ultrasound propagation and attenuation can be related to their physical properties (Benedito, Carcel, Sanjuan, & Mulet, 2000; Nielsen & Martens, 1997; Povey & Harden, 1981).

The velocity (v_L) at which longitudinal ultrasound waves travel through a solid material depends on the material's density (ρ) and the elastic moduli of the material including the bulk modulus (K) and the modulus of rigidity (G) (Povey, 1998)

$$v_L = \left(\frac{K + \frac{4G}{3}}{\rho} \right)^{1/2}. \tag{1}$$

The attenuation coefficient of a material gives an indication of the extent of decrease in amplitude of an ultrasonic wave as it travels through a material (McClements, 1997). The attenuation coefficient of a material has units of Nepers per meter (Np/m) when defined by the following equation given by McClements (1997):

$$\alpha = \frac{1}{x} \times \ln \left(\frac{A_0}{A} \right). \tag{2}$$

Here, A_0 is the initial amplitude of the wave, x is the distance traveled through the material, and A is the amplitude of the wave at a distance x.

Dough is a complex material whose structural, physico-chemical, and therefore rheological properties will change in response to different formulations (e.g. water content) and processing conditions (e.g. mixing time). The use of ultrasound to characterize the rheological properties of dough, and thereby serving as an on-line means of quality control, is promising since ultrasound takes rapid, non-invasive measurements, and can be used in systems that are optically opaque (e.g. dough). There are also examples in the literature of the use of ultrasound to measure the rheological properties of dough. Lee, Luan, and Daut (1992) used ultrasound via the through transmission technique to measure the rheological properties of dough via ultrasound velocity measurements. Kidmose, Pedersen, and Nielsen (1999) also used ultrasonics and conventional rheology for measurement of the rheological properties of dough. Letang et al. (2001) characterized the rheological properties of wheat-flour doughs using ultrasound. The objective of this work was to explain the effect of mixing time on ultrasonic measurements and rheological characteristics with particular emphasis placed on explaining the role played by water in respect to the effect of mixing on water mobility/availability at constant moisture content.

2. Materials and methods

2.1. Composition of flours

Three different types of flour, which were purchased from a local grocery store, were used in the experiments. A bread flour (Pillsbury Bread Flour), an all-purpose flour (Robin Hood All-Purpose Flour), and a cake flour (Swans Down Cake Flour). The bread flour had a protein content of 12%, the cake flour had a lower protein content of 8% whereas the all-purpose flour had an intermediate protein content of 10%. The flours with the lower protein content have higher starch or carbohydrate content. The moisture content of all flour types was approximately 14%.

2.2. Dough preparation

The moisture content of the bread flour dough, all-purpose flour dough, and cake flour dough were 41.5%, 40%, and 41%, respectively. These moisture contents were chosen in response to the data provided by the mixograph.

2.3. Mixograph

A 35 g mixograph (National Manufacturing, Lincoln, NB) was used. This mixograph was equipped with a 0.125 h.p. (93.2 W) speed motor, with a torque capacity of 32 lb-in/min (0.06023 W). A constant spring setting was used. The mixograph was operated at 90 rpm. The flour sample was placed into the mixer bowl, a well was created in the flour, and water was added. The mixograph recorded resistance versus mixing time for the various doughs. The optimum mixing time was approximately 4.5 min for the bread dough, 4 min for the all-purpose dough, and 2 min for the cake dough.

Mixing times above and below the optimum mixing times were chosen for all of the doughs. The tested doughs were mixed at these times in the mixograph mixer. The mixing times chosen were 1, 3, 6, and 9 min in addition to the optimum mixing times for all of the dough types. The doughs were removed from the mixing bowls, gently formed by hand into balls, covered in plastic wrap, and were allowed to rest at room temperature (25 ± 2 °C) for 1 h prior to testing.

2.4. Density measurements

The densities of the different doughs mixed for various times were measured. All density determinations were performed at room temperature (25 ± 2 °C) and were taken as sub-samples from the dough rested for 1 h. All doughs being tested for density measurements were hand sheeted (i.e. rolled with a rolling pin to 1 mm thickness). The sheeting technique was the same for all dough types. The doughs were sheeted to 1 mm thickness since both the conventional rheology measurements and ultrasound measurements were obtained on samples that were compressed to a thickness of 1 mm by virtue of the dimensions of the testing conditions. This is important since Letang et al. (2001) reported that as pressure is placed on dough the air present in the dough decreases. Therefore, the density measurements were made under the same conditions that the rheological and ultrasonic measurements. A cork borer (2.0 cm diameter) was used to obtain cylindrical specimens from the dough sub-samples sheeted to 1mm thickness. Therefore, these cylindrical specimens had a height of 1 mm and a diameter of 2.0 cm. The mass of the samples was read on an electronic (±0.01 g) balance (Denver Instruments Co., Denver, CO). The average of three readings was noted. The specimens had a simple cylindrical volume (V), which was calculated from the dimensions of the cylindrical samples as $V = \frac{\pi D^2}{4} h$, where D and h were the diameter and the height of the samples. All density determinations were performed in triplicates. The density was obtained by the following equation:

$$\rho = \frac{m}{V}. \tag{3}$$

Here, m is the mass and V the volume of the sample.

2.5. Conventional low frequency rheological measurements

A controlled stress rheometer (Viscotech, Lund, Sweden) was used to perform both strain and frequency sweep experiments on the doughs. A serrated plate-plate geometry was used with a 1 mm gap thickness. The serrated plates were chosen in order to minimize slippage. The upper serrated plate had a 25 mm diameter. Both strain and frequency sweep tests were performed at room temperature (25 ± 2 °C). For these strain and frequency sweep tests, approximately 0.5 g of dough, which was sub-sampled from the original ball of dough that was rested for 1 h, was placed under the plates for conventional rheological testing. Dynamic strain sweeps for all of the doughs were performed at a frequency of 1 Hz to determine the strain level in the linear elastic regime. The strain in the linear elastic region was determined to be 0.003 (or 0.3%). The strain controlled dynamic frequency sweep for the doughs employed frequencies ranging from 0.1 to 10 Hz and a strain level of 0.003. All measurements were performed in triplicates.

2.6. Ultrasound experiments

2.6.1. Experimental set-up

The experimental set-up consisted of a pulse generator-receiver (model 5800, Panametrics, Waltham, MA), a 3.5 MHz piezoelectric transducer (V609, V155, Panametrics, Waltham, MA), a delay line (Panametrics, Waltham, MA), a custom-made measurement cell, and a PC with acquisition hardware and data analysis software (LABVIEW for Windows, National Instruments, Austin, TX). Honey was used as a couplant between both the delay line and the transducer and the delay line and the sample. This was done to ensure good contact and transmission of ultrasound waves. Approximately, 1.0 g sub-samples of dough were taken from the original ball of dough and placed between the transducer in the measurement cell. It should be noted that these sub-samples of dough were taken from the original dough which was subjected to a 1 h rest time. However, the sub-samples of dough placed between the transducers for ultrasound measurements were not subjected to a significant resting time.

The experimental set-up employed to measure the ultrasonic velocity and attenuation of the dough systems was a pulse transmission technique, which propagated and received compressional waves. All experiments were replicated six times. A schematic diagram of the ultrasound set-up is given in Fig. 1. In these pulse transmission experiments, the delay line was utilized to separate the signal through the sample from the trigger signal. The first arrival time (i.e. the start of the first peak relative to the trigger signal) contains the time of the electronics of the system (i.e. the transducers), the time of the delay line, and the time of the sample. In Fig. 1, the first arrival time is denoted by t. The time of the system (t_{system}) was determined by transmitting the ultrasound signal through the system set-up without any sample present. Therefore, the time of the signal through the sample (t_{sample}) was calculated by subtracting t_{system} from t (i.e. $t - t_{\mathrm{system}} = t_{\mathrm{sample}}$). The time of the sample (t_{sample}) was used to determine the velocity of the ultrasound wave propagating through the sample, which was calculated by dividing the thickness of the sample by t_{sample} by the following equation:

$$v_{\mathrm{L}} = \frac{d}{t_{\mathrm{sample}}}. \tag{4}$$

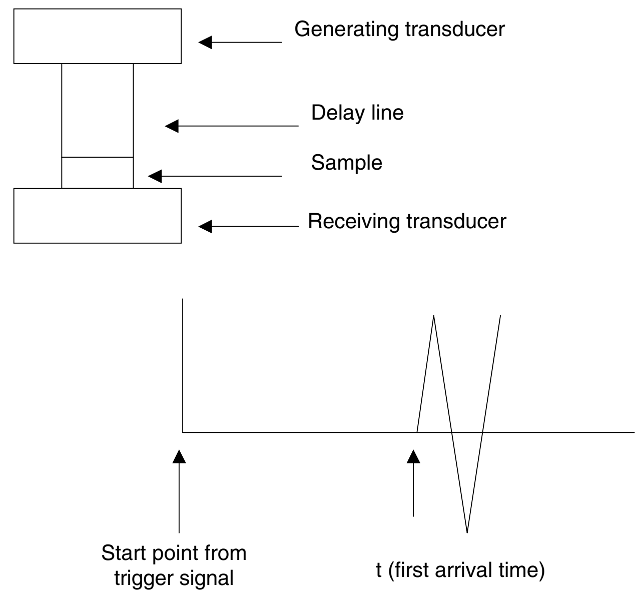

Fig. 1. Schematic of ultrasound set-up used in the research.

Also, the ultrasound pulse data was processed using a simple computer code written in Matlab. The original signal was tapered which selected the portion of the ultrasound signal of interest. The selected signal was then processed using a fast Fourier transformation (FFT) procedure thereby converting the selected ultrasound signal from the time domain into the frequency domain. This treatment allowed for attenuation measurements to be expressed as frequency-dependent measurements. Moreover, for this experimental work, the relative attenuation coefficient ($\Delta\alpha$) is discussed and it was calculated by comparing the reduction in amplitude of the pulse that traveled through the dough with the mixing time being analyzed, with that of a pulse that traveled through the dough with a mixing time that was least attenuating. Each dough type's (i.e. bread, all-purpose, or cake) attenuation coefficient for a certain mixing time was calculated relative to the least attenuating dough of the same dough type. This method of calculating attenuation relative to the least attenuating sample is in accordance with the attenuation calculations prescribed by Lee et al. (1992). The calculation of the relative attenuation coefficient ($\Delta\alpha$) was performed by using the following equation:

$$\alpha(k) = \frac{1}{d} \times \ln\left(\frac{A_0}{A}\right), \tag{5}$$

where A_0 is amplitude of signal of the least attenuating sample and A is the amplitude of the signal of the sample whose attenuation coefficient is being calculated, d is the sample thickness, and k is the wave number, which is defined by $2\pi f/v$, f is frequency.

3. Results and discussion

3.1. Density measurements

The density measurements for all of the dough types and different mix times were all within experimental error and thus there was no significant different in the densities. The density was approximately 1280 kg/m^3. This result may seem strange since it has been noted that a key result of mixing is to incorporate air into dough (Campbell et al., 1998). Therefore, it would seem likely that different doughs subjected to different mix times would have different densities. Again, it is important to note that the density measurements were made on the doughs after they were hand sheeted to a thickness of 1 mm and therefore removed much of the air imposed during mixing. This was done in order to obtain a density measurement that would be representative of the density of the dough samples undergoing both conventional rheology and ultrasound tests, where samples were compressed to a gap of 1 mm in the rheometer and to a thickness of nearly 1 mm when subjected to ultrasound measurements.

3.2. Fundamental ultrasound measurements

3.2.1. Velocity measurements

The measurements of ultrasound velocity shows that there is a distinctive peak in velocity at the optimum mixing time for all of the doughs, regardless of the flour type from which they were prepared (Fig. 2). These results are in agreement with those of Kidmose et al. (1999) who showed that there was a decrease in ultrasound velocity when doughs were mixed past their optimum mix time. At the optimum mixing time, the glutenin polymers will have aligned due to the shear and extensional forces imposed during increased mixing time. This leads to a dough with increased strength, i.e. high modulus (Letang et al., 1999). Also, at optimum mixing time there is full hydration of the key molecules present in the dough. Work performed by Sakai, Minamisawa, and Takagi (1990) indicated that ultrasound velocity in woods is affected by the degree of water absorption. They noted that there was a marked change in the behavior of the ultrasound velocity which was related to the wood containing free water held in vacant spaces in the cellular spaces or fully absorbed water in the cell walls of the wood. It is believed that a similar situation exists in dough as it is being mixed and moving from a non-fully hydrated to a fully hydrated system. When doughs were mixed for a period longer than their optimum mix time, breakage of the disulphide bonds holding the polypeptide subunits together may occur. This would cause partial depolymerization of the glutenin proteins yielding smaller molecules in overmixed dough. These smaller molecules lead to a weakening of the dough structure (i.e. low modulus). Dreese, Faubion, and Hoseney (1988) noted that water binding capacity is reduced due to the breakdown of the protein structure.

3.2.2. Relative attenuation measurements

Figs. 3–5 depict the frequency-dependent relative attenuation coefficients determined using the FFT for the bread flour dough, all-purpose flour dough, and cake flour dough, respectively. There seemed to be a peak in attenuation at the optimum mixing time but also a rising attenuation coefficient for the longest mixing time. These results are seen most dramatically in the bread

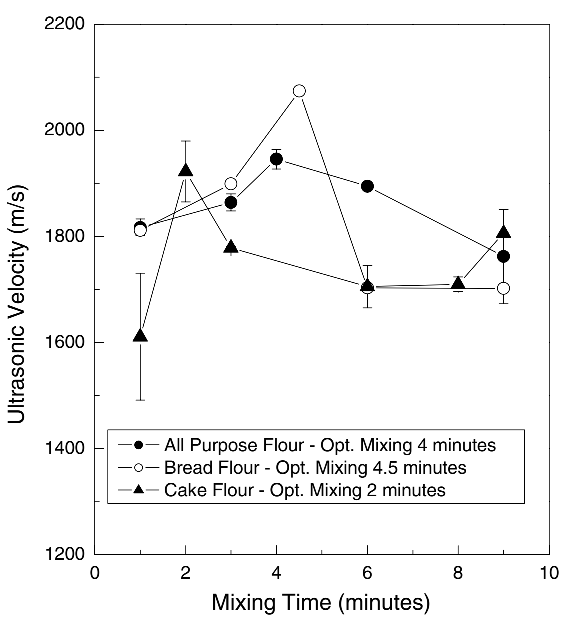

Fig. 2. The effect of mixing time on ultrasound velocity.

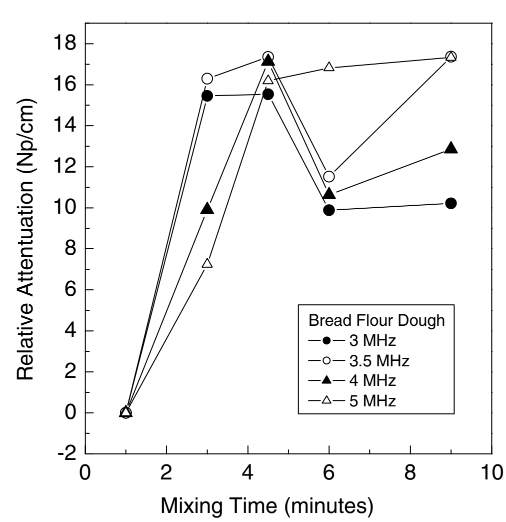

Fig. 3. The effect of mixing time on relative attenuation coefficient for bread flour dough.

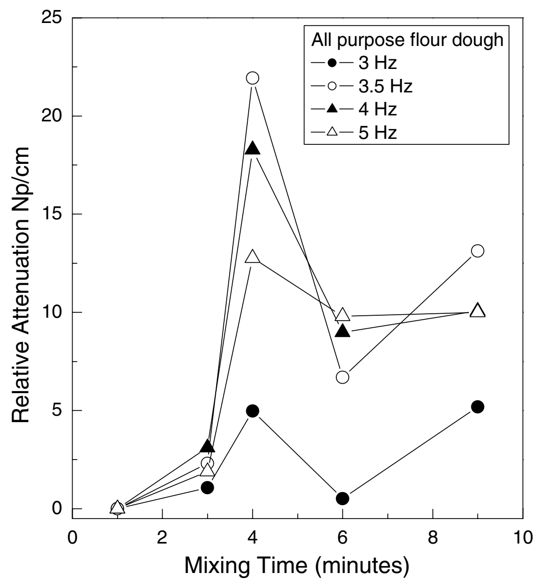

Fig. 4. The effect of mixing time on relative attenuation coefficient for all-purpose flour dough.

flour dough and the cake flour dough. An explanation for the results seen in these experiments is attempted in consideration with the change in water availability in the system throughout the mixing process. At the beginning of mixing there is free water present in the system and the key molecules are not hydrated (Dreese et al., 1988). This implies that there is a high degree of friction in the molecular arrangement of the system. This statement is based on the commonly held belief that the formation of dough can be explained on the basis of the glass transition (Hoseney, 1998). Initially the key molecules in flour component have low moisture content and are therefore immobile within the system exhibiting a high degree of friction (Hoseney, 1998; Maache-Rezzoug et al., 1998). Mixing will hydrate the key molecules of the system moving from an immobile system with high frictional forces to a rubbery and more lubricated system (Hoseney, 1998). Work performed in the discipline of geophysics has indicated that the attenuation experienced by seismic waves in rocks is dependent on the friction of the system (Johnston, Toksoz, & Timur, 1979). The work of Johnston et al. (1979) on dry and saturated rocks indicated that in the absence of water, the Coulomb forces across the grain of the rock are very strong. Therefore, the frictional forces are very high and no sliding motion, which would dissipate the propagating waves, takes place across the surface. Consequently, attenuation is very low (Johnston et al., 1979; Mavko, 1979). This may be what is happening in the dough as it is mixed. The dough at optimal mixing is fully hydrated and therefore the key molecules of the system are well lubricated. Frictional forces existing in the system are minimized and therefore molecular movement and attenuation are maximized. In fact, hydrated water associated with proteins is more dense and therefore more attenuating than bulk or free water (McClements, 1997; Pavlovskaya, McClements, & Povey, 1992). This also helps to explain why attenuation is peaked at the optimum mixing time.

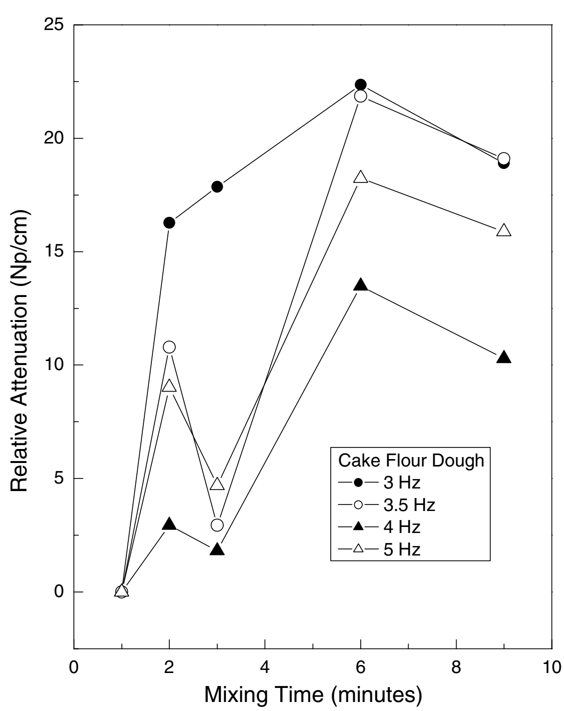

Fig. 5. The effect of mixing time on relative attenuation coefficient for cake flour dough.

When dough is overmixed, there is breakage of the covalent disulphide bonds that were formed upon mixing to optimum. There are now shorter chain key molecules present, these shorter molecules may exhibit more movement than the longer chain molecules which would lead to enhanced attenuation of the ultrasound wave. Also, the presence of these shorter chain molecules and free water implies a more heterogeneous and discontinuous system, which based on the concept of percolation systems, implies that there would be enhanced attenuation (Schriemer, Pachet, & Page, 1996). It was speculated that since upon excessive overmixing there is an increase in the free or bulk water of the system, the effect of moisture content might be increased although the absolute moisture content of the system remains unchanged. This might be important since it has been noted that an increase in moisture content gives an increase in attenuation (Lee et al., 1992).

3.3. Rheological measurements

3.3.1. Oscillatory shear tests

Figs. 6–8 show the effect of mixing time on the rheological properties of the different dough systems. The

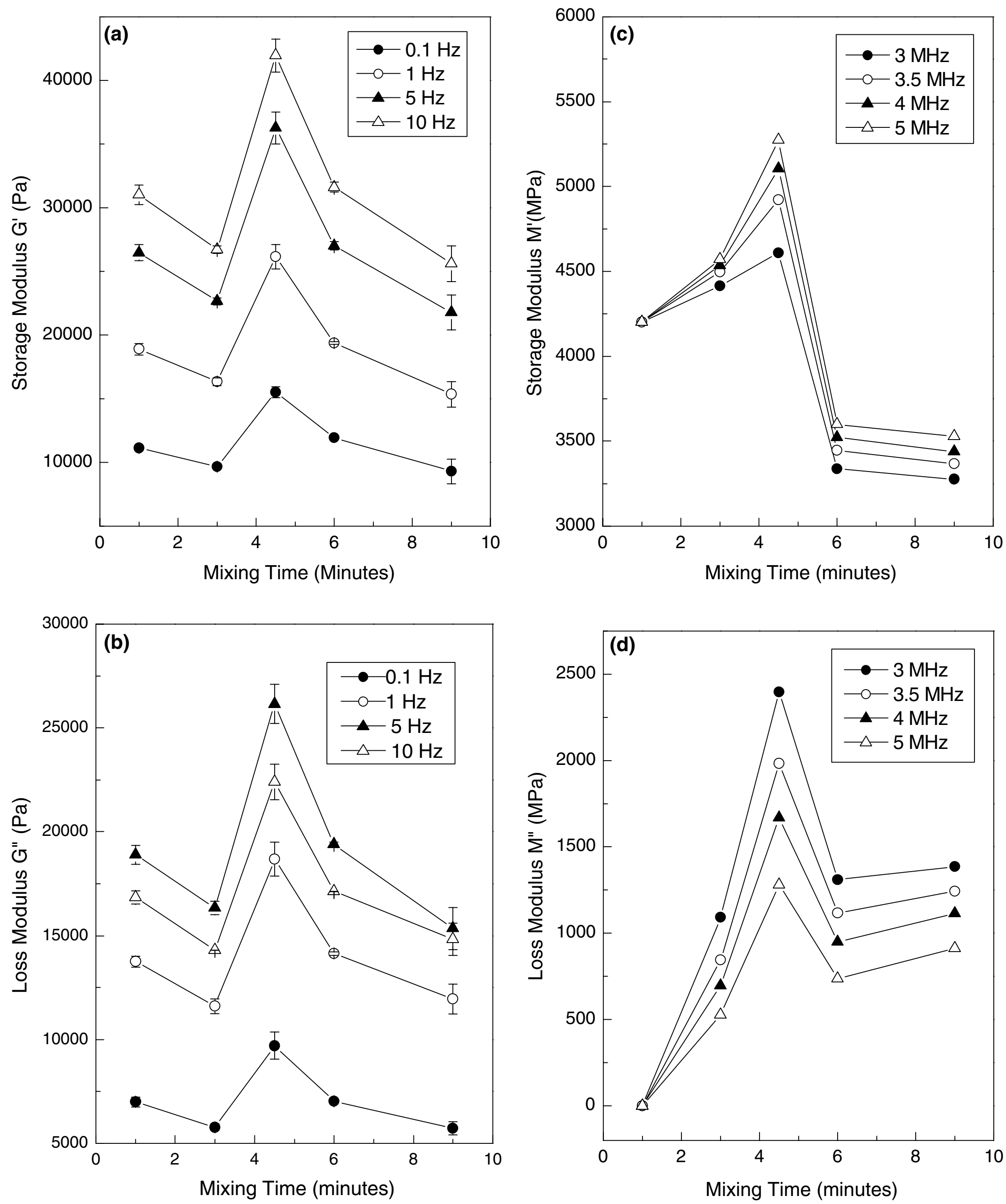

Fig. 6. (a) The effect of mixing time on G' – bread flour dough. (b) The effect of mixing time on G'' – bread flour dough. (c) The effect of mixing time on M' – bread flour dough. (d) The effect of mixing time on M'' – bread flour dough.

results are in general agreement with those of Kidmose et al. (1999), Letang et al. (1999), and Zheng et al. (2000) who showed that G' and G'' of dough decreased when subjected to mixing times past the optimum mixing time. The result of G' having a maximum value at the optimum mixing time is intuitive in that the dough has the highest elasticity at optimum mixing. The G'' having a maximum value at the optimum mixing time is less straightforward since a maximum in G'' indicates that the loss or viscous component is maximized. Ultrasonic tests have shown that at the optimum mixing time there is a maximum in attenuation. It was previously noted that at optimum mixing time the dough systems were fully hydrated, frictional forces were diminished and therefore the molecules had the greatest degree of mobility. This may indicate that there is a great degree of viscous dissipation of the ultrasound energy. This large viscous component in the dough would lead to the observed peak in G''.

3.3.2. Ultrasound-deduced high frequency modulus measurements

The storage modulus (M') and loss modulus (M'') from the high frequency ultrasound measurements were

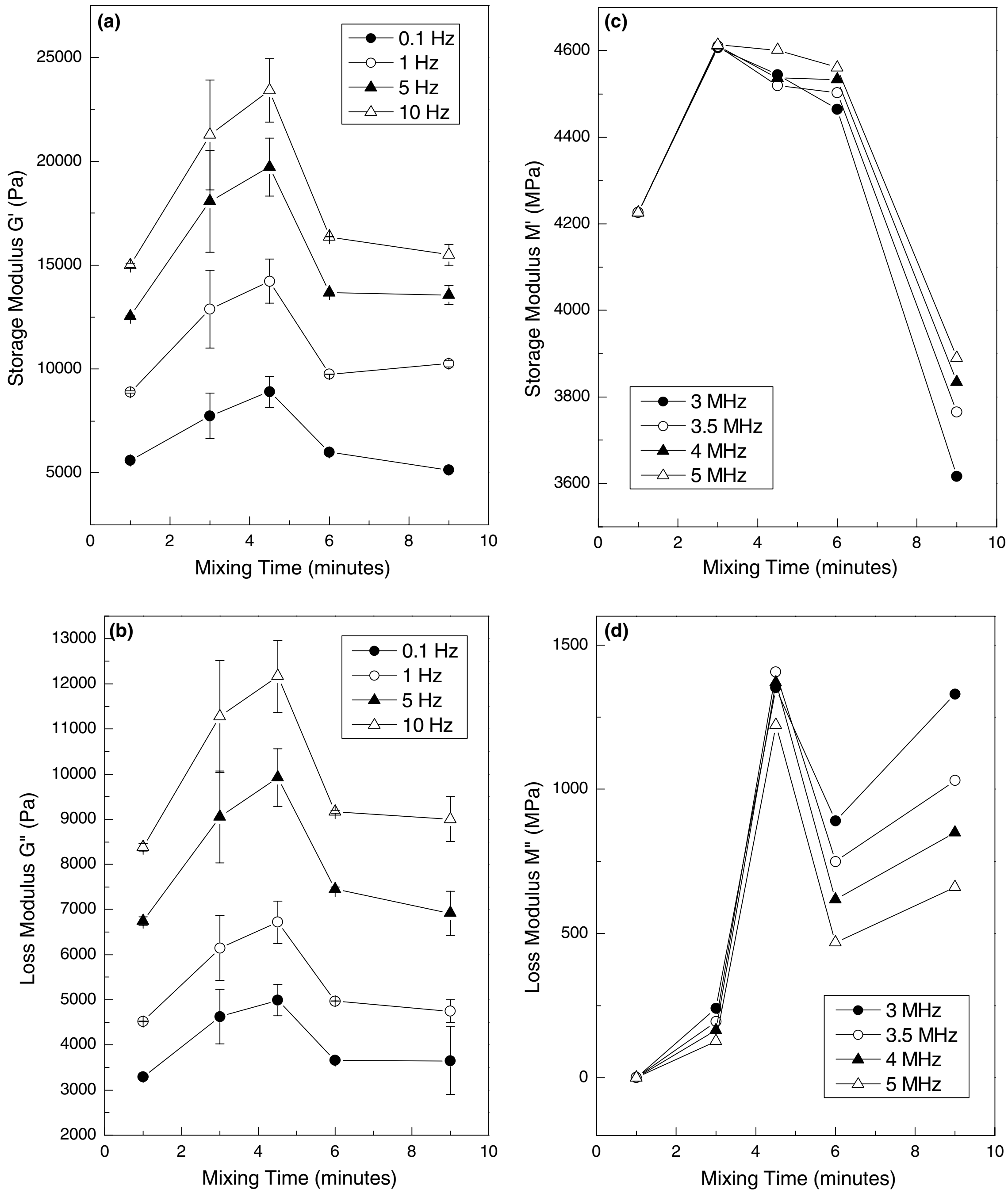

Fig. 7. (a) The effect of mixing time on G' – all-purpose flour dough. (b) The effect of mixing time on G'' – all-purpose flour dough. (c) The effect of mixing time on M' – all-purpose flour dough. (d) The effect of mixing time on M'' – all-purpose flour dough.

calculated using the following equations given by Letang et al. (2001):

$$M' = \frac{\rho v_{\mathrm{L}}^2 \left(1 - \frac{\alpha^2 v_{\mathrm{L}}^2}{\omega^2}\right)}{\left(1 + \frac{\alpha^2 v_{\mathrm{L}}^2}{\omega^2}\right)^2}, \tag{6}$$

$$M'' = \frac{2\rho v_{\mathrm{L}}^2 \frac{\alpha v_{\mathrm{L}}}{\omega}}{\left(1 + \frac{\alpha^2 v_{\mathrm{L}}^2}{\omega^2}\right)^2}, \tag{7}$$

where M' is the elastic or storage component of the modulus, M'' is the viscous or loss component of the modulus obtained from fundamental compression wave ultrasound measurements, ω is the angular frequency and α is the attenuation of the ultrasound wave.

It is noted that the aforementioned equations used for calculating the viscoelastic moduli, M' and M'', were calculated from compressional measurements so they include information that contains a combination of the bulk and shear moduli. However, at ultrasonic fre-

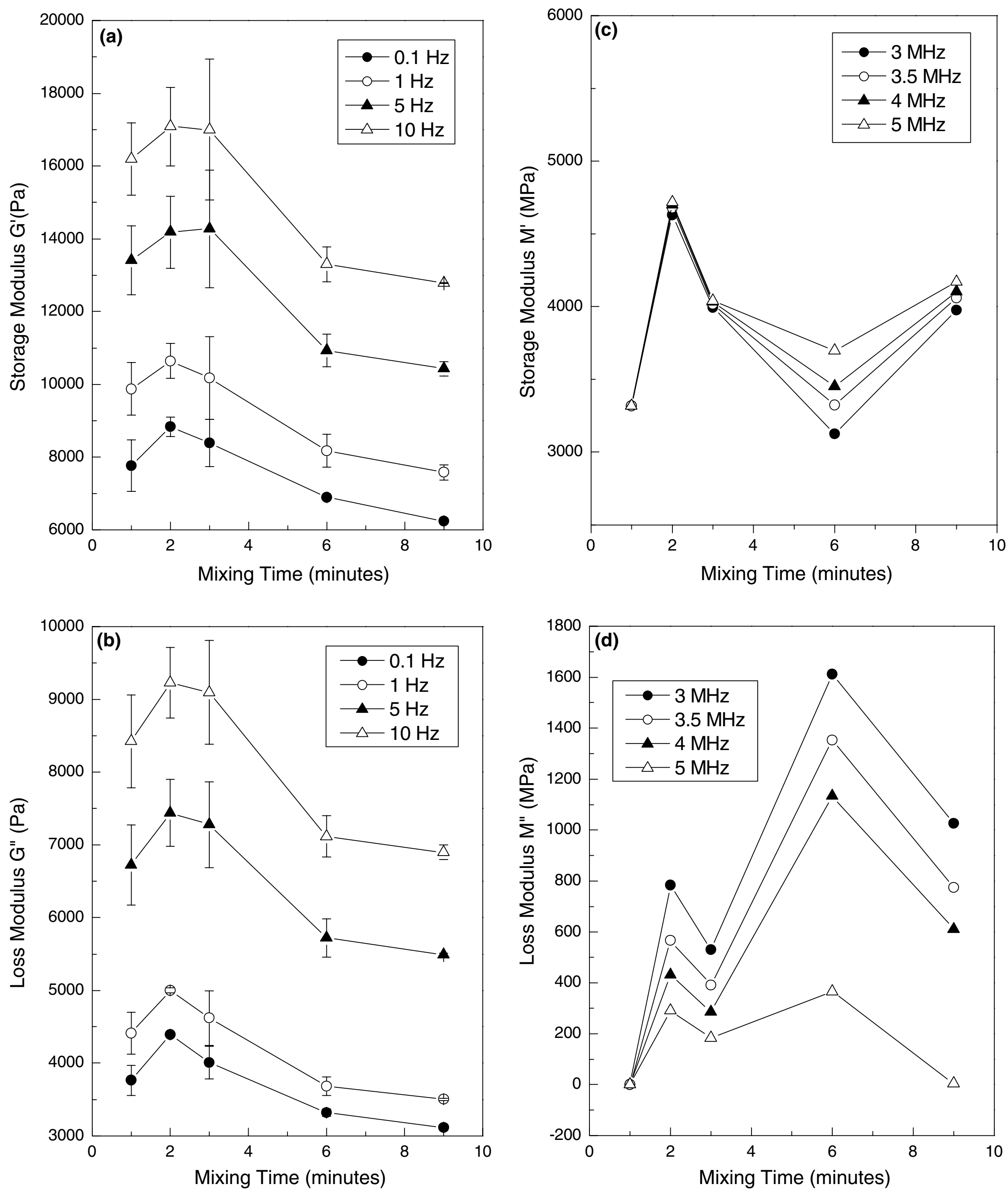

Fig. 8. (a) The effect of mixing time on G' – cake flour dough. (b) The effect of mixing time on G'' – cake flour dough. (c) The effect of mixing time on M' – cake flour dough. (d) The effect of mixing time on M'' – cake flour dough.

quencies employed in these experiments both the storage and loss compressibility components dominate over both the storage and loss shear components (Lee, 2003; Letang et al., 2001). Also, it was realized that Eqs. (6) and (7) use the absolute attenuation coefficient in their calculation of M' and M'', respectively, while the values of M' and M'' presented in this paper were calculated using a relative attenuation coefficient values. This is problematic in terms of global comparison of the data. Yet this condition is relatively benign when considering the scope of these experiments, which was to determine the effect of mixing time within a certain dough type. Therefore, making comparisons within a certain dough type relative to a certain mixing time deems the use of the relative attenuation coefficient acceptable.

The graphs showing M' for the different dough types are given in Figs. 6(c), 7(c) and 8(c), and the graphs showing M'' for the different dough types are given in Figs. 6(d), 7(d) and 8(d). It appears that the high frequency ultrasound based moduli follow a similar trend than the low frequency moduli obtained with conventional low strain oscillatory rheology. There are peaks in M' and M'' at the optimum mixing times for the three different flour doughs. There is a difference in the absolute values of the moduli obtained from these two different methods (i.e. ultrasound versus rheometer tests) of nearly five orders of magnitude. One major explanation for these results is that the ultrasound derived viscoelastic moduli were obtained from compressional waves where the compressibility components dominated over the shear components. Another fact worth discussing is the difference in the timescale at which high frequency ultrasound measurements and low frequency rheometer measurements are performed (Kudryashov, Hunt, Arikainen, & Buckin, 2001). Presumably, the movements within a dough system at very short time scales (high frequency test) appear frozen at ultrasonic frequencies. This apparent freezing of movement in the dough with increasing frequency may cause the increase in moduli of the system. An interesting, experimental result supported by the previous statement is that the M'' values are lowest at the highest frequencies while the M' are highest at the highest frequencies. This result seems to indicate that there is a "freezing" in the movement of the molecules and, as expected, the contribution of viscous component is lessened at the higher frequencies.

4. Conclusions

This work has shown that conventional rheology and ultrasound measurements can be used to determine the effect of mixing on the rheological characteristics of wheat doughs. There is agreement between the results obtained by conventional rheology and ultrasound. The results from the conventional rheology and ultrasound base rheology appear to be sensitive to the different flour types used to produce the doughs. A wider range of moisture contents along with different mixing times should be investigated for all doughs obtained from different flour types to produce results that are more global. Nevertheless, from these results, it appears that the fundamental measurements obtained from ultrasound, namely, velocity and attenuation have the potential to be used as an effective on-line dough quality control technique.

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