AN ULTRASONIC APPROACH TO INVESTIGATE THE PROPERTIES OF CEREAL FOODS

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ABSTRACT

Two ultrasonic parameters that give information about the structural properties of materials are the longitudinal ultrasonic velocity, v_L, and the attenuation coefficient, α. The sensitivity of these parameters to gas bubbles means that ultrasound is ideal for investigating the properties of baked foods where cell structure is a vital component of product quality. Results of experiments performed at 54 kHz show how ultrasound can be used to investigate the role of gas bubbles and the surrounding matrix in determining the mechanical properties of dough during mixing and during fermentation. These experiments showed that these ultrasonic parameters are sensitive to both gas bubbles and matrix properties of the dough. In particular, α was found to increase as the amount of air entrained in the dough increased. On the other hand, v_L, was found to decrease as the bubbles increased in size and/or in number. The results reported in this paper demonstrate that ultrasonic techniques can be used to measure those changes in the physical, chemical and biological properties of dough which relate to baking quality.

1. INTRODUCTION

Fundamental characterizations of structure and rheology are basic prerequisites for developing robust models that will accurately predict the effect of processing operations on those properties that govern consumer acceptance of the food product [1]. One technique that has been used to measure both the rheology and the structure of food materials is low-intensity ultrasound [2]. Like light scattering, a range of frequencies can be employed so that structural features at a number of length scales can be probed [3], but ultrasound can also be used to investigate the properties of foods that are optically opaque. Therefore, the structure and mechanical properties of various opaque foods such as vegetables [4], cheese [5] and dough [5,6] have been studied by measuring ultrasonic parameters such as the velocity and the attenuation coefficient. The velocity of propagation, the phase velocity (v_L), in a solid material is related to the longitudinal modulus, β, of the material and its density, Δ, by

$$v_L = [\, \beta / \rho \,]^{1/2} \qquad (1)$$

The longitudinal modulus is a function of the bulk and shear moduli. Thus, independent measurements of density and velocity enable a value of this combined elastic modulus to be determined. The attenuation coefficient depends on other material properties; for a heterogeneous system such as dough, the two mechanisms that contribute to the attenuation coefficient are absorption and scattering [7]. By judicious selection of the ultrasonic frequency, the contributions of specific structural features to changes in the originally transmitted ultrasonic pulse can be enhanced, and their effect measured.

One structural feature which interacts strongly with ultrasound [4], and which is present in many solid and liquid foods, is the gas bubble (or any other low-density inclusion). Such inclusions within wheat flour dough are considered to be absolutely critical to the manufacture of baked goods of acceptable appearance and textural quality [8]. The purpose of this paper is to show how ultrasound can be used to measure the effect of gas bubbles on the rheology of dough, and in particular to demonstrate how ultrasound can readily monitor two of the processing operations that are performed on this optically opaque food material.

2. MATERIALS AND METHODS

Dough samples were prepared using a short breadmaking process that is used in Canadian plant bakeries [9]. Canadian Western Red Spring (CWRS) flour (100 g) was mixed with 63 ml of water and 2.4 g of salt. For investigations of the effect of gas cell expansion during fermentation, 3.2 g of yeast was added. The ingredients were mixed using a GRL-200 high-speed mixer to

10% past peak consistency (about 7 min). The mixing bowl could be made airtight and was connected to a vacuum pump, allowing manipulation of mixer headspace pressure.

A pulsed ultrasonic system operating in transmission mode at 54 kHz (Fig. 1) was used for all experiments. The transducers were held in place using a custom-made sample holder, which allowed the gap between the transducers and hence the sample thickness to be set precisely. Sub-samples of dough (approx. 4 g) were cut from the dough piece immediately after mixing, and were placed either directly between the two transducers (mixing experiments) or between two acrylic plates. For the fermentation experiments, the sample holder and the dough density measurement system were placed in a proving cabinet to control the temperature and the humidity (37 ^{0}C and 83% R.H.).
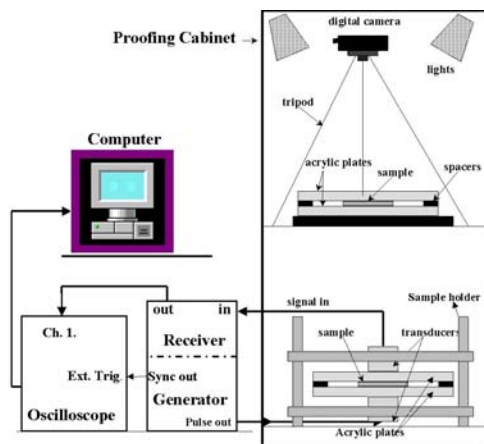

Figure 1: Ultrasonic and dough density deter-minations (fermentation experiments)

For the mixing experiments, the longitudinal ultrasonic velocity was determined by measuring the pulse transit time for sub-samples of different thicknesses (1 to 9 mm), but taken from the same batch of dough. The velocity was determined from the inverse slope of the transit time versus sample thickness. This was performed for mixer headspace pressures ranging from 13 to 101 kPa.

For the fermentation experiments, the thickness of the dough samples was fixed at 1.97 mm. One sub-sample was used for the ultrasonic measurements, and another one was clamped (at a thickness of 1.97 mm)

between similar acrylic plates and placed directly under a digital camera to record the radial expansion of the dough. The ultrasonic velocity was determined by measuring the time taken for the signal to propagate through the dough, with measurements being taken every few minutes of fermentation time.

For both mixing and fermentation experiments, the amplitude of the ultrasonic signal was measured directly from the peak signal height. This was converted to an attenuation coefficient (see below) for the mixing experiments, or expressed as a change in amplitude as a function of fermentation time.

3. RESULTS AND DISCUSSION

3.1 Bubble entrainment during mixing

Air bubbles are introduced into the dough during mixing. Early research showed that the number of bubbles per unit volume was much less when doughs were mixed under reduced pressure than when the doughs were mixed at atmospheric pressure [10]. More recently it was shown [11] that mixing under reduced pressure produced fewer bubbles per unit volume in the dough, but that the size distribution of the bubbles stayed the same. Therefore, by mixing the dough under various mixer headspace pressures, doughs with different numbers of air bubbles could be produced and the extent to which the bubbles influenced the mechanical properties of the dough could be investigated by ultrasound.

The velocity as a function of headspace mixer pressure (P) is shown in Fig. 2. It can be seen that the velocity decreases dramatically in the range 13 kPa $<$ P $<$ 33 kPa, dropping from a velocity near to that of water to values somewhat below the velocity of sound in air. At higher P values, the velocity decrease is less rapid. The rapid increase in the velocity at low P values suggests that there are other mechanisms in addition to the effect of gas content which contribute to the change in velocity as the number of bubbles decreases. Based on an analysis using an effective medium model [12], it was postulated that in addition to the effect of bubbles on ultrasonic propagation, dough matrix properties were altered due to air entrainment.
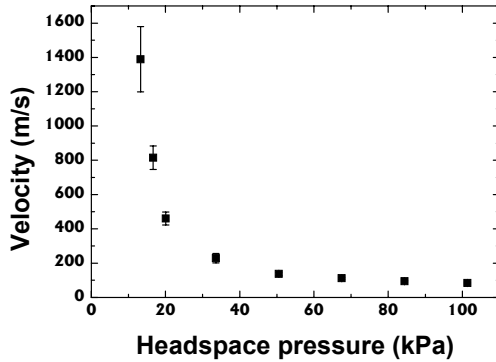
Figure 2: Phase velocity as a function of mixer headspace pressure

The amplitudes of the transmitted signal for samples mixed at a given pressure but of various thicknesses are shown in Fig. 3. It can be seen from these exponentially decaying curves that as the mixing pressure decreased the decay rate of the amplitude also decreased, implying less attenuation. Thus, the amplitude of the signals decreased as the mixing pressure was increased, an effect attributable to the presence of more air bubbles within the sample, resulting in very low signals. This suggests that as the pressure in the mixer is lowered, the sample becomes less absorbent, and/or that there is less scattering of the ultrasonic signal. The attenuation coefficients were calculated from these curves by fitting the data to a single exponential decay curve plus a background (Tab. 1). It can be seen that the attenuation coefficient increased in proportion to the amount of air entrapped in the sample and that the gas bubbles make a significant contribution to α.

3.2 Effect of bubble expansion during fermentation

The addition of yeast to the dough formula results in fermentation of the sugars in the dough leading to the production of CO_2. The CO_2 then diffuses through the dough matrix to the air nuclei [13]. Since there are no new bubbles generated during fermentation [10], the nuclei entrained during mixing act as sites for collection of CO_2 and growth of the gas bubbles. The net effect is that the

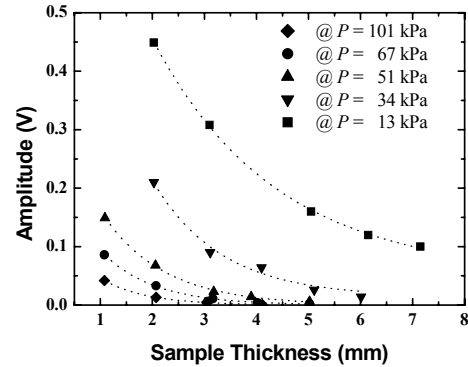density of the dough decreases as the dough ferments [14].

Figure 3: The amplitudes of the ultrasonic signal for dough samples mixed under various headspace pressures

The change in dough density as a function of fermentation time is shown in Fig. 4 for dough mixed under the two extreme headspace pressures (13 and 101 kPa). These extrema were selected because of the drastic differences in ultrasonic properties shown in Figs. 1 and 2.

Table1: Attenuation coefficient for unyeasted dough mixed under various headspace pressures

Headspace pressure (kPa)	Attenuation coefficient (mm^{-1})
101	0.980 ± 0.035
84	0.860 ± 0.042
67	0.705 ± 0.065
51	0.647 ± 0.095
34	0.463 ± 0.066
20	0.490 ± 0.051
17	0.420 ± 0.066
13	0.347 ± 0.023

Four observations are apparent from Fig. 4. First, the dough mixed under high vacuum starts at a higher density than the dough mixed at one atmosphere. This is expected because the dough mixed under high vacuum contains fewer air nuclei per unit volume [11,14]. The second observation is that the dough density falls as fermentation proceeds [14,15]. This is a direct result of the expansion of the air nuclei by CO_2, thereby decreasing the density. In fact, the densities fall by approximately the same amount, an indication that the same amount

of CO_2 is produced and retained in both doughs. The third observation is that there is a lag in the density drop in the first few minutes of fermentation, and this persists for the dough mixed under high vacuum. This lag represents the time taken for CO_2 to reach the expansion sites (air nuclei). Since there are fewer air bubbles per unit volume in the dough mixed under high vacuum, the diffusion path is expected to be longer. Hence the density will remain constant for longer time. The last observation is that the differences between the dough densities for the two doughs lessened as fermentation proceeds.
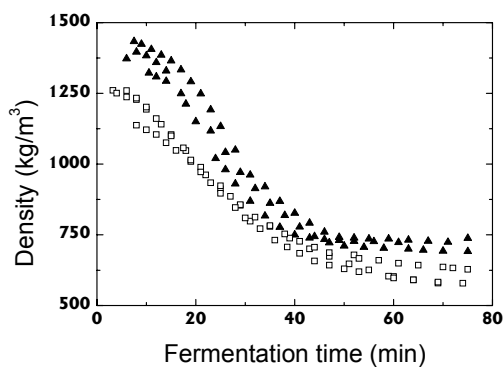

Figure 4: Dough density changes with fermentation time for high vacuum (▲) and atmospheric (□) mixing conditions (replotted from [16], courtesy AACC).

The change in the velocity as a function of fermentation time is shown in Fig. 5, and it can be seen that the early time velocities are similar to the velocity measurements on unyeasted doughs (Fig. 2): there are large differences in velocity depending on mixer headspace pressure. As fermentation proceeds, ultrasonic velocity decreases for both doughs. At later fermentation times, the velocities for the extremes in mixing conditions converge to the same value. Similar results were obtained for signal amplitude [16].

A comparison with the density results of Fig. 4 shows that this decrease in velocity is not entirely due to the bubble expansion as had been expected. In fact, dough density was changing little during the time interval in which both the signal amplitude and the velocity decreased sharply. Therefore, in the case of doughs containing yeast, ultrasonic properties appear to be probing the two mechanisms that occur during fermentation. At later fermentation times, the air nuclei expand resulting in an increase in the volume of the gaseous phase. Large differences in the density between the gaseous phase and the dough matrix phase will result in the absorption and/or scattering of sound. Consequently, the velocity and amplitude of the ultrasonic signal will decrease [12]. However, the effect of the expansion of the gas bubbles cannot entirely explain the observed drop in the velocity and amplitude in the early stages of fermentation, particularly for the dough mixed at high vacuum. By changing the amount of CO_2 entering the dough matrix with time, it was shown [16] that these ultrasonic parameters were sensitive to the properties of the matrix, independent of the effect of gas bubble expansion. The rapid drop in velocity and amplitude was attributed to the drop in the pH of the dough arising from the generation of CO_2 by the yeast [17]. As a consequence, the intermolecular interactions between the sidechains of the gluten polymers were thought to be altered [16]. Thus, ultrasound is probing molecular interactions within the dough matrix, as well as changes in gas bubble expansion.
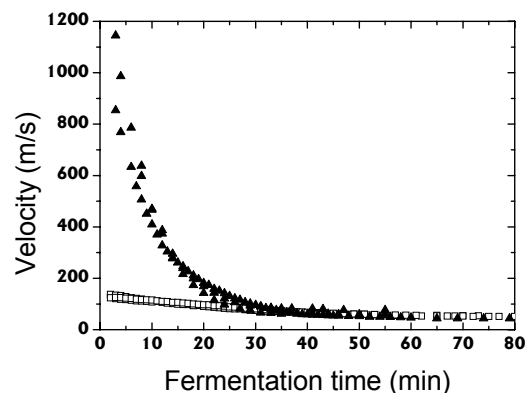

Figure 5: Ultrasonic velocity changes with fermentation time for high vacuum (▲) and atmospheric (□) mixing conditions (replotted from [16], courtesy AACC).

4. CONCLUSIONS

Ultrasound is not only sensitive to the presence of gas bubbles in dough, but also to the changes in the dough matrix that arise from changes in processing conditions.

Further work is required to quantify the separate effects of gas cells and matrix on ultrasonic velocity and attenuation in the various breadmaking unit operations.

ACKNOWLEDGMENTS

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