

# DETERMINATION OF ULTRASONIC-BASED RHEOLOGICAL PROPERTIES OF DOUGH DURING FERMENTATION<sup>1</sup>

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## ABSTRACT

*An ultrasonic technique was used to study the changes of the rheological properties of dough during fermentation at 37C and compared with the extensional properties of fermented dough obtained from tensile tests carried out in a Universal Testing Machine. The velocity and attenuation of a longitudinal wave (P-wave) propagated through the dough samples were measured and analyzed to obtain the viscoelastic moduli of the dough; the storage modulus  $M'$  and the loss modulus  $M''$ . These moduli include both the bulk and the shear moduli. A wavelet analysis also was used to determine the effect of frequency on the ultrasonic-based viscoelastic moduli and the effect of the fermentation*

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*process on the ultrasonic velocity dispersion. A decrease in ultrasonic velocity was observed with increasing fermentation times. Ultrasonic waves were strongly attenuated in the dough subjected to long fermentation times and fermentation had a large influence on the viscoelastic moduli of the dough. The ultrasonic velocity increased with increasing frequency, clearly showing the viscoelastic nature of the fermented dough. The analysis also showed significant ultrasonic velocity dispersion upon fermentation. Ultrasonic measurements yielded results that agreed with those obtained from conventional rheology commonly used to characterize the extensional properties of dough. Both tests clearly showed the loss of elasticity by the dough samples upon fermentation.*

## INTRODUCTION

Dough fermentation is an important stage in the bread-making process, in which the most distinctive change is the increase in the volume of dough. This stage produces the light, aerated, and spongy characteristics of bread. During the fermentation process, the forces exerted by the growing gas bubbles deform the dough matrix which resists the growth of these bubbles. Therefore, the deformation of the dough matrix produced by the growth of the bubbles is predominantly that produced by an extensional flow.

It is well known that the rheology of dough during the fermentation stage has a strong influence on the final quality of baked bread. Thus, and particularly during the fermentation stage, a knowledge of the extensional properties of dough would allow the fermentation process to be controlled so that the best quality of the baked products could be achieved. However, the measurement of the rheology of fermenting dough is not simple because fermenting dough is a complex and dynamic system. The dimensions and rheological properties of the dough vary with time during fermentation (Czuchajowska and Pomeranz 1993; Rasanen *et al.* 1997). In addition, fermenting dough is extremely fragile, making it extremely difficult to mount a sample in the rheological testing device without disturbing it.

In the past, several investigators have studied the changes in dough properties during fermentation. A rheofermentometer has been used to examine the gas production of fermented dough (Wehrle and Arendt 1998). Microscopy has also been utilized to investigate changes in gas distribution during dough fermentation (Rasanen *et al.* 1997; Shimiya 1997). Ito *et al.* (1992) developed a dielectric method to monitor gas production in fermenting bread dough. Collado and Deleyn (2000) used a test known as the Zymo-expansion-meter to measure the evolution and retention of gas in fermenting dough from 14 different types of wheat. While these methods have been valuable in providing useful information about gas distribution and gas evolution during dough

fermentation, they do not provide information about dynamic changes in the rheological properties of dough during fermentation. It would be desirable to directly measure the rate and extent of deformation and the stresses during the entire fermentation process to fully understand the rheological properties of the fermenting dough. Furthermore, there is a need for on-line, rapid, and nondestructive methods for evaluating dough properties.

Rheologically, time-dependent viscoelastic materials, such as fermenting dough, can be studied by propagating ultrasonic waves through the material. The energy in these waves is very low and does not affect the structure of the dough. As they travel through the material, the waves are attenuated and the velocity of the waves changes in response to differences in physical properties. Ultrasound is a novel and challenging method that is being developed for use in the field of food science where nondestructive and noninvasive techniques are of great interest. However, only a few studies have evaluated the rheological properties of dough using ultrasonic techniques. Lee *et al.* (1992) evaluated the rheological properties of dough using ultrasonic waves and found a good agreement between the ultrasonic technique and conventional rheometry. Kidmose *et al.* (2001) obtained the rheological properties of dough during aging using measurements of the velocity of ultrasonic waves. In another study the physical properties of dough were analyzed using a theory that describes the propagation of ultrasonic waves through a viscoelastic material (Letang *et al.* 2001) who studied the effects of the dough water content and mixing time and found that the ultrasonic properties of dough were dependent on frequency which is the typical behavior of viscoelastic materials.

To our knowledge, the feasibility of using ultrasound to characterize the rheological properties of dough during fermentation has not been studied. Therefore, the main objectives of this work were (1) study the changes in the ultrasonic properties of dough throughout the fermentation process, (2) determine changes in dough rheological properties during fermentation using ultrasonic data, (3) evaluate extensional properties of dough upon fermentation and compare them with the ultrasonic-based rheological properties and (4) highlight the potential of ultrasound for dough testing during processing.

## MATERIALS AND METHODS

### Sample Preparation

Commercial all-purpose flour (14% moisture basis) was used to prepare the dough samples used in this study. The dough was prepared using 35 g of flour, 27 g distilled water, and 0.35 g dry yeasts (Red Star® Yeast, Milwaukee, WI). The ingredients were mixed in a 35 g mixograph mixer (National MFG. Co.,

Lincoln, NE) for 6 min (approximately optimum mixing time). No other ingredients beyond flour, water and yeast were used to prepare the dough samples.

### Ultrasonic Measurements

**Experimental Set-up.** Figure 1 illustrates the experimental set-up used for the ultrasonic measurements. A Panametrics (Waltham, MA), model 5800, pulser-receiver system connected to a PC was used for the ultrasonic measurements. LABVIEW software (National Instruments, Austin, TX) was used for data acquisition and analysis. The transducers used in this experiment were two Panametrics broad-band V609, 5 MHz piezoelectric transducers which were calibrated prior the tests by measuring the speed of sound through distilled water. In order to follow the physical changes of the dough samples during the fermentation process ultrasonic measurements were carried out using the transmission mode. As illustrated in Fig. 1, one of the two transducers was used as the source while the other was used as the receiver. A suitable measurement cell was designed for the test. It consisted of two Plexiglas™ plates having threaded holes for the insertion of the transducers. The region surrounded by the dotted circle in Fig. 1 has been expanded in the same figure to show the measurement cell in more detail. The sample was placed between the two transducers and inside the cell which was sealed by the two plates to prevent moisture evaporation during the fermentation process. During measurements the distance between the two transducers was held constant at 3 mm. Fermentation of the sample was facilitated by placing the measurement cell containing the dough sample in an oven at 37°C. Ultrasonic signals were collected every 5 min for a total of 30 min. All experiments were carried out in triplicate.

**Analysis of Ultrasonic Wave Propagation Through a Viscoelastic Material.** The ultrasonic velocity and attenuation coefficient were determined from the propagation time or Time of Flight (TOF) and from the decrease in the amplitude of the ultrasonic wave that propagated through the sample of known thickness, respectively. The propagation time or TOF was calculated by measuring the time period between the peak of the emitted and transmitted pulse waves and the ultrasonic wave velocity as the sample thickness divided by the determined TOF.

For longitudinal waves propagating in a viscoelastic material, the longitudinal-wave complex modulus  $M^*$  can be calculated as  $M^* = M' - iM'' = K^* + \frac{4}{3}G^*$

where  $K^* (= K' - iK'')$  and  $G^* (= G' - iG'')$  are the complex bulk and shear moduli, respectively (Marvin *et al.* 1954; Kono 1960).  $K'$  and  $G'$  are the bulk

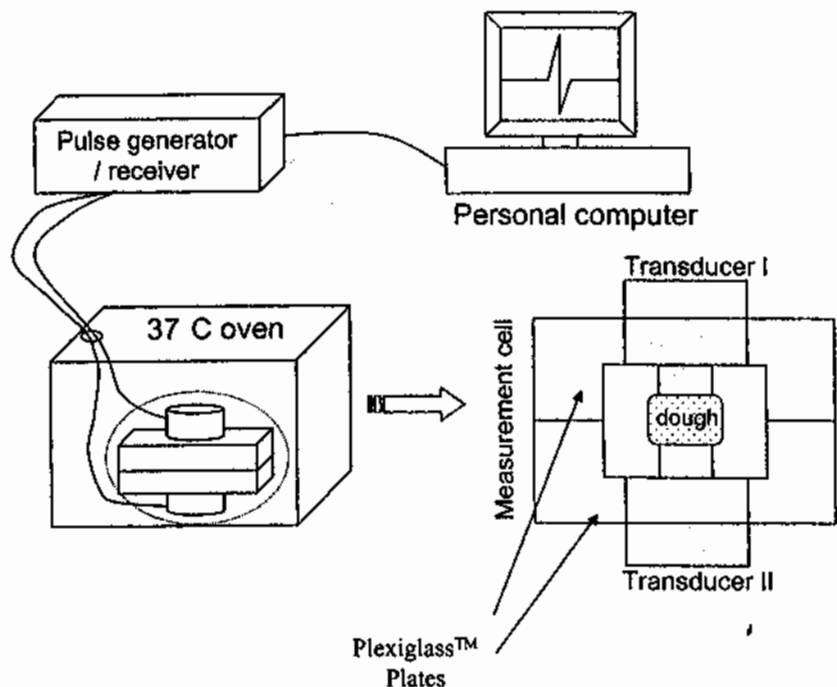


FIG. 1. ILLUSTRATION OF THE EQUIPMENT USED FOR THE ULTRASONIC MEASUREMENTS ON DOUGH DURING FERMENTATION

and shear storage moduli, whereas  $K''$  and  $G''$  are the bulk and shear loss moduli, respectively. The former give an indication of the elastic properties whereas the latter give the viscous properties of the dough. The relationships among the moduli, ultrasonic velocity, and attenuation at a given frequency ( $\omega$ ) are used to calculate the moduli  $M'$  and  $M''$ :

$$M' = K' + \frac{4}{3}G' = \frac{\rho v^2(1 - \frac{\alpha^2 v^2}{\omega^2})}{(1 + \frac{\alpha^2 v^2}{\omega^2})^2} \quad (1)$$

$$M'' = K'' + \frac{4}{3}G'' = \frac{2\rho v^2 \alpha v}{\omega} \frac{1}{\left(1 + \frac{\alpha^2 v^2}{\omega^2}\right)^2} \quad (2)$$

where  $\rho$ ,  $v$ , and  $\alpha$  are the density, the ultrasonic velocity, and the attenuation coefficient of the dough, respectively, and  $\omega$  is the frequency of the wave.

The dough density, needed to calculate the moduli of dough using Eq. (1) and (2) was evaluated, separately from the ultrasonic measurements, during the fermentation process. The density of the fermented dough was found by placing the sample between two transparent Plexiglass™ plates separated by a fixed distance of 3 mm before it was placed in the 37C oven. During the fermentation process, pictures of the fermenting dough located between the plates were taken with a digital camera Kodak, DC290. As a consequence of the fermentation the dough spread radially between the plates and the cross-sectional area of the dough sample was determined from the digital picture using image processing software (Photoshop®, Adobe Systems, San Jose, CA). The density was calculated using the measured area, the thickness, and the weight of the dough piece. Density measurements were done in triplicate and a plot of measured dough densities as a function of fermentation times is illustrated in Fig. 2.

Wavelet analysis was also used to study the ultrasonic signals. Wavelet analysis is a time-frequency localization procedure that provides information on ultrasonic velocity dispersion and structural characteristics of the material that cannot be obtained with the traditional Fast Fourier Transformation (FFT). The use of this analysis is relatively new in the field of food science. It was used in the investigation of the properties of frozen food systems (Lee *et al.* 2004) using ultrasonic techniques. The analysis was implemented in the Matlab software (The MathWorks, Natick, MA) and is based on the method described in these previous studies (Nolte *et al.* 2000; Lee *et al.* 2004).

### Extensional Properties Measurements

An Universal Testing Machine (MTS Systems Corp., Madison Heights, MI) was used to characterize the extensional properties of the dough samples during fermentation. The method introduced by Uthayakumaran *et al.* (2000) was modified and used for this work. An oven set at 37C was installed on the Universal Testing Machine to allow rheological measurement to be taken during the fermentation process. The dough sample was placed between two circular 3 cm diameter plates. The plates were serrated to increase the adhesion of the sample to the plates and the sample, and thus to ensure that the sample did not

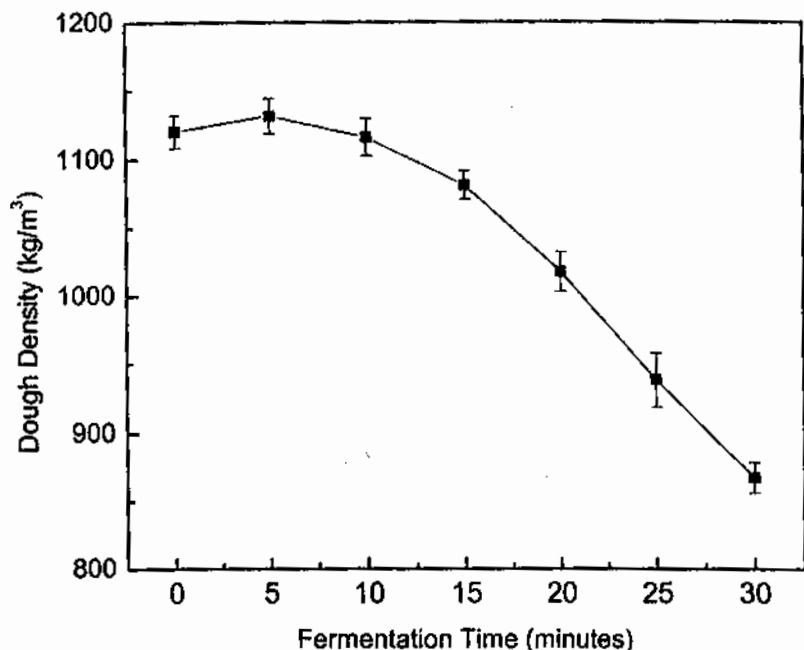


FIG. 2. THE EFFECT OF FERMENTATION TIME ON THE DOUGH DENSITY

separate from the plate during tensile testing. The lower plate was fixed and the upper plate was attached to the crosshead of the Universal Testing Machine. The crosshead and plate moved upwards with a velocity of 50 mm/min to elongate the dough sample until it was broken (Fig. 3). To avoid artifacts that could be caused by fracture of the sample during loading and/or lack of adhesion to the plates, only samples in which the breakage occurred in the midsection of the sample were analyzed. The force and distance recorded by the Universal Testing Machine software were used to obtain strain, strain rate, stress and extensional viscosity of the samples. As described by Uthayakumaran *et al.* (2000), stress and strain were calculated from the crosshead displacement and the sample momentary cross-sectional area, which was estimated assuming that the sample volume was kept constant and the sample shape was kept cylindrical during the measurement. The extensional viscosity of the samples was the ratio of the calculated stress during extension and the strain rate. All the measurements were done in triplicate using a different sample for each fermentation time. In this method the strain rate is not constant during the extension of the sample. A method to achieve constant strain rates during extensional flow tests is discussed by Uthayakumaran *et al.* (2000). It consists in varying the cross-head speed so

that the imposed Hencky's strain rate is constant. Methods that use constant crosshead speeds, and thus time varying strain rates, as applied to squeezing flow viscometry are discussed by Campanella and Peleg (2003). The fact that the applied strain rate during the test is not constant may not qualify the applied extensional test used as a fundamental one. However, the main objective of this work was to introduce a novel technique to testing fermenting dough and compare it with results of commonly used techniques in dough research.

The SAS ANOVA test (SAS Institute, Cary, NC) was used to determine significant differences among the samples.

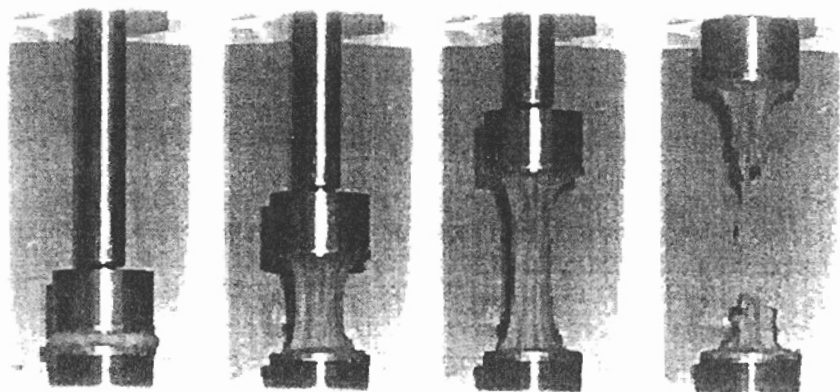


FIG. 3. PICTURES OF A DOUGH SAMPLE DURING AN UNIAXIAL EXTENSIONAL TEST

## RESULTS

The measured ultrasonic velocity decreased significantly during fermentation (Fig. 4). The change in the density of the dough sample due to the increase of the bubble volume during fermentation is a possible reason for the reduction in the ultrasonic velocity [Fig. 2]. Wehrle and Arendt (1998) showed that the presence of CO<sub>2</sub> bubbles produced by yeast in fermenting dough may affect the elastic dough network, resulting in a more viscous structure. This more viscous behavior of the fermenting dough would cause a decrease in the measured ultrasonic velocity.

