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## Using ultrasound to investigate the cellular structure of bread crumb

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### Abstract

In this paper, ultrasonic techniques were used to study how the mechanical properties of bread crumb are affected by changing the size, concentration and shape of the crumb cells. Since the gas cells determine the structural integrity of the bread crumb, these effects can form the basis of methods for predicting loaf quality, and hence are of considerable importance to food and cereal scientists. Freeze-dried bread crumb samples were prepared using red spring wheat flour. The density ( $\rho$ ) of crumb was varied from 100 to 300 kg/m<sup>3</sup> by proving the dough for various times. Both the ultrasonic velocity and the amplitude of 54 kHz longitudinal waves increased with  $\rho$ , with the velocity varying approximately as  $\rho^{0.5}$ . The signal amplitude was found to increase linearly with density. To investigate the effects of anisotropy in the cell structure of bread crumb, freshly baked samples were compressed uniaxially, thereby transforming the shape of the cells from approximately spherical to ellipsoidal. Ultrasonic measurements were taken in the directions parallel and perpendicular to the applied stress. The density dependence of the velocity in the compressed samples was opposite to that in the non-compressed samples, with velocity decreasing with increasing compression, more prominently along the direction parallel to the stress. Signal amplitude showed a slight increase. These results demonstrate that the mechanical properties of the compressed and non-compressed samples are different. The sensitivity of ultrasonic waves to changes in the size and shape of crumb cells demonstrates the potential for using ultrasound as a tool for characterizing the mechanical and structural properties of bread crumb, and hence for measuring some of the determining factors of bread quality.

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### 1. Introduction

From a structural point of view, bread crumb is a porous material consisting of gas cells and crumb cell walls. Often the crumb wall phase is referred to as the matrix (Scanlon and Zghal, 2001; Keetels et al., 1996). It is this material that contributes to the bread's mechanical strength and structural architecture. The crumb cell walls consist of partly gelatinized starch in a heterogeneous protein-based matrix (Eliasson and Larsson, 1993).

The final structure in the bread crumb (and in many baked goods) depends to a large extent on creating and controlling the development of gas bubbles in the dough matrix, and then retaining them as distinct bubbles until the bread is baked (and thus the matrix fixed) (Campbell et al., 1998; Cauvain, 1999). The crumb structure contributes to

the texture (or grain quality), mechanical strength and perceived product freshness of the bread as well as to its visual appearance. Each of these product attributes varies with the numbers, sizes and uniformity of distribution of these gas bubbles, which may be determined and controlled in the breadmaking process as early as the mixing stage (Cauvain, 1999). In general, the gas bubbles have a relatively small size; for example, at the end of mixing their mean diameter is about 75  $\mu\text{m}$ , but they expand to reach a mean diameter as large as a few millimetres (Shimiya and Nakamura, 1997). In the creation of fine-celled white bread, such as sandwich loaves, it is generally accepted by consumers that small holes that are uniformly distributed throughout the crumb are required and that large holes or irregular cell distributions are undesirable (Cauvain, 1999). For a good product, the crumb cell wall, or matrix, is required to be as thin as possible, yet it must be resilient enough to recover from modest deformation, such as squeezing and pressing—the two most common ways by which consumers assess product freshness (Ponte and

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Ovadia, 1996). Several research groups have studied gas cells in the bread crumb. For example, a digital imaging technique has been used to analyse crumb grain (Sapirstein, 1999; Zghal et al., 1999, 2001) and obtain an objective characterization of the cellular structure of the bread crumb based on measurements such as mean gas cell area, crumb wall thickness and cell density. A second example is the study of Cauvain et al. (1999), who investigated how different stages of the breadmaking process (mixing, moulding, etc.) affected the gas cell structure within the dough and how the latter influenced the resulting bread crumb cellular structure.

The mechanical properties of bread crumb are complex, in part attributable to the heterogeneity of the system (Scanlon and Zghal, 2001), since the porous structure gives rise to complex combinations of stresses when the specimen is tested (Ponte and Faubion, 1987; Lásztity, 1980). Other difficulties in defining the mechanical properties of bread crumb arise because structural heterogeneity creates variability in the mechanical properties of the bread crumb, so that there are differences between different loaves, but also within the same loaf of bread (Ponte and Faubion, 1987). Despite these difficulties, quantification of the mechanical properties of the bread crumb is essential because the elastic properties of bread crumb have been considered a significant determining factor of bread quality (Nussinovitch et al., 1992; Piazza and Masi, 1995; Wassermann, 1979).

A number of techniques have been used to measure the mechanical properties of bread crumb, including indentation (AACC, 1983; Liu and Scanlon, 2002), compression (Nussinovitch et al., 1992; Piazza and Masi, 1995; Liu and Scanlon, 2002), tension (Zghal et al., 2001; Chen et al., 1994), and shear measurements (Persaud et al., 1990). Numerical values for Young's modulus and the shear modulus from these techniques have been summarized (Scanlon and Zghal, 2001). There have also been studies of the mechanical properties of dehydrated bread crumb (Stokes and Donald, 2000; Chang et al., 2000), where the focus has been on evaluating structure-property relationships. The objectives of this paper are to describe how the mechanical properties of freeze-dried bread crumb can be measured by a non-destructive technique: low intensity ultrasound. It will also be shown how this technique can provide information on the structure of bread crumb.

## 2. Ultrasound measurements in relation to crumb properties

Ultrasound is the name given to the study and application of mechanical sound waves propagating at frequencies greater than the upper limit of audibility of the human ear (larger than 16–20 kHz) (Anderson, 1965). Ultrasound is very sensitive to the presence of internal defects and structural flaws, such as air pockets and fractures.

Ultrasound has been widely used in medicine and in the investigation of the properties of inorganic materials. However, to date, it has found relatively little application in cereal products, even though ultrasonic methods ranging in frequency from 20 kHz up to the MHz range can be used to examine food and related systems. The great advantage of ultrasound compared with other non-intrusive methods such as light scattering is that the majority of food materials transmit ultrasound even though they may be optically opaque. Therefore, there remains a wide range of liquid based foods (McClements et al., 1993; Povey, 1997), and even certain solids (Fairley, 1992; Miles and Fursey, 1977), which are amenable to analysis using ultrasonic methods.

In general, the propagation of ultrasound through a system depends upon its response to rapid pressure fluctuations; in principle all the food's mechanical properties, and indirectly some of its thermal properties, have an effect on the propagation of sound through the material (Povey, 1997). Foods are rarely homogeneous, and the transmission of ultrasound through a multi-phase material is influenced not only by the properties of the various phases in isolation, but also by the physical structure. These structural features include the concentration, size and distribution of phases or particles, and ultrasound sensitivity to these features depends on the mismatch in the acoustic properties of the constituents. The full picture is very complex but the corollary is that the ultrasonic response is sensitive to many of the key mechanical properties of foods. Therefore, there is considerable interest in using ultrasound in the food industry to monitor food properties (Povey, 1997).

A longitudinal ultrasonic wave, propagating through the food medium in the  $x$ -direction is described by (Anderson, 1965)

$$A = A_0 \exp(-\alpha x/2) \exp\{i(kx - \omega t)\}. \quad (1)$$

Here  $A$  is the amplitude at position  $x$ ,  $A_0$  is the amplitude at  $x = 0$ ,  $\alpha$  is the attenuation coefficient (in  $\text{m}^{-1}$  in S.I. units),  $k = 2\pi/\lambda$  is the wave number (in  $\text{m}^{-1}$ ),  $\lambda$  is the wavelength and  $\omega$  is the angular frequency ( $= 2\pi f$  where  $f$  is the frequency in Hz). The phase velocity at which the sound travels is  $v = \omega/k$ . The phase velocity of longitudinally polarized waves in a solid material is related to the longitudinal modulus,  $\beta$ , of the material and its density,  $\rho$ , by

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

where

$$\beta = B + \frac{4}{3}\mu. \quad (3)$$

Here  $B$  is the bulk modulus (equal to the inverse of the compressibility),  $\mu$  is the rigidity modulus (shear modulus) and the subscript  $l$  in Eq. (2) denotes longitudinal. The features of ultrasonic wave propagation of which most use has been made experimentally are the velocity and attenuation of the wave. For most purposes, it is only

necessary to appreciate that a measurement of the ultrasonic velocity provides information about the ratio of an elastic modulus to the density of the material through which it propagates. Thus, independent measurements of density and velocity enable a value of the elastic modulus to be determined. Whereas knowledge of the wave speed provides information about the modulus of the material, the attenuation coefficient depends on other material properties; even in pure homogeneous materials, there are many possible causes of attenuation.

### 3. Experimental

#### 3.1. Breadmaking and sample preparation

All flour samples were milled from Canada Western Red Spring (CWRS) wheat grade No. 1, with a flour protein content of 12.4%. The wheat was milled in the Canadian International Grains Institute (CIGI) pilot mill (Winnipeg, MB, Canada). The dough samples were prepared using the Canadian Short Process Method (Preston et al., 1982), which was carried out using the following constituents: flour (200 g), compressed yeast (3.0%, fw), salt (2.4%) and water (26 ml to give optimum absorption). In addition to these ingredients, the following were added: sugar (4.0%), phosphate (0.1%), shortening (3.0%), whey (4.0%), malt (0.2%), potassium bromate (30 ppm) and ascorbic acid (37.5 ppm, fw). The ingredients were mixed in a GRL-200 mixer at 165 rpm to 10% past peak consistency while maintaining a temperature of 30 °C (Preston et al., 1982). The dough was allowed to rest for 15 min in the proving cabinet at 30 °C and 83% R.H., then rounded by hand and given a further 15 min rest time at 30 °C and 83% R.H. Doughs were then sheeted, moulded and panned, as described for the Remix procedure (Irvine and McMullen, 1960; Kilborn and Tipples, 1981), proven at 37.5 °C for 70 min, and baked for 30 min at 205 °C. To vary the density of the bread crumb, the proving time was also varied from the optimum of 70 min. Samples were prepared from loaves baked on at least three separate days, each bake consisting of 18 loaves proven for various times.

In preparation for the ultrasonic experiments the fresh baked bread was stored in a temperature controlled cabinet overnight. The next day, the loaves were cut into slices of 1–5 cm thickness using an electric slicer (Tefal, model 220) and the crust was removed using an electric knife (Van Wyck, model 0601). The slices were then freeze dried in a Unitop 600L freeze-dryer (The VirTis Co. Inc., Gardiner, NY, USA) by freezing for a minimum of 3 h to a temperature of –45 °C. This low temperature ensured that collapse of the structure would not occur during sublimation. After evacuating to a pressure of 10 Pa, the sample was freeze-dried for 24–26 h, typically at a pressure of 2–4 Pa. The advantages of freeze-drying the samples included accurately fixing the delicate bread structure, thus making

the task of preparing samples with parallel sides relatively easy, and permitting the bread crumb to be dehydrated rapidly and completely, thereby increasing the rigidity of the samples and facilitating subsequent handling. Freeze-drying was also important for obtaining reliable ultrasonic measurements because of the requirement that good coupling of the ultrasonic displacements between the transducer and the sample be achieved via a bonding agent; since it was found that fresh bread absorbed most ultrasonic bonding agents, it was difficult to achieve adequate coupling for freshly baked samples, but this difficulty was not encountered for freeze-dried bread. After freeze-drying, the bread crumb was cut into slabs with parallel faces using a high speed circular blade saw (Micro-Matic Precision Wafering Machine, made by Micromech Mfg. Corp., Union, NJ, USA). Each of these steps was important and had to be done with extra caution to eliminate any errors that might arise from such factors as non-parallelism and density variations in the compressed bread samples.

#### 3.2. Experimental methods

A block diagram of the apparatus is shown in Fig. 1. A Portable Ultrasonic Non-destructive Digital Indicating Tester (PUNDIT 6, CNS Farnell, Borehamwood, UK) was used to generate a short (+ve) voltage pulse (or spike). A 3.5 V positive pulse with a rise time of 2  $\mu$ s, synchronized with the main output signal, was used to trigger the oscilloscope. The voltage spike from the PUNDIT was connected to a transducer, which generated the ultrasonic signal that travelled through the sample. The ultrasonic pulse was detected at the other face of the sample with a similar transducer, which converted the transmitted ultrasonic signal back into an electromagnetic (EM) signal. This EM signal was then amplified at the receiver amplifier and displayed on the oscilloscope. The central frequency of the transducers used in the measurements was 54 kHz.

The data were acquired using a computer-controlled digitizing oscilloscope (Tektronix model TDS 420A, Tektronix Canada Inc., Toronto, Canada), which was set

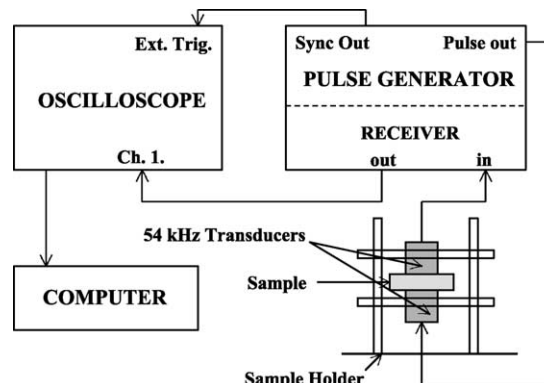


Fig. 1. Block diagram of the apparatus used for ultrasonic measurements of freeze-dried bread crumb.

in averaging mode. The signal averaging, which consisted typically of 1000 sweeps, greatly improved the signal-to-noise ratio. The triggering of the sweeps was performed by the synchronization output on the pulse generator, so as to synchronize data acquisition with each repetition of the pulse from the signal generator. The digitized waveforms were transmitted directly to the hard disk of the computer for subsequent analysis.

### 3.3. Amplitude and velocity measurements

The amplitude of the ultrasonic pulse was directly measured from the peak height of the detected waveform in Volts. The velocity was measured by calculating the time taken for the signal to travel from one side of the sample to the other. This was done in two steps. In the first step, a reference waveform was acquired. This waveform was taken with the two transducers separated by a material plate of well-known acoustic properties (acrylic). The two transducers were bonded to the plate via a thin coupling layer (Ultragel, Diagnostic Sonar Ltd, Scotland). After the reference signal was acquired, the sample was placed between the two transducers and the sample waveform was measured as described above. The transit time difference between the two waveforms (reference and sample) was then measured after aligning their initial phase oscillations using the pulse shape as a guide. This time difference was then corrected for the propagation time through the acrylic reference medium to obtain the time taken for the signal to travel through the sample,  $\Delta t$ . The transit time in conjunction with the sample thickness  $d$  yields the velocity of sound through the sample,  $v = d/\Delta t$ . All ultrasonic measurements were performed at room temperature.

## 4. Results and discussion

Measurements of the ultrasonic velocity and attenuation were performed on freeze-dried bread to investigate how these ultrasonic parameters vary in response to changes in the crumb structure effected by varying the size and shape of the gas cells. In this work, the samples were freeze dried so that the structure of the bread crumb could be fixed, and so that there would be minimal changes due to damage or modification of the structure during the course of experimental measurements. This was an important step for obtaining reproducible and quantitative measurements. While freeze drying does cause some shrinkage, volumetric reductions arising from freeze-drying have been reported to be as low as 2% (Shishegarha et al., 2002). In bread, our measurements have shown that the shrinkage due to freeze-drying is larger than this, with changes in the length, width and height of the cells of order 8%. Since the shrinkage is isotropic, the initial cell structure is preserved on freeze drying apart from a scale factor. Therefore, even though the absolute values of the velocity and attenuation

may be quite different in freeze-dried and fresh crumb, it is reasonable to expect that the way in which the velocity and attenuation change with density and cell shape will be similar. Thus, the main experimental findings reported in this paper, which focus on changes in cell size and shape due to variation in proving times and application of uniaxial stress, will likely have wider application beyond freeze-dried bread crumb per se.

### 4.1. The effect of changing the size of gas cells (isotropically) on phase velocity

By proving the samples at times varying between 0 and 108 min, the effect of changing the size of the gas cells on the ultrasonic velocity was investigated. As the dough samples are proved for longer times, the gas cells increase in size. Consequently, the number of gas cells per unit volume decreases and the crumb cell walls (generally) become thinner. Therefore, the density of the freeze-dried bread crumb samples is expected to decrease as a function of proving time. Fig. 2 confirms this hypothesis. The density  $\rho$  of the bread crumb was determined by measuring the mass  $m$ , thickness  $d$ , and surface area  $A$  of each sample after it had been cut into a rectangular parallelepiped for the ultrasonic measurements ( $\rho = m/Ad$ ). In order to improve the accuracy with which the surface area was measured, a digital imaging technique was used. Fig. 2 also compares our density results to those of Zghal et al. (1999), which were obtained from fresh (moist) bread crumb samples. Interestingly, the density of the fresh samples is quite close to that of the freeze-dried samples, indicating that the mass change due to removal of water during freeze-drying is partially compensated by the volume change due to shrinkage. This is

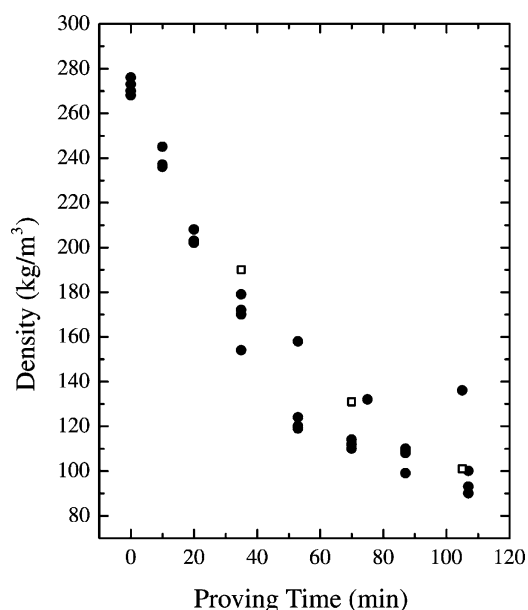


Fig. 2. Density of freeze-dried bread crumb as proving time is varied (closed symbols). For comparison, the results obtained by Zghal et al. (1999) are shown as open symbols.

confirmed by measurements that were performed on similar bread samples both before and after freeze drying, using the same freeze-drying procedure.

The phase velocity as a function of proving time is shown in Fig. 3. It can be seen that the velocity is strongly affected by the size of the gas cells with velocity decreasing markedly as the gas cells become bigger. To relate the velocity to the longitudinal modulus via Eq. (2), the velocity was first plotted as a function of density using the density versus proving time results (Fig. 4). It can be observed from Fig. 4 that the velocity increases with density approximately as  $\rho^{1/2}$ , as indicated by the solid curve, which is a least squares fit of the function  $c\rho^{1/2}$  to the data ( $c$  is a constant). To gain quantitative understanding of these results, the data were examined in light of theoretical models developed by Gibson and Ashby (1997) for cellular solids. The cellular structures may have open or closed cell walls. According to these models, Young's modulus ( $E$ ) for an open cell structure can be related to the density by

$$\frac{E}{E_w} = C \left( \frac{\rho}{\rho_w} \right)^2, \quad (4)$$

where  $C$  is a constant (experimental data (Gibson and Ashby, 1997) have shown that  $C \approx 1$ ) and  $\rho$  is the density. The subscript  $w$  refers to properties of the wall material of the cellular solid.

For a closed-cell foam structure (the statement whether the cell walls are open or closed is determined by the wall's permeability to gas and/or liquid), a fraction,  $\Phi$ , of the solid is contained in the cell edges as in the open cell structure; the remaining fraction ( $1 - \Phi$ ) is in the faces. The prediction of Gibson and Ashby's closed cell model for Young's modulus becomes

$$\frac{E}{E_w} = \Phi^2 C_1 \left( \frac{\rho}{\rho_w} \right)^2 + (1 - \Phi) C_2 \left( \frac{\rho}{\rho_w} \right) + C_3 (1 - \Phi)^3 \left( \frac{\rho}{\rho_w} \right)^3, \quad (5)$$

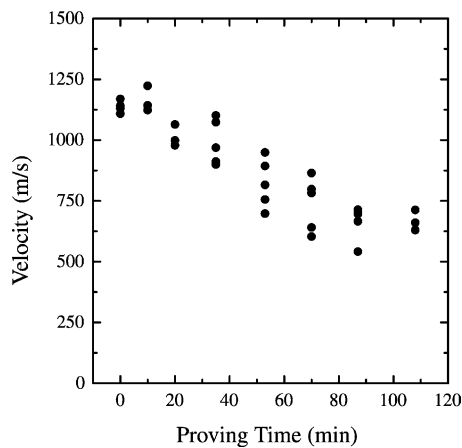


Fig. 3. The phase velocity of the 54 kHz longitudinal ultrasonic signal through bread crumb baked after proving the dough for various proving times.

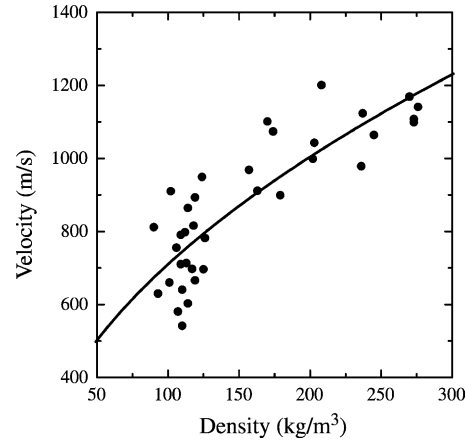


Fig. 4. Ultrasonic phase velocity as a function of bread crumb density. The solid line shows the least squares fit of the expression  $c\rho^{1/2}$  to the data, as discussed in the text. (It is interesting to note that if both the constant  $c$  and the density exponent are allowed to vary, the best fit value of the exponent is found to be 0.49 instead of 0.5, and the resulting fitted curve is almost indistinguishable from the curve shown.)

where  $C_1$ ,  $C_2$  and  $C_3$  are constants (experimental data (Gibson and Ashby, 1997) showed that  $C_1, C_2, C_3 \approx 1$ ).

To test the Gibson and Ashby models, the longitudinal modulus,  $\beta$ , was first calculated from the velocity data using the formula  $\beta = \rho v^2$  (c.f. Eq. (2)). The next step was to relate  $\beta$  to the predictions of the Gibson and Ashby models for  $E$ . In their models for foam, the cells are represented by a staggered cubic array of beams, with the addition of solid cell faces in case of a closed foam, and Young's modulus of the structure is determined by the bending of the beams in response to an external load. Since, as can be shown using standard elasticity theory for an isotropic material (e.g. see Nye, (1972)), the longitudinal modulus is simply related to Young's modulus and Poisson's ratio  $\nu$  by the expression

$$\beta = \frac{1 - \nu}{(1 + \nu)(1 - 2\nu)} E, \quad (6)$$

$\beta = E$  when  $\nu = 0$ , and  $\beta \approx E$  when  $\nu$  is small. For a value of  $\nu = 0.2$ , typical for bread at small strains (Rohm et al., 1997), the difference between  $\beta$  and  $E$  is only 12%. Furthermore, Gibson and Ashby suggest that Poisson's ratio is independent of density (Gibson and Ashby, 1997). Thus, the predictions for the density dependence of  $E$  in the Gibson–Ashby model should hold equally well for  $\beta$ , so that the two moduli should scale in the same way with density:

$$\frac{\beta}{E_w} = C' \frac{E}{E_w}, \quad (7)$$

where the constant  $C' \sim 1$ . Consequently, the Gibson–Ashby model can be used to interpret the behaviour of both the longitudinal modulus and the ultrasonic velocity in foam-like structures. In particular, the open cell model provides an explanation of the observed  $\rho^{1/2}$  dependence of

the velocity, since Eqs. (2), (4) and (7) predict that

$$\frac{v}{v_w^E} = \sqrt{\frac{\beta/\rho}{E_w/\rho_w}} = \sqrt{C' \frac{\rho}{\rho_w}} \quad (8)$$

Using the measured value of the average cell wall density for freeze-dried bread crumb,  $\rho_w = 1601 \text{ kg/m}^3$  (Zghal et al., 2002), and assuming  $C' = 1$  (Gibson and Ashby, 1997), Eq. (8) can be used in conjunction with the least squares fit shown in Fig. 4 to estimate the ultrasonic velocity  $v_w^E$  in the cell wall material. (This value,  $v_w^E = \sqrt{E_w/\rho_w}$ , corresponds physically to the ultrasonic velocity of guided waves in the cell walls when the dimensions of the cell walls are much smaller than the ultrasonic wavelength.) While one should always be cautious about extrapolating beyond the range of the actual measurements, the result of this analysis gives a very reasonable value for cell-wall velocity,  $v_w^E = 2840 \text{ m/s}$ . This corresponds to a wall modulus,  $E_w = 13 \text{ GPa}$ , which is also a physically reasonable value based on Eq. (4) and measurements of the elastic modulus of dried bread crumb (Stokes and Donald, 2000).

To gain further insight into the predictions of the Gibson–Ashby models, it is instructive to plot the longitudinal modulus for bread crumb as a function of relative density  $\rho/\rho_w$ , as shown in Fig. 5. Again the value  $\rho_w = 1601 \text{ kg/m}^3$  (Zghal et al., 2002) was used to present these data as a function of relative density; any uncertainty in this number will introduce a small systematic effect that does not affect the exponent found in a power law fit to the data. The predictions of the Gibson and Ashby models are shown on the graph by the solid line (open cell model) and dotted line (closed cell model). For the closed cell model,  $\Phi$

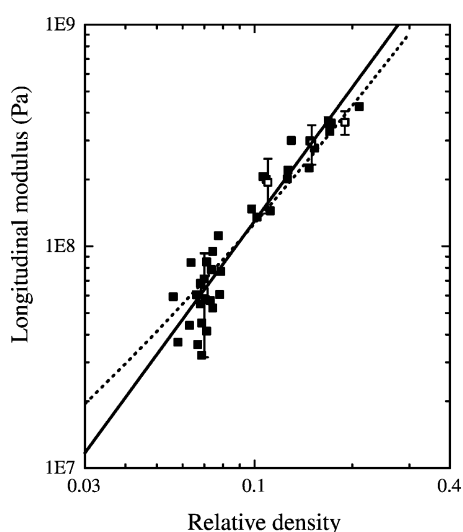


Fig. 5. The longitudinal modulus for bread crumb as a function of its relative density. Gibson and Ashby's models are shown by solid line (open cell model) and dashed line (closed cell model). The uncertainties were estimated from the standard deviation of the measured modulus values for four ranges in crumb density ( $\pm 25 \text{ kg/m}^3$ ), and are represented by the error bars associated with the mean values shown by the open symbols.

was assumed to be independent of the density (Gibson and Ashby, 1997) and its value, determined from a least square fit to the data, was 0.96. Although the open cell model gives very good agreement with the experimental data over the entire relative density range, the closed cell model gives a slightly better fit to the experimental results. This is not surprising since there is one additional fitting parameter. The difference in the two fits is probably not significant.

Despite the considerable simplification of the structure, the Gibson and Ashby simple beam models for both open and closed cells appear to fit the data very well. Since the bread crumb has a finite permeability (Baker, 1939), implying that the cell walls are not completely closed, close inspection of the bread crumb structure shows that a plausible model is one where the structure is dominated by the large cells, which have an appearance of 'closed' quasi-spherical cells with porous cell walls. The effect of cell wall porosity on the physical properties of bread crumb has been discussed previously (Zghal et al., 1999; Stokes and Donald, 2000). Thus, these results obtained by comparing the Gibson and Ashby models for open and closed cell foams with the ultrasonic data are indeed very reasonable physically.

#### 4.2. The effect of changing the shape of the gas cells (anisotropically) on phase velocity

To increase the density of the bread crumb samples and to study the effects of elastic anisotropy on their mechanical properties, fresh bread samples were compressed uniaxially to a pre-determined strain by placing a 2.5-kg mass on top of each sample (corresponding to a compressive force of about 25 N). The samples were then freeze-dried. Using this method, the density of the samples was increased up to five times the normal density of non-compressed bread, allowing the ultrasonic investigations to be undertaken over a wider density range. However, the structure of these samples was different to that of the non-compressed samples. In particular, the gas cells are no longer spherical and thickness of the cells in the direction parallel to the applied stress is greatly reduced. This behaviour is represented schematically in Fig. 6(a) and (b), and shown directly by digital images of typical uncompressed and compressed samples in Fig. 6(c) and (d), respectively. Because the structure of the material is now anisotropic due to the compression procedure, the ultrasonic velocity and attenuation depends on the direction in which the sample is probed. In particular, independent measurements of the velocity both parallel and perpendicular to the applied compressive strain allow the effect of these differences in gas cell structure to be investigated. It should be noted that the final thickness of the compressed samples was set to be identical for all samples and the same load was used for compressing every sample. Because Poisson's ratio is close to zero for the as-baked bread at these large strains (Rohm et al., 1997), the density

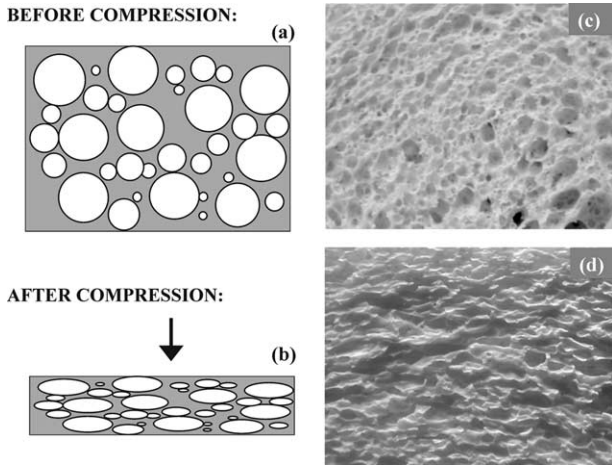


Fig. 6. *Left side*: Schematic diagrams showing that the approximately spherical cells of uncompressed bread crumb (a) become pancake-shaped as a result of uniaxial compression (b). *Right side*: Images of typical freeze-dried bread samples showing the uncompressed (c) and compressed (d) structures. The image in (d) is magnified to show clearly the compressed shapes of the cell cross sections.

increase is therefore almost entirely determined by the decrease in original sample thickness.

The variation in the density of the compressed samples as the applied compressive strain was increased is plotted in Fig. 7. The increase in the density is expected since the net effect of straining the sample is to compress the spherical gas cells, resulting in their compression along the direction in which the stress is applied. Furthermore, since density is defined as the mass divided by volume and the mass of the sample does not change as a result of the compression, the change in the density reflects the change in the sample volume as the thickness of the sample is decreased. Once the cells start to collapse, so that Poisson's ratio is essentially zero (Gibson and Ashby, 1997; Rohm et al., 1997), then the density,  $\rho$ , of the compressed samples will increase as

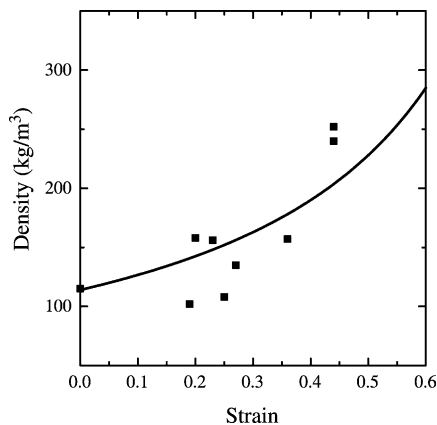


Fig. 7. The density of freeze-dried compressed samples as a function of the compressive strain. The strain was measured along the direction of the uniaxial stress that was applied to the fresh bread crumb prior to freeze-drying. The solid curve represents the behaviour predicted by Eq. (9).

follows,

$$\rho(\epsilon) = \frac{M}{V} = \frac{M}{V_0 - \Delta V} = \frac{M}{V_0(1 - \Delta V/V_0)} = \frac{M}{V_0(1 - \epsilon)}$$

$$= \frac{\rho_0}{1 - \epsilon} \quad (9)$$

where  $M$  is the mass of the sample,  $V$  is the sample volume after it has been decreased by  $\Delta V$  from its original volume  $V_0$ ,  $\epsilon = \Delta l/l \approx \Delta V/V$  is the strain,  $l$  and  $\Delta l$  are the length of the sample and its change in the compression direction, and  $\rho_0 = M_0/V_0$  is the original density. The curve in Fig. 7 shows this prediction for the strain-dependent density. The agreement between this prediction and the data is consistent with the idea that Poisson's ratio is close to zero for bread. Rohm et al. (1997) reported that Poisson's ratio for white bread ranges between 0.17 and 0.25 for small strain and 0.07–0.15 for large strain. For the strains used here, the applicable values for Poisson's ratio found by Rohm et al. range from 0.11 to 0.15, confirming that Poisson's ratio is indeed small for these bread samples.

To illustrate the substantial difference in the velocity resulting from the change in structure brought about by compression of the cells, the ultrasonic velocity in the compressed samples was compared with the velocity in the isotropic non-compressed samples created by varying the proving time. The velocity in the compressed samples was measured parallel to the compression direction, and these samples were created from bread proved for 70 min, the optimal proof time for the baking procedure used. Relative to the baking pan, the compression direction was the same as the direction in which the non-compressed samples were probed. Fig. 8 shows the velocity for these two sets of measurements as a function of density. The dependence of the velocity on the density of the compressed samples is clearly seen to be different to that of

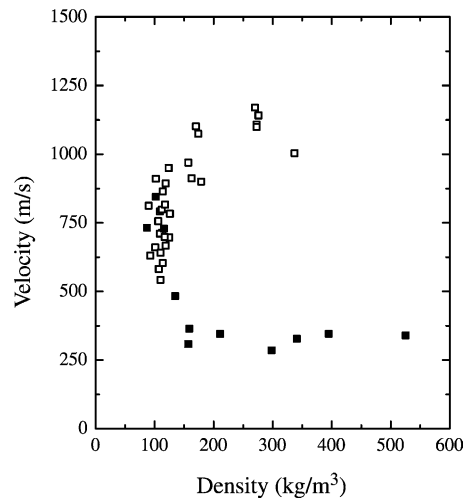


Fig. 8. Comparison of the density dependence of the ultrasonic velocity for uncompressed samples (open, □) and compressed samples (closed, ■), whose velocity was measured parallel to the direction in which stress was applied.

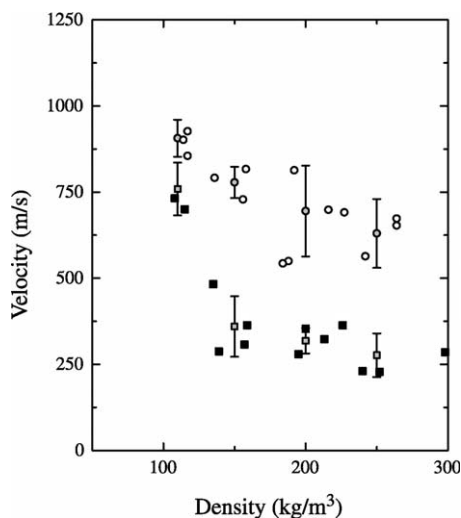


Fig. 9. The velocity along two orthogonal directions in the compressed samples: parallel to the applied stress (closed, ■), and perpendicular to the applied stress (open, ○). The error bars were determined as described in the caption to Fig. 5.

the non-compressed samples. The velocity for both sets of samples starts at the same value at low densities, but their behaviour thereafter is opposite. While the velocity of the non-compressed samples increases with density, the velocity of the compressed samples decreases. In particular, the velocity of the compressed samples drops off dramatically as the gas cells depart from their approximately spherical shapes and the cells attain a pancake-like structure. At higher densities,  $\rho > 250 \text{ kg/m}^3$ , the phase velocity levels off at a minimum value, which is about 300 m/s. The different behaviour of the phase velocities for the compressed and non-compressed samples is a clear indication that the structure of the samples has been altered as a result of the induced strains.

To further examine the effect of structural anisotropy on sound propagation characteristics, slab-shaped samples of thickness 4–6 mm were cut in two orthogonal orientations to allow ultrasound propagation to be measured along directions both parallel and perpendicular to the applied stress. These samples were cut from compressed samples that had been excised from loaves baked on the same day. The phase velocity as a function of density (Fig. 9) shows that the velocity–density relationship is indeed different for the two propagation directions. For samples probed along the direction parallel to the stress, the decrease, as discussed above, is very pronounced: the velocity starts at 700 m/s at zero strain and decreases sharply to a velocity of approximately 300 m/s as the density is increased. However, for samples probed along the direction perpendicular to the stress, the velocity shows a decrease of only about 30% over the range of densities for which the measurements were performed. Thus, in addition to a decrease in the average of the two velocities resulting from the strain, there is a very pronounced anisotropy in the velocity, and hence in the elastic modulus. These results demonstrate that

measurements of the ultrasonic velocity in different directions can be used to probe the average anisotropy of the cell structure of bread.

#### 4.3. Attenuation results

In bread crumb samples, it is not possible to excise samples that have exactly the same density. This is true for samples cut from the same loaf and is due to the intrinsic inhomogeneities within the sample (Ponte and Faubion, 1987). In fact, for samples proven for the same time, the density variation was found to be as large as  $10 \text{ kg/m}^3$ . Such density fluctuations make it difficult to make measurements for a range of sample thicknesses and hence unambiguously determine the attenuation coefficient (Elmehti, 2001). As a result, the attenuation results will be expressed in terms of the amplitude of the propagating signal, for a fixed input amplitude, in samples of fixed thickness, rather than by the attenuation coefficient. This still allows qualitative trends in the density dependence of the attenuation to be inferred from our measurements, thus providing information on the changes in the size of gas cells and their concentration.

For the uncompressed samples whose density was varied according to proving time, the signal amplitude increased as the density increased (Fig. 10). In other words, for the denser samples, where the gas bubbles are smaller and the cell walls are thicker, the signal suffers less loss due to absorption or scattering of the signal. The thickness of these samples was 6.3 mm.

For the compressed samples (note that all compressed samples were of the same thickness which was 4.2 mm), the signal amplitude depended on whether the ultrasonic signal propagated in the perpendicular or parallel direction (Fig. 11). The signal amplitudes start at the same value as the uncompressed samples, but as the density is increased as a result of compression, there is a slight increase in the signal amplitude for the perpendicular samples and a slight

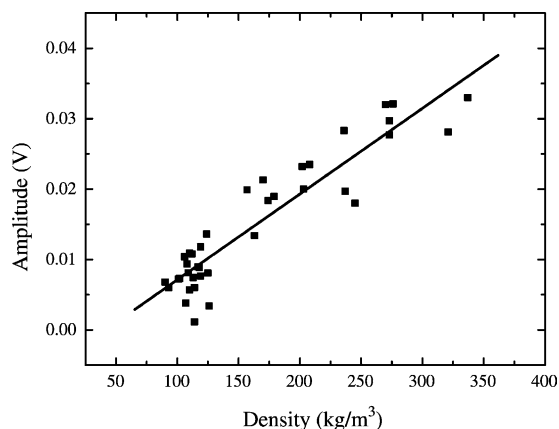


Fig. 10. The amplitude of the transmitted ultrasonic signal as the density of bread crumb is varied by varying the proving time. The line represents a linear fit to the data.



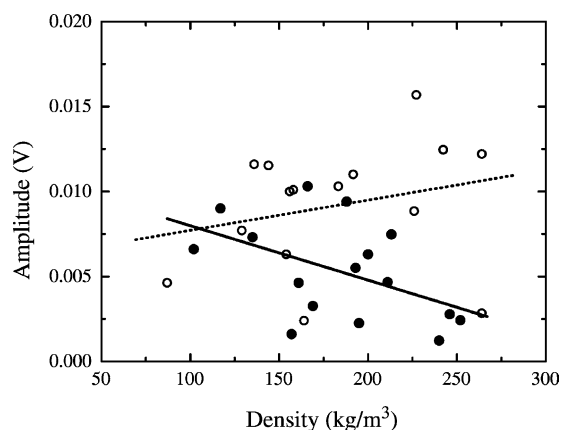


Fig. 11. The amplitude of the transmitted ultrasonic signal as the density of bread crumb is varied by applying uniaxial stress to the sample prior to freeze-drying. The solid symbols (●) represent the amplitude of the signal propagating along the direction in which the bread was compressed, and the open symbols (○) represent the amplitude of the signal propagating along the direction perpendicular to the compression. The lines represent linear fits to the parallel and perpendicular data.

decrease in the signal amplitude in the parallel samples. In both cases, the signal amplitude stays substantially smaller than that of the uncompressed samples at comparable density values. To explain the increase and decrease in the signal amplitude with the density for the perpendicular and parallel samples respectively, it is sufficient to re-examine the structure of the compressed samples (Fig. 6). The relevant factor that has to be accounted for is the amount of strain in the two directions.

For the parallel samples, the cross section of the gas cells remains about the same, but the number of cells per unit length is increased ( $\propto 1/\epsilon$ ), so that a strain of 0.5 gives twice as many cells per unit length. Therefore, the amount of scattering is expected to increase, with a corresponding decrease in the signal amplitude. By contrast, for the perpendicular samples, the average cross section of gas cells decreases, but the number of cells per unit length is similar to the uncompressed one. Thus, the ultrasonic waves encounter less scattering, and the signal amplitude is bigger.

These arguments suggest that for the parallel strain, the amplitude is expected to be less than that for the uncompressed samples, but that for the perpendicular strain, the amplitude should be bigger. However, this is not the case, as the amplitudes in both directions are less. Thus, there must be an additional mechanism that causes the average ultrasonic attenuation to increase with strain, and it is likely to be the same as the one that reduces the average velocity and weakens the matrix. The most obvious mechanism would be changes to cell wall structure resulting from compression of the fresh bread crumb (Stokes and Donald, 2000; Andrews et al., 2001), motivating the development of a model to interpret these observations quantitatively. Understanding this effect would have potential application in characterizing the textural properties of bread crumb.

## 5. Conclusion

The experimental results presented in this paper demonstrate that the velocity and attenuation of ultrasonic waves are sensitive probes of changes in the structure of freeze-dried bread crumb as its density is varied. As the density increases due to changes in the proving time, the ultrasonic velocity also increases, varying approximately as the square root of the density. A satisfactory description of the experimental velocity data, as well as the corresponding behaviour of the longitudinal elastic modulus, is provided by both the closed and open cell models of Gibson and Ashby. These models, which were developed to characterize only the static elasticity of foams, can therefore also be applied to the dynamic elastic response in the low amplitude, finite frequency regime of ultrasonic measurements. While these models do not enable the absolute sizes of the cells to be deduced from ultrasonic measurements at a single frequency, a quantitative basis for establishing how the ultrasonic velocity is affected by changes in porosity and cell size has been established. When anisotropy in the crumb structure is induced by compressing fresh bread uniaxially prior to the freeze-drying process, large differences are found in the ultrasonic velocity depending on the direction of propagation relative to the compression direction. Work is in progress to relate the anisotropy in the velocity to the anisotropy of the underlying crumb structure with a view to developing a model for predicting cell shape anisotropy from ultrasonic measurements. These results could then have practical importance by providing a new means of assessing cell shape anisotropy—an important crumb grain quality determinant. Complementary information on bread crumb is provided by the attenuation of the ultrasonic waves, which is affected by absorption and scattering from heterogeneities in the crumb. In particular, the transmitted signal amplitude was found to increase as crumb cells became smaller, i.e., as the density increased, consistent with the simple physical picture that scattering and absorption is decreased when the sizes of the cells become smaller relative to the ultrasonic wavelength. These experiments show that ultrasonic velocity and attenuation measurements are very sensitive to changes in both size and shape of the gas cells in bread crumb, motivating further work to develop a fully quantitative ultrasonic method for measuring these changes.

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## References

- AACC, 1983. AACC method 74-09: bread firmness by universal testing machine, 8th ed., Approved Methods of the American Association of Cereal Chemists, II. American Association of Cereal Chemists, Inc, St Paul.
- Anderson, O.L., 1965. In: Mason, W.P. (Ed.), Physical Acoustics, III. Academic Press, New York, pp. 43–97, Part B.
- Andrews, E.W., Gioux, G., Onck, P., Gibson, L.J., 2001. Size effects in ductile cellular solids. Part II: experimental results. *International Journal of Mechanical Sciences* 43, 701–713.
- Baker, J.C., 1939. The permeability of bread by air. *Cereal Chemistry* 16, 730–733.
- Campbell, G.M., Rielly, C.D., Fryer, P.J., Sadd, P.A., 1998. Aeration of bread dough during mixing: effect of mixing dough at reduced pressure. *Cereal Foods World* 43, 163–167.
- Cauvain, S.P., 1999. Breadmaking processes. In: Cauvain, S.P., Young, L.S. (Eds.), *Technology of Breadmaking*, Aspen Publishers, Inc, Gaithersburg, MD, pp. 18–44.
- Cauvain, S.P., Whitworth, M.B., Alava, J.M., 1999. The evolution of bubble structure in bread doughs and its effect on bread structure. In: Campbell, G.M., Webb, C., Pandiella, S.S., Niranjan, K. (Eds.), *Bubbles in Food*, Eagan Press, St Paul, pp. 85–88.
- Chang, Y.P., Cheah, P.B., Seow, C.C., 2000. Variations in flexural and compressive fracture behavior of a brittle cellular food (dried bread) in response to moisture sorption. *Journal of Texture Studies* 31, 525–540.
- Chen, P., Whitney, L.F., Peleg, M., 1994. Some tensile characteristics of bread crumb. *Journal of Texture Studies* 25, 299–310.
- Eliasson, A.-C., Larsson, K., 1993. *Cereals in Breadmaking*, Marcel Dekker, Inc, New York.
- Elmehdi, H.M., 2001. An Ultrasonic Investigation of the Effect of Voids on the Mechanical Properties of Bread Dough and the Role of Gas Cells in Determining the Cellular Structure of Freeze-dried Bread Crumb, University of Manitoba, Ph.D. Thesis.
- Fairley, P., 1992. Ultrasonic Studies of Food Containing Air, Leeds University, UK, Ph.D. Thesis.
- Gibson, L.J., Ashby, M.F., 1997. *Cellular Solids: Structure and Properties*, 2nd ed., University Press, Cambridge.
- Irvine, G.N., McMullen, M.E., 1960. The 'remix' baking test. *Cereal Chemistry* 37, 603–613.
- Keetels, C.J.A.M., van Vliet, T., Walstra, P., 1996. Relationship between the sponge structure of starch bread and its mechanical properties. *Journal of Cereal Science* 24, 27–31.
- Kilborn, R.H., Tipples, K.H., 1981. Canadian test baking procedures. I. GRL remix method and variations. *Cereal Foods World* 26, 624–628.
- Lásztity, R., 1980. Rheological studies on bread at the Technical University of Budapest. *Journal of Texture Studies* 11, 81–115.
- Liu, Z.Q., Scanlon, M.G., 2002. Understanding and modeling the processing-mechanical property relationship of bread crumb assessed by indentation. *Cereal Chemistry* 79, 763–767.
- McClements, D.J., Povey, M.J.W., Dickinson, E., 1993. Absorption and velocity dispersion due to crystallization and melting of emulsion droplets. *Ultrasonics* 31, 433–437.
- Miles, C.A., Fursey, G.A.J., 1977. Measurement of the fat content of meat using ultrasonic waves. *Food Chemistry* 2, 107–118.
- Nussinovitch, A., Steffens, M., Chinachoti, P., Peleg, M., 1992. Effect of strain level and storage time on the recoverable work of compressed bread crumb. *Journal of Texture Studies* 23, 13–24.
- Nye, J.F., 1972. *Physical Properties of Crystals*, University Press, Oxford.
- Persaud, J.N., Faubion, J.M., Ponte, J.G. Jr, 1990. Dynamic rheological properties of bread crumb. I. Effects of storage time, temperature, and position in the loaf. *Cereal Chemistry* 67, 92–96.
- Piazza, L., Masi, P., 1995. Moisture redistribution throughout the bread loaf during staling and its effect on mechanical properties. *Cereal Chemistry* 72, 320–325.
- Ponte, J.G. Jr, Faubion, J.M., 1987. Rheology of bread crumb. In: Faridi, H. (Ed.), *Rheology of Wheat Products*, The American Association of Cereal Chemists, Inc, St Paul, pp. 241–273.
- Ponte, J.G. Jr, Ovadia, D.Z., 1996. Instrumental methods. In: Hebeda, R.E., Zobel, H.F. (Eds.), *Baked Goods Freshness*, Marcel Dekker, Inc, New York, pp. 151–170.
- Povey, M.J.W., 1997. *Ultrasonic Techniques for Fluid Characterization*, Academic Press, San Diego.
- Preston, K.R., Kilborn, R.H., Black, H.C., 1982. The GRL pilot mill. II. Physical dough and baking properties of flour streams milled from Canadian red spring wheats. *Canadian Institute of Food Science and Technology Journal* 15, 29–36.
- Rohm, H., Jaros, D., deHaan, M., 1997. A video-based method for determination of average stress-strain relations in uniaxial compression of selected foods. *Journal of Texture Studies* 28, 245–255.
- Sapirstein, H.D., 1999. The imaging and measurement of bubbles in bread. In: Campbell, G.M., Webb, C., Pandiella, S.S., Niranjan, K. (Eds.), *Bubbles in Food*, Eagan Press, St Paul, pp. 233–243.
- Scanlon, M.G., Zghal, M.C., 2001. Bread properties and crumb structure. *Food Research International* 34, 841–864.
- Shimiya, Y., Nakamura, K., 1997. Changes in size of gas cells in dough and bread during breadmaking and calculation of critical size of gas cells that expand. *Journal of Texture Studies* 28, 273–288.
- Shishegharha, F., Makhlof, J., Ratti, C., 2002. Freeze-drying characteristics of strawberries. *Drying Technology* 20, 131–145.
- Stokes, D.J., Donald, A.M., 2000. *In situ* mechanical testing of dry and hydrated bread crumb in the environmental scanning electron microscope (ESEM). *Journal of Materials Science* 35, 599–607.
- Wassermann, L., 1979. Relationship between structure and rheological properties of bread crumb. In: Sherman, P. (Ed.), *Food Texture and Rheology*, Academic Press, London, pp. 283–289.
- Zghal, M.C., Scanlon, M.G., Sapirstein, H.D., 1999. Prediction of bread crumb density by digital image analysis. *Cereal Chemistry* 76, 734–742.
- Zghal, M.C., Scanlon, M.G., Sapirstein, H.D., 2001. Effects of flour strength, baking absorption, and processing conditions on the structure and mechanical properties of bread crumb. *Cereal Chemistry* 78, 1–7.
- Zghal, M.C., Scanlon, M.G., Sapirstein, H.D., 2002. Cellular structure of bread crumb and its influence on mechanical properties. *Journal of Cereal Science* 36, 167–176.