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Advances on Ultrasonic Techniques Used for Characterizing Biofomic Materials

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***Abstract*— Acoustic waves at the ultrasonic range have been shown to provide accurate quantitative description of the properties of brittle biofoams. Of particular interest, the effect of anisotropy of gas cells on the structure of a brittle bio-foam system, which determines the structural integrity of these biofams. In this paper, we report the results of recent experiments in which we investigated using an ultrasonic approach. It was found that both the shape and the concentration of the voids, ϕ, in the foam have an impact of the values of the measured acoustic parameters. The results show that ultrasonic parameters are sensitive to voids in these foams. For anisotropic foams, the ultrasonic parameters were also found to depend on the orientation of the voids within the foam. Theoretical models gave a satisfactory description of the experimental results.**

***Keywords*— Ultrasound, biofoams, anisotropy, elastic properties.**

I. INTRODUCTION

Foam-like materials are characterized by their disordered structure and low density, which may present a challenge in experimentally characterizing such materials. They have attracted great deal of interest over the past years [1]. For example, many of the foods that we eat, such as bread, cakes and a wide range of desserts are foamed structures [2]. The increase in scientific interest has the objective in many cases of attaining a better understanding of the technological properties of the foams for a particular application, but acquiring a fundamental understanding of foam properties is also an objective of physicists because of their unique properties.

In a comprehensive assessment of the properties of foamed cellular solids, Gibson and Ashby [3] showed that to first order, many foam properties scaled according to the relative density (ρ^*/ρ_s) of the foam:

$$\frac{P}{P_s} = C\left(\frac{\rho}{\rho_s}\right)^n \qquad (1)$$

Where P is a specific property of the foam, P_s is the value of that property exhibited by the material that constitutes the walls of the foam, ρ is the density of the foam and ρ_s is the value of the density of the foam wall material. However, this relative density scaling approach must be modified when the foamed material exhibits anisotropy in the cells that make up the foam, either by specifying two or more direction-dependent values for P, or by adding additional terms associated with the anisotropy.

Acoustic waves at ultrasonic frequencies have been successfully employed to investigate the elastic properties of anisotropic materials [4]. 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 heterogeneous physical structure into which the proteins are assembled. These structural features include the concentration, size and distribution of phases, 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 structural and mechanical properties. Therefore, there is considerable interest in using ultrasound in the food industry to monitor food properties, provided that the samples are otherwise well characterized [4, 5,6, 7].

A longitudinal ultrasonic pressure wave, propagating through a fluid medium in the x-direction with a pressure field,ψ, is described by [8]:

$$\psi = \psi_0 \exp(-\alpha x/2)\exp\left(i\left[kx-\omega t\right]\right) \qquad (2)$$

Here ψ_0 is the pressure field at $x = 0$, α is the attenuation coefficient in m^{-1}, $k=2\pi/\lambda$ is the wave number, λ is the wavelength and ω is the angular frequency ($= 2\pi f$). The phase velocity at which the sound travels is $v=\omega/k$. In materials where attenuation is not too large, the phase velocity of longitudinally polarized waves is related to the longitudinal modulus, β, of the material and its density, ρ by

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$$v_l = \left[\frac{\beta}{\rho}\right]^{1/2} \quad (3)$$

Where in a solid material, the modulus is given by:

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

Here B is the bulk modulus (equal to the inverse of the compressibility), μ is the rigidity modulus (shear modulus) and the subscript l in equation 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 combined 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 [9].

For brittle biofoams such as beadcrumb foams, have been reported that both longitudinal ultrasonic velocity and attenuation coefficient are not only sensitive to void fraction, but also to the propagation direction; anisotropy. Elastic moduli, which are determined from the acoustic speed and the material density ($E = \rho v^2$), provide quantitative information about the elastic properties of these foams. By probing the material along the two symmetry axes, which are orthogonal to each other, ultrasonic parameters are expected to provide additional quantitative information of the effect of anisotropy on the properties of these foams. The objective of our research is to use acoustic waves at the ultrasonic range to probe the effect of anisotropy on the mechanical properties of these foams.

II. Materials And Methods

Samples Samples used in this research are freeze-dried cereal brittle foams of different anisotropy ratio, R. The anisotropy ratio was varied by compressing freshly backed samples into slabs of thicknesses 4-6 mm and then freeze-dries them to obtain the desired brittle foams. The elastic properties of these anisotropic samples were examined using low frequency (~50 kHz) ultrasonic waves.

These waves were generated using a short positive voltage pulse, which was converted to an ultrasonic signal via the generating transducer. After the waves propagated through the sample, they were detected on the other side of the sample by a similar transducer and reconverted to an electromagnetic (EM) signal. The converted EM signal was then amplified, viewed on the oscilloscope and downloaded to a computer for analysis. Details of the set-up and the analysis of the data are explained by Elmehdi et al. [10].

Ultrasonic velocity and attenuation measurements:

The ultrasonic velocity is the distance the ultrasonic wave moves through the sample per unit time, whereas the attenuation coefficient is a measure of the decrease in the amplitude of the ultrasonic wave per unit distance traveled. The ultrasonic velocity can be determined by measuring the time, t taken for a pulse of ultrasound to travel a known distance, x: $v=x/t$. The attenuation coefficient is determined by measuring the reduction in amplitude of an ultrasonic wave, which has traveled a known distance through a material:

$$\alpha = -\frac{1}{x}\ln\left(\frac{A_x}{A_0}\right) \quad (5)$$

Where A_0 is the initial amplitude of the ultrasonic wave (at x = 0), and A_x is the amplitude after it has traveled a distance x.

The sample to be analyzed is sandwiched between two ultrasonic transducers: a transmitter and a receiver (Fig. 1).

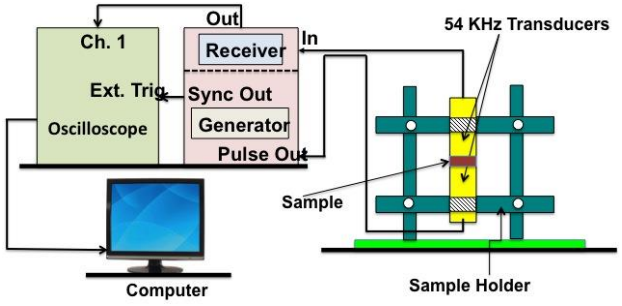

Fig. 1. Ultrasonic Experimental setup

The transmitting transducer produces a pulse of ultrasound, which travels across the sample and is detected by the receiving transducer. The ultrasonic velocity and attenuation coefficient of the sample are determined by measuring the time-of-flight (Δt) and amplitude (A) of the ultrasonic pulse, which has traveled across the sample.

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The ultrasonic velocity is equal to the length of the sample, *d*, divided by the time required to travel this distance. The attenuation coefficient is calculated by comparing the reduction in the amplitude of the pulse that has traveled through the sample with that of a pulse, which has traveled through a calibration material, i.e. a reference material of known acoustical properties:

$$\alpha_s = \alpha_c - \frac{1}{d}\ln\left(\frac{A_s}{A_c}\right) \qquad (6)$$

Where the subscripts *c* and *s* refer to the properties of the calibrant and sample, respectively. To obtain accurate attenuation measurements it is necessary to ensure that the measurement cell is well designed to minimize temperature fluctuations, reverberation of ultrasonic pulses in cell walls and transducers, diffraction effects and phase cancellation due to nonparallel walls [11].

The ultrasonic transducer generates a pulse of ultrasound, which travels across the sample, and is reflected from the back wall of the measurement cell, travels back through the sample, and is then detected by the same transducer.

To obtain accurate and reliable measurements it is important to take extreme care in designing and manufacturing measurement cells, for all types of ultrasonic technique. Some of the most important factors to con- sider are nonparallelism of surfaces, imperfect reflection at boundaries, reverberations in cell walls, temperature fluctuations and diffraction losses [11].

III. Results And Discussion

Experimentally, the transit (or flight) time, Δt, was calculated by measuring the time difference between the first two oscillations of the reference and the sample waveforms as follows. This was accomplished by aligning the two waveforms using the pulse shape as a guide. The delay time introduced by the reference signal (through the acrylic plates) was then subtracted from the measured time, Δt, to give the time taken for the signal to travel through the sample. Figure 2 shows an example of the reference, the transmitted waveforms and Δt. The above procedure was repeated for several sample thicknesses ranging from 1 mm to 5 mm, that were washed from the same flour, and measured the time taken for the ultrasonic signal to travel through the sample, i.e., the transit time, Δt.

After that, the transit time was plotted versus the sample thickness generating a linear behavior and the velocity is calculated from the slope of the linear fit.

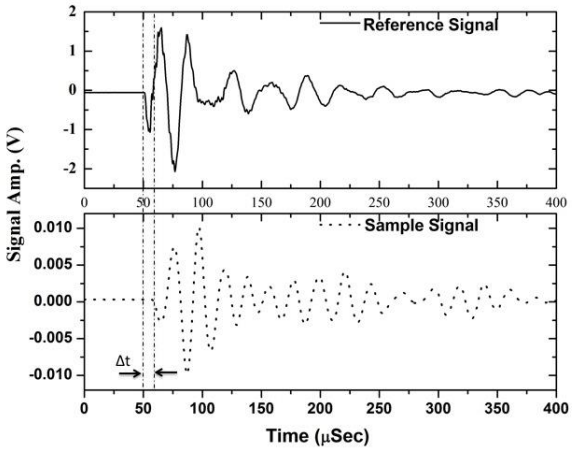

Fig. 2. Typical example of the reference and the transmitted waveforms used to calculate the transit time Δt.

As shown in Fig. 3, the ultrasonic velocity was found to depend not only on the anisotropy (the shape of the gas cells), but also on the direction in which sound was propagated, i.e. along the compression direction or perpendicular to it. The difference in velocity due to propagation direction is shown in Fig. 3. For samples probed along the direction perpendicular to the strain, the velocity shows a significant decrease of about 30% over the range of density for which the measurements were performed. For samples probed along the direction parallel to the strain, the decrease is even more pronounced: the velocity starts at 850 m/s at zero strain and decreases sharply to a velocity of 250 m/s as the density is increased. Hence, independent measurements of the velocity both parallel and perpendicular to the compressive strain allow us to observe the effect of the difference in structure as a result of the air cell compression.

To interpret our data using the Gibson Ashby model [3], we first need to calculate the anisotropy ratio, *R*, using high-resolution digital images of the freeze-dried samples. Using the obtained *R*-values from digital image analysis [4], the longitudinal modulus are calculated using the prediction of Gibson and Ashby's for open and closed cell models and compared to the results obtained in our ultrasonic experiments, see Fig. 4.

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The experimental results agree with both the open and closed cell models in the range $0.6<R<1$. However, at lower values of R, the data are larger than this theoretical prediction. The prediction of the Gibson and Ashby's closed cell model has an odd feature that at $R = 1$, the ratio is bigger than 1, which has to be further examined.

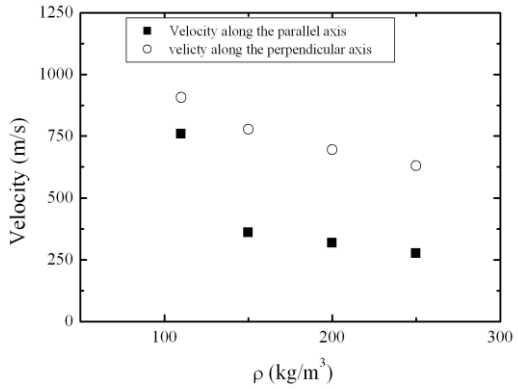

Fig. 3. Ultrasonic velocity probed along the strain direction (par) and perpendicular to strain direction (per).

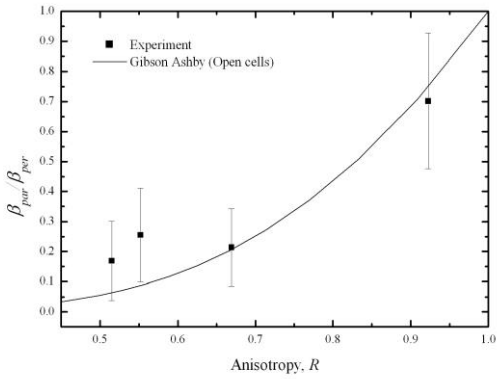

Fig. 4. The ratio of the longitudinal modulus as a function of cell anisotropy. The solid line represents Gibson and Ashby's open cells model; dotted line represents Gibson and Ashby's closed cells model.

The attenuation on the other hand was calculated from the sample and reference signals using Eq. (3). The results of such calculations are shown in Fig 5. Because of the nature of the sample, the attenuation results are expressed in terms of the amplitude of the propagating signal in samples rather than by the attenuation coefficient.

This still allows the 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 air cells and their concentration. Figure 5 shows that the signal amplitude increases as the density increases. In other words, for the more dense samples, in which the air bubbles are smaller and the cell walls are thicker, the signal suffers less loss due to either absorption or scattering.

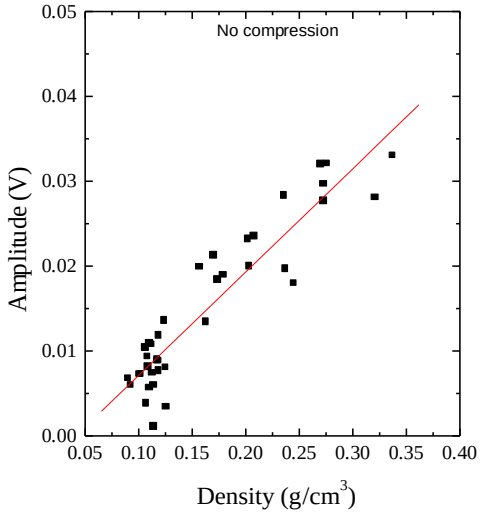

Fig. 5. The amplitude of the signal taken as an indication of the reduction of the attenuation coefficient as the density of the sample increases.

IV. Conclusions

Longitudinal ultrasonic velocity was successfully used to investigate the properties anisotropic biofoams. Theoretical models were used to predict the longitudinal moduli along the parallel and perpendicular to the compression direction using the anisotropy parameter R. The results show that useful information can be obtained on the effect of changing both size and shape of the foam cells on the mechanical properties of these foams.

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