# The Complex Shear Modulus of Dough Over a Wide Frequency Range

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## ABSTRACT

It is shown from small strain shear rheometry and low intensity ultrasonic shear wave measurements that power law behaviour describes the frequency dependence of the complex shear modulus of dough made from a strong North American breadmaking wheat flour. This is the first characterization of the linear viscoelastic behaviour of dough over such a wide frequency range (more than eight decades). Standard rheometry was used to measure shear moduli at low frequencies while an inclined incidence wave reflection technique was used to measure the complex shear modulus in the $10^5$ Hz region. The ultrasonic data demonstrate that previous descriptions of the constitutive properties of this rheologically complex material do not incorporate a sufficiently broad range of relaxation times to comprehensively model the rheology of dough at all frequencies.

## INTRODUCTION

Wheat flour doughs are interesting, rheologically complex materials (Bloksma and Bushuk 1988). To date, it has not been possible to agree upon a constitutive model that comprehensively predicts their mechanical behaviour (Tanner et al 2008), especially since these highly hydrated materials are strongly strain and strain-rate dependent (Bloksma and Bushuk 1988).

In any investigation of the rheology of dough, it is vital that a wide range of testing rates is covered. This is necessary because doughs are subject to a wide variety of strain rates during processing (Bloksma 1990). Therefore, any constitutive model for dough that is developed from a restricted range of rates is unlikely to correctly predict mechanical behaviour at high or low rates of stress application. As a result, the constitutive model is unlikely to be utilized by cereal scientists seeking to optimize their dough processing operations.

An important aspect of the mechanical behaviour of dough is its response to shear solicitations in the linear viscoelastic regime (Longin et al 1998). Despite its importance, the shear modulus of dough has been mostly analysed over a limited frequency range, typically less than five decades (Dreese et al 1988; Phan-Thien and Safari-Ardi 1998).

The objective of this paper is to measure the complex shear modulus of dough in the linear viscoelastic regime over a very wide frequency range using both small strain shear rheometry and low intensity ultrasonic shear wave measurements and to use this information to model the constitutive properties of dough.

## MATERIALS AND METHODS

### Dough Preparation

Breadmaking doughs were made from hard red spring wheat flour (straight grade milling). The dough was prepared using a short-time mechanical dough development process. Lean formula doughs were prepared using only Flour (100 g), Salt (2.4 g) and Water (60 mL), so as to give optimum dough handling characteristics).

### Dough Density

Density of dough samples was measured using Archimedes' principle (Elmehdi et al 2004). The density was 1198 ± 7 kg $m^{-3}$.

### Shear Rheometry

Each mixed dough piece was sheeted to a thickness of 3-4 mm using successive reductions in roll gap using a National Manufacturing dough sheeting rollstand. A dough specimen was excised from the dough sheet using a circular steel cutter. The specimen was carefully placed on an AR 2000 rheometer with 40-mm-diameter parallel plates. Dough specimens were relaxed in the rheometer for 45 min prior to testing. All testing was performed at 20°C. Frequency sweeps were performed (0.01-100 Hz) at a constant shear stress of 1.0 Pa. This stress was determined from preliminary analyses to be well within the linear viscoelastic region for these breadmaking doughs.

### Ultrasonic Shear Wave Measurements

The complex shear modulus at ultrasonic frequencies was measured using an inclined incidence wave reflection technique (Fig. 1). In this set-up, a shear transducer emitted a pulse into an acrylic block. The dough specimen was placed on the acrylic block after having been excised from the mixed dough piece using a pathology blade. Dough specimens were equilibrated for 5 min on the block to eliminate initial signal variation arising from small temperature changes. In this technique, shear pulses reflected back to the transducer were detected with and without a dough specimen in position on the acrylic block. Fast Fourier transforms of these two pulses (reference of air and with dough specimen in place) are related to shear impedance of the dough, real (G′) and imaginary (G″) parts of the complex shear modulus at frequencies of 300, 400 and 500 kHz were determined.

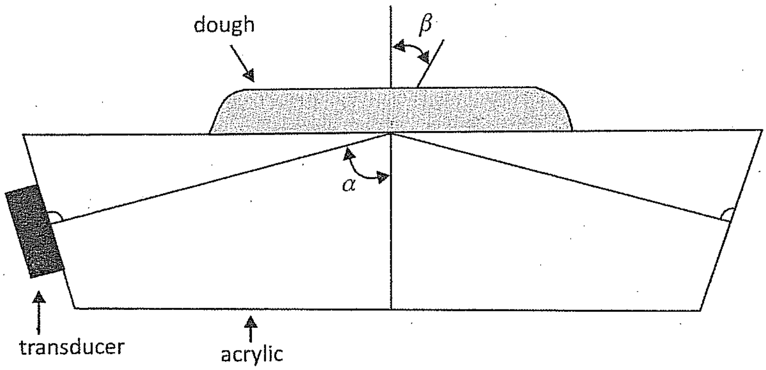


**Fig. 1.** Experimental set-up for measuring shear wave velocity in dough specimens.

## RESULTS AND DISCUSSION

The real and imaginary parts of the complex shear modulus of doughs made from a strong North American spring wheat flour over eight decades of frequency are shown in Fig. 2. It can be seen that the shear moduli exhibit power law behaviour over the entire frequency range (solid lines, least squares fits). Therefore, it is possible to extrapolate rheometry data to the ultrasonic range reasonably accurately with the best-fit lines for the whole range of the data.

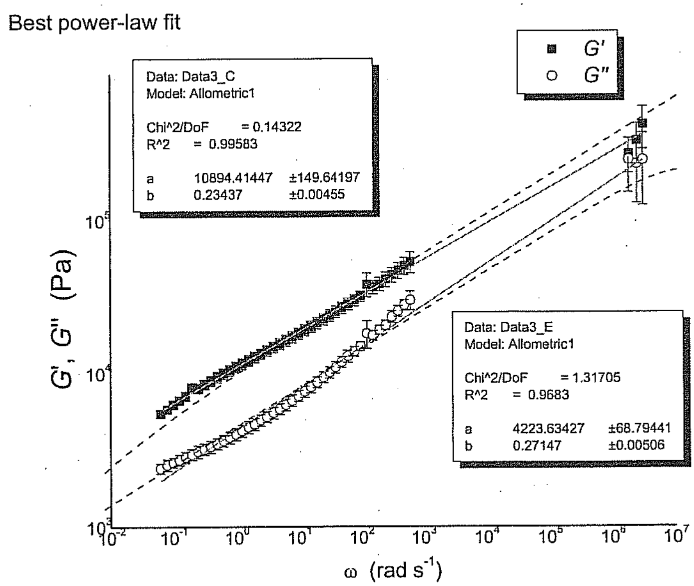


**Fig. 2.** Real and imaginary parts of complex shear modulus of dough as a function of angular

The frequency dependent mechanical response of the dough in Fig. 2 can be used to evaluate parameters that can be used in a constitutive model for dough. One common means of modeling the rheological behaviour of complex viscoelastic materials such as dough is to use a number of discrete Maxwell relaxation modes (Charalambides et al 2006; Tanner et al 2008). Since the exponents for the frequency dependence of G′ and G″ are sufficiently close, they can be considered identical with an average value of 0.253. The method of Baumgärtel and Winter reported by Tanner et al (2007) was used to determine the magnitudes of the different relaxation time strengths for relaxation times equally spaced at half-decade intervals. The fits of this model to the experimental data are shown as the dotted lines in Fig. 2. Although only two adjustable parameters were employed (average slope and overall magnitude), 24 relaxation times ranging from 31.6 ns, 100 ns, 316 ns, etc, up to 10,000s were required to obtain the displayed fit.

## CONCLUSIONS

Measurements of the small strain shear modulus of a breadmaking flour dough is extended to eight decades of frequency using ultrasonic shear waves. Extension of shear modulus measurements into the MHz regime indicates that there is no change in the frequency dependence of the complex modulus from that of dough at low frequencies. It is clear from this that the shear modulus of dough must be modeled with a broad range of relaxation times and that short timescale relaxations contribute significantly to the rheology of dough.

## ACKNOWLEDGEMENT

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