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On the compressibility of bread dough

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Abstract

Few investigations of bread dough compressibility have been reported in the literature, despite the fact that high compression stresses are often reached in processing. Here we report some experiments on the compressibility of an Australian wheat bread dough under compressive stresses up to 5 MPa, and show that the results are consistent with a mathematical model of bread dough containing entrained air. The implications for tensile testing are also considered.

Keywords : bread dough, compressibility, bulk modulus

1. Introduction

Bread dough is a soft viscoelastic solid, often considered to be incompressible. However, in processing quite high compressive stresses may be reached (~3 MPa) and compressibility may be important. There are some results in the literature, for example Glucklich and Shelef (1962), and Bloksma (1957). However, Glucklich and Shelef used quite low pressures (~0.1 MPa) in their experiments, and Bloksma simply quoted their work. Charalambides *et al.* (2002) in fitting their biaxial extension data, considered the material as either incompressible or with a value of the bulk modulus of 7.3 kPa. They did not do any experiments to determine compressibility directly. Given the paucity of data available, we present here some new experiments up to 5 MPa compression stress, plus a model of the bulk modulus. In this paper the bulk response of the dough is regarded as elastic; further work would be needed to refine this picture. We also consider the implications for tensile testing.

2. Materials and methods

2.1. Materials

The wheat flour was a brand of commercial Australian flour, variety JANZ wheat, grown in 2001 at Narrabri, NSW, and milled in a Buhler experimental mill. The bread dough was mixed in a Dough-10 g mixograph. 9.5 g of wheat flour was mixed, together with 6 g distilled water and 0.2 g salt, as determined by using a digital high precision scale. The mixing operation was conducted at a temperature of 24 °C and under ambient humidity in an air-conditioned laboratory. The rotation speed of the Dough-10 g mixograph was measured to be 71 rpm. The mixing time to peak bread dough development was determined from the mixing curve, which was 7 minutes for each mixing. After mixing, a little Vaseline oil was smeared on the outside surface of the bread dough sample, and the bread dough was put into a plastic bag and then the bag was sealed to prevent moisture loss. The bread dough sample relaxed for 45 min in the bag before the compression experiment. In every compression experiment the quantity of the bread dough sample was equal to 62.8 g including wheat flour, distilled water and salt. The density of the dough was about 1207 kg/m^3.

The bread dough sample was made as a cylinder with a diameter of about 37 mm before the bread dough sample was put into the compression chamber of the compression unit that was designed for the project. The compression unit is shown in Fig. 1. The internal diameter of the steel cylinder of the compression unit was 48 mm and the wall thickness was 5 mm. All compression experiments were performed with this unit.

2.2. Experimental method

To begin, the chamber was filled with silicone oil (Dow Corning grade 200). Before the compression experiments were conducted the air vent was opened and the air in the compression chamber was expelled by pressing on the plunger by hand. An Instron 5567 testing machine was used to apply and measure the load. The maximum compression stress was 4.97 MPa, the plunger moved at 0.05 mm/s, and the interval of information sampling was 5s.

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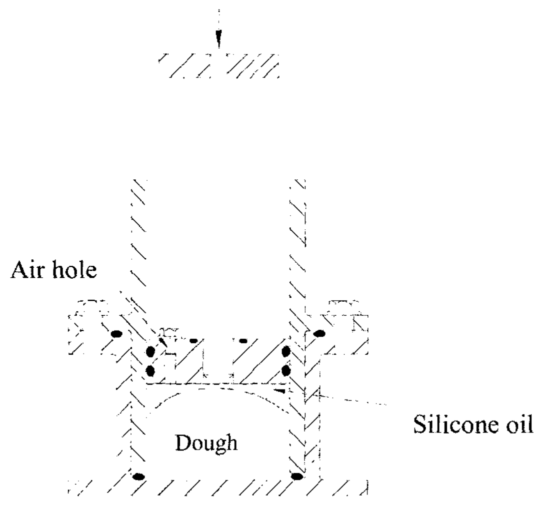
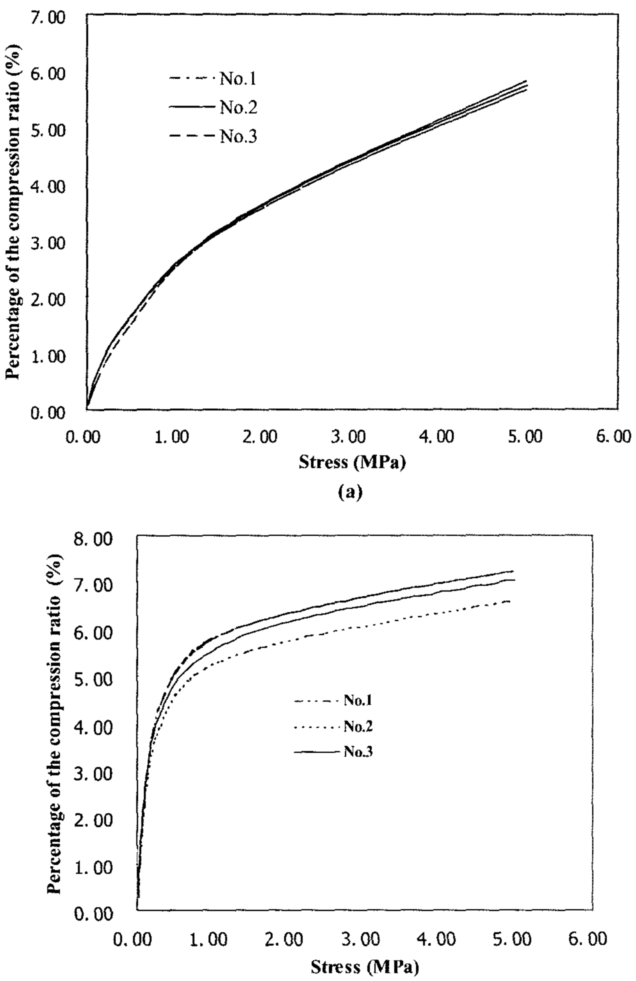


Fig. 1. The compression unit. The steel walls are 5 mm thick and the inner diameter is 48 mm.



(a)

(b)

Fig. 2. (a) The compression stress as a function of the percentage volume strain of the silicone oil. (b) The compression stress as a function of the percentage volume strain of the bread dough and silicone oil.

Every experiment was carried out in triplicate, and the results were averaged.

We show the effect of using silicone oil alone in the chamber in Fig. 2(a). As can be seen, the percentage compression (or volume strain) vs. pressure curve is reproducible and is a nonlinear function of the pressure. We now consider the case of dough.

Before placing the bread dough sample into the compression chamber 30 ml of silicone oil was placed there, and then the Vaseline-coated bread dough sample was put into the silicone oil. The top surface of the bread dough sample in the compression chamber was the same height as or a little lower than the surface of the silicone oil. The results are shown in Fig. 2(b); some scatter in the results is evident, and the mean value of the three trials was used in subsequent analysis.

3. Compressibility

The magnitude of the bread dough compressibility is clearly not constant and depends on the pressure acting on the bread dough. So, the pressure in the compression chamber and the diminution of the total volume of the bread dough and the silicone oil, as well as the diminution of the volume of the silicone oil, were measured in the experiments, and then the diminution of the volume of the bread dough was calculated from the experimental results. We used equation (1).

$$\Delta v = \Delta v_d + \Delta v_o \qquad (1)$$

where Δv is the diminution of the total volume, mm^3, Δv_d is the diminution of the volume of the bread dough, mm^3 and Δv_o is the diminution of the volume of the silicone oil, mm^3. In equation (1) we need, in principle, to consider the expansion of the steel chamber. Using elastic cylinder theory (Timoshenko, 1951) we calculated that the increase in cylinder volume due to inner pressure was only of order 1 % of the total volume change of the samples under the same pressure. Hence we have neglected the effect of cylinder expansion as being outside the precision of the measurements.

We assume that the diminution in volume of the silicone oil can be computed using the results of Fig. 2(a) and the fact that the silicone oil initial volume is 30 ml. The initial volume of the dough was 52 ml, and hence the change in dough volume can be found by subtraction. Results are shown in Table 1.

The formula for the percentage volume strain is the following.

$$\gamma = \frac{\Delta v}{V} \times 100 \qquad (2)$$

where γ is the percentage volume strain, Δv and V are the diminution of the volume and the initial volume respec-

Table 1. The diminution of volume (total, silicone oil and bread dough)

Diminution of the volume/(mm^3)	Stress/(MPa)									
	0.02	0.04	0.06	0.08	0.10	0.40	0.60	0.80	1.00	1.20
Total (Δv)	533	1016	1413	1742	2015	3667	4039	4280	4446	4567
Silicone oil (Δv_o)	42	79	108	134	161	406	524	643	740	817
Bread dough (Δv_d)	491	937	1305	1608	1854	3261	3515	3637	3706	3750
Diminution of the volume/(mm^3)	Stress/(MPa)									
	1.40	1.60	1.80	2.00	2.50	3.00	3.50	4.00	4.50	4.97
Total (Δv)	4667	4750	4825	4891	5037	5165	5283	5396	5499	5597
Silicone oil (Δv_o)	885	943	998	1048	1167	1275	1378	1475	1570	1663
Bread dough (Δv_d)	3782	3807	3827	3843	3870	3890	3905	3921	3929	3934

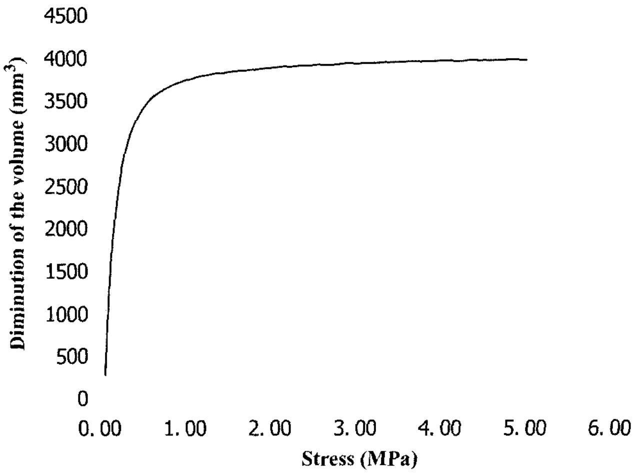


Fig. 3. Showing the diminution of the volume of the bread dough with the compression stress.

tively, mm^3. The average bulk modulus K is just $\Delta p/\gamma$.

The relationship between the diminution of the volume of the bread dough and the compressive stress is given in Fig. 3 and Table 1.

When the compression stress is 1 MPa considerable compressibility of the bread dough is evident, about 7.13 %. But when the compressive stress reaches nearly 5 MPa the change of the volume of the bread dough is only about 7.56%. Thus the compressibility of the bread dough begins to lessen with the increase of stress when the compression stress is more than about 1 MPa.

4. Bulk modulus

In the experiments the initial volume of the bread dough and the silicone oil were 52000 mm^3 and 30000 mm^3, respectively. The bulk modulus of the bread dough was calculated according to the experimental results in Table 1. The calculated results for the bulk modulus K of the bread dough are presented in Table 2.

The relationship curve between the bulk modulus and the volume strain and the compression stress are given in Fig. 4 and Fig. 5, respectively.

The slope of the curve in Fig. 4 changes significantly with strain. The curve can be divided into two sections according to the slope. The volume strain in the first section is zero through about 6.8%. In this section the increase of the bulk modulus is slow. When the volume strain of the bread dough is increased to 6.8% the bulk modulus increases from the minimum value to about 10 MPa. In the second section, the percentage of the compression ratio of the volume is more than 7.0%. In this section, for larger strains, the bulk modulus of the bread dough increases very quickly, up to about 66 MPa, and the bread dough begins to stiffen rapidly.

Table 2. The bulk modulus and the volume strain of bread dough

Stress/(MPa)	0.02	0.04	0.06	0.08	0.10	0.40	0.60	0.80	1.00	1.20
Volume strain/(%)	0.94	1.80	2.50	3.09	3.57	6.27	6.76	6.99	7.13	7.21
Bulk modulus/(MPa)	2.12	2.22	2.39	2.59	2.81	6.38	8.85	11.48	14.12	16.70
Stress/(MPa)	1.40	1.60	1.80	2.00	2.50	3.00	3.50	4.00	4.50	4.97
Volume strain/(%)	7.27	7.32	7.36	7.39	7.44	7.48	7.51	7.54	7.56	7.56
ulk modulus/(MPa)	19.2	21.9	24.6	27.1	33.6	40.1	46.6	53.1	59.5	65.7

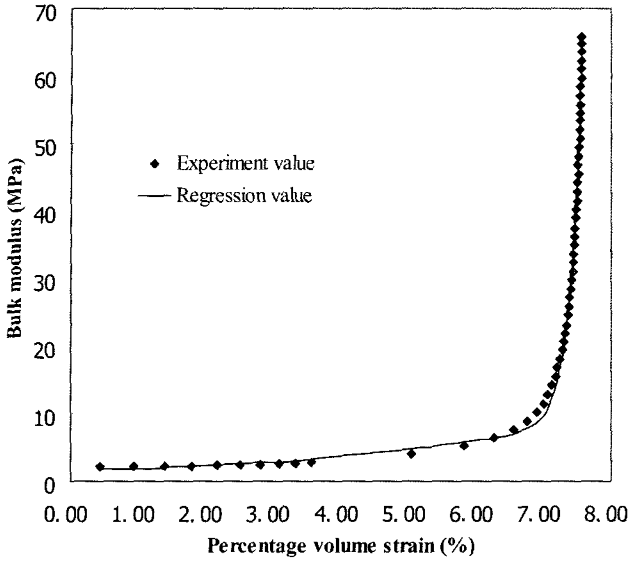


Fig. 4. The relationship between the bulk modulus of the bread dough and the percentage volume strain of the bread dough.

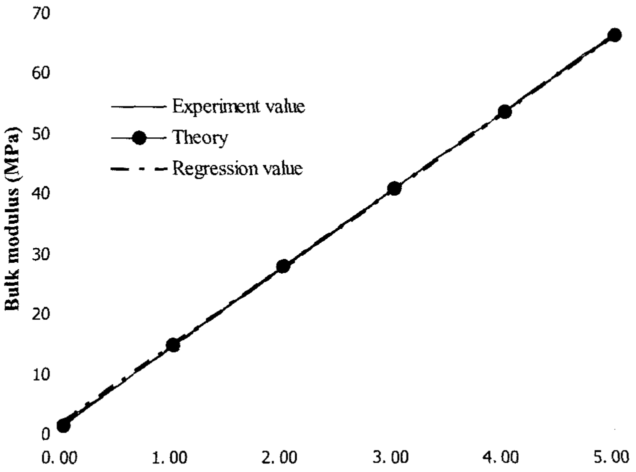


Fig. 5. The relationship between the bulk modulus of the bread dough and the compressive stress experimental results. The correlation (3) and the theoretical curve (6) are all in good agreement.

We also found that the average bulk modulus of the bread dough increased nearly linearly with the increase of the compression stress, see Fig. 5.

In order to find the functional relationship between the bulk modulus of the bread dough and the compression stress, as well as the percentage of the compression ratio of the volume of the bread dough, we analyzed the functional relationship between the (average) bulk modulus and the compression stress, as well as the percentage of the compression ratio of the volume of the bread dough, by a regression method. Two correlations to predict the bulk modulus of the bread dough were developed. The correlation of the average bulk modulus K with the compression stress as well as the bulk modulus with the percentage volume strain are given as equations (3) and (4), respectively.

$$K = 12.81\Delta p + 1.379 \qquad R^2 = 0.9999 \tag{3}$$

$$K = 1.779 + 0.117\gamma^2 + 5.47 \times 10^{-17} e^{(-1.05+5.614\gamma)} \qquad R^2 = 0.9940 \tag{4}$$

Here K is the bulk modulus of the bread dough, MPa, Δp is the compression stress, MPa, γ is the percentage volume strain, and R is the correlation factor.

When the compression stress Δp or the volume strain γ is equal to zero the bulk moduli of the bread dough are found to be 1.379 and 1.779 MPa respectively. These two values are reasonably close. These results indicate that the two correlations to predict the bulk modulus of the bread dough are appropriate. The regression curves are given in Fig. 4 and Fig. 5, respectively.

5. Prediction of the bulk modulus of dough

The dough mixing process inevitably entrains air, and so we adopt a model which recognizes this. Let us suppose that the dough initially contains a volume fraction x of air, plus a volume fraction $(1-x)$ of solid dough. Suppose the bulk modulus of the solid phase, in the absence of entrained air, is k. The entrained air is considered to be at atmospheric pressure initially, say p_0. Upon compression to a pressure $(p_0 + \Delta p)$, the volume strain in the solid is $\frac{\Delta p}{k}$, and the volume of the air also changes, by a factor $\frac{\Delta p}{p_0+\Delta p}$ times the initial volume, assuming isothermal compression. Thus the total diminution in a unit volume of dough is:

$$(1-x)\frac{\Delta p}{k} + x\frac{\Delta p}{p_0+\Delta p} \tag{5}$$

The mean bulk modulus (K) of the dough is then $\frac{\Delta p}{volume\ strain}$, which gives

$$\frac{1}{K} = \frac{(1-x)}{k} + \frac{x}{p_0+\Delta p} \tag{6}$$

Using the data of Fig. 5, fitting the data at $\Delta p = 1$ MPa and $\Delta p = 5$ MPa, we find $k = 5830$ MPa and $x = 0.077$. Thus the solid phase is typical of a solid polymer; the 7.7 % air entrained is typical of our experiments and those of others (Bloksma 1971).

6. Conclusion

the main purpose of this work is to measure and analyze the compressibility and the bulk modulus of the bread dough by direct experiment. based on the experimental results the bulk modulus of the bread dough was calculated up to 5 mpa compressive stress. two correlations to predict the bulk modulus of the bread dough were developed. we find that the relationship between the compression stress and the bulk modulus of the bread dough is nearly linear. the study indicates that the experimental results show an excellent agreement with a simple model that includes entrained air. clearly this may have implications for tensile and biaxial testing of dough, where large below-atmospheric pressures may occur and for processing, where large positive pressures occur. for example, using the same dough, we found that at an elongation rate of 0.1 s^{-1} fracture occurred at a tensile stress of about 35 kpa. thus a negative gauge pressure of about 30% of this, say 0.01 mpa, exists in the specimen. according to the simple entrainment model used here, the bulk modulus then decreases; very high rates of extension would decrease it even further leading to failure. hence, we conclude that the incompressible model of dough is generally valid, but occasionally compressibility needs to be considered.

Acknowledgments

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