JOURNAL OF MATERIALS SCIENCE 24 (1989) 3249–3253

The effect of moisture content on the mechanical properties of extruded food foams

R. J. HUTCHINSON, S. A. MANTLE
Sunderland Polytechnic, Chester Road, Sunderland, SR1 3SD, UK
A. C. SMITH
AFRC Institute of Food Research, Norwich Laboratory, Colney Lane, Norwich, NR4 7UA, UK

The mechanical properties of extrusion-cooked foams have been measured as a function of density and moisture content. Extrusion conditions were varied to give a wide range of densities for which the flexural strength and modulus increased with density. The increase of density by low levels of water absorption caused very little change in this response. However, the density increase by absorption of greater quantities of water resulted in a decrease in foam mechanical properties. This has been largely attributed to the changes in the foam wall mechanical properties which have been discussed in terms of plasticization of polymers. There is some evidence that compared to the flexural test method, the higher strain rate of impact testing requires a higher level of water addition in order to cause a decrease in strength.

1. Introduction

Extrusion cooking is a continuous process for the production of snackfoods, crispbreads and breakfast cereals [1, 2]. A wide range of solid foams may be produced from the same starting material. In the majority of studies the mechanical properties have been measured as a function of extrusion conditions. Recently the mechanical properties of extruded foams have been related to the bulk density [3, 4] which had been shown much earlier for foamed plastics [5]. The relationship between mechanical properties and density is a special case of the Ashby treatment of foams which normalizes the foam properties by their foam wall values [6, 7].

The mechanical properties of food materials are highly sensitive to moisture content as shown for wafers and snack products [8, 9]. This results in textural properties that depend markedly on storage conditions. This study considers the stability of extruded foams in humid environments and the effect of water uptake on the density and mechanical properties. The trends in the results have been interpreted with reference to changes in the foam wall properties. These studies show that the post-extrusion environment has as profound an effect on the foam properties as the extrusion conditions themselves.

2. Experimental approach

2.1 Materials

A commercial wheat flour was used for the extrusion experiments (Read Woodrow Mills, Norwich). Starch is the major constituent (approximately 80% by weight) of the flour. A commercial wheat starch (Tenstar Products, Ashford, Kent) was also used.

2.2. Extrusion

All extrusion experiments were carried out with a Baker Perkins MPF 50D co-rotating twin screw extruder. The wheat starch samples were produced using a feed rate of $25\,kg\,h^{-1}$ and a set temperature profile of 27, 27, 27, 80, 120° C. The wheat flour samples were produced using a feed rate of $15\,kg\,h^{-1}$ and a set temperature profile of 27, 27, 27, 80, 100° C. In both cases the screw speed was varied from 400 to 800 r.p.m. and the moisture content from 12 to 16% (wet weight basis). Two dies of 2 mm diameter were used. The different extrusion conditions were necessary to produce foams in the same density range.

2.3. Sample characterisation

Bulk densities were calculated from the mass and volume of the extrudates assuming a cylindrical geometry. This method was considered preferable to the displacement of fine sand since the same specimens are tested mechanically following conditioning.

2.4. Mechanical testing

Flexural testing was performed using an Instron 1122 universal testing machine. The following test conditions were used as in previous experiments [4].

Specimen length = 150 mm
Span = 100 mm
Crosshead speed = $5\,mm\,min^{-1}$

A three-point bend test rig was used in the form of three bars of 10 mm diameter.

Impact testing was carried out using an instrumented pendulum [3, 10]. A potentiometer on the axis of the hammer provides a measure of the hammer movement into the sample. All the energy is absorbed in penetrating the sample; the penetration being used as a measure of the compressive strength. The sample is clamped against a back plate and the hammer in the form of a 10 mm diameter cylindrical bar strikes it orthogonally.

0022–2461/89 $03.00 + .12

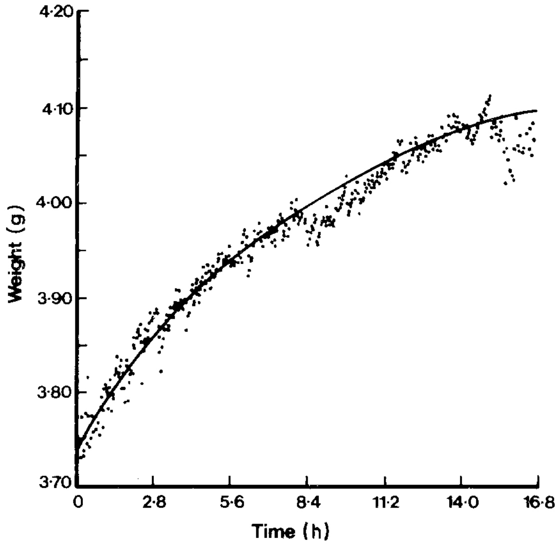

Figure 1 The weight of extruded wheat starch foams as a function of time in a 100% relative humidity environment obtained by microcomputer logging.

2.5 Sample conditioning

Samples of each extrusion condition were stored in a constant temperature and relative humidity room ($20 \pm 1^\circ C$, $63 \pm 1\%$ R.H.). The mass change of these samples was monitored over a period of one month in conjunction with mechanical testing.

An accelerated conditioning system was also used for some samples. An equilibrium apparatus was constructed around a desiccator. The chamber was partially filled with distilled water and the equilibrium state accelerated by water pump evacuation followed by agitation using a headspace fan. A sample pan in the form of aluminium mesh was suspended into the desiccator from an analytical balance. This enabled the weight gain to be continuously monitored and logged via a microcomputer (Fig. 1).

A conditioning procedure was used as shown in Fig. 2. Samples were initially equilibrated at 20° C and 63% RH (point A). They were then conditioned in the 100% RH environment for 1, 2 and 3 h (points B, C and D). The equilibrated samples at point A were also oven dried at 60° C for 15 h (point A^1). All samples were tested using flexural and impact techniques.

3. Results

3.1. Calculation of mechanical properties

The flexural strength and modulus were calculated according to the formulae

$$\sigma_f = \frac{8FL}{\pi d^3} \qquad (1)$$

where σ_f is the flexural strength, F the maximum force, L the span and d the specimen diameter.

$$E_f = \frac{4L^3}{3\pi d^4}\frac{dF}{dY} \qquad (2)$$

where E_f is the flexural modulus and dF/dY is the initial slope of the force–deflection curve.

The impact strength was calculated from

$$\sigma_i = \frac{E}{Ax} \qquad (3)$$

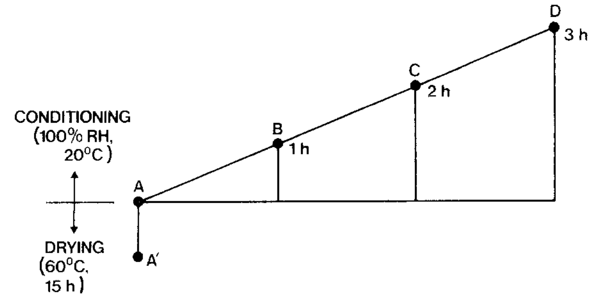

Figure 2 The moisture conditioning sequence for the extruded samples.

where E is the energy absorbed by the sample, x the penetration of the hammer into the sample and A the area of impact of the hammer with the sample.

3.2. Flexural testing

The density changes as a result of storage at 63% RH were of order 1% over a period of a month for both starch and flour extrudates. The mechanical properties for the first day of testing are plotted against the bulk density on logarithmic axes in Figs 3 and 4. The data were fitted to a power law for each testing period

$$\sigma = K\varrho^n \qquad (4)$$

where σ is the mechanical property and ϱ the density. The values of K and n are given in Table I for both materials. They did not vary significantly over the conditioning period of a month although the strength was a factor of up to four higher for the flour.

Much greater density changes were effected by conditioning in a 100% RH environment and by drying. Data for two samples of different starting density (point A) are shown in Figs 3 and 4. The density decrease due to drying (A → A^1) caused a reduction in strength but an increased modulus. The density increase due to water uptake (A → D) caused a decrease in both strength and modulus. It is immediately evident from Figs 3 and 4 that these data do not fall on the mechanical property – density relationship as established by varying the extrusion conditions and described by Equation 4.

3.3. Impact testing

The impact strength was monitored as a function of density changes following conditioning at 100% RH

TABLE I Conditioning of samples at 20° C and 63% RH. Variation of K and n in Equation 4.

	Strength		Modulus	
	K ($\times 10^6$ Nm^{-2})	n	K ($\times 10^9$ Nm^{-2})	n
Wheat Starch				
1 day	7.1	1.1	2.6	2.2
2 days	5.1	1.0	2.6	2.2
3 days	12.3	1.4	2.8	2.3
28 days	4.2	0.8	1.9	2.1
Wheat Flour				
1 day	22.4	1.8	1.5	2.0
2 days	22.4	1.8	1.8	2.0
3 days	23.4	1.7	1.8	2.0
28 days	24.0	1.8	2.4	2.2

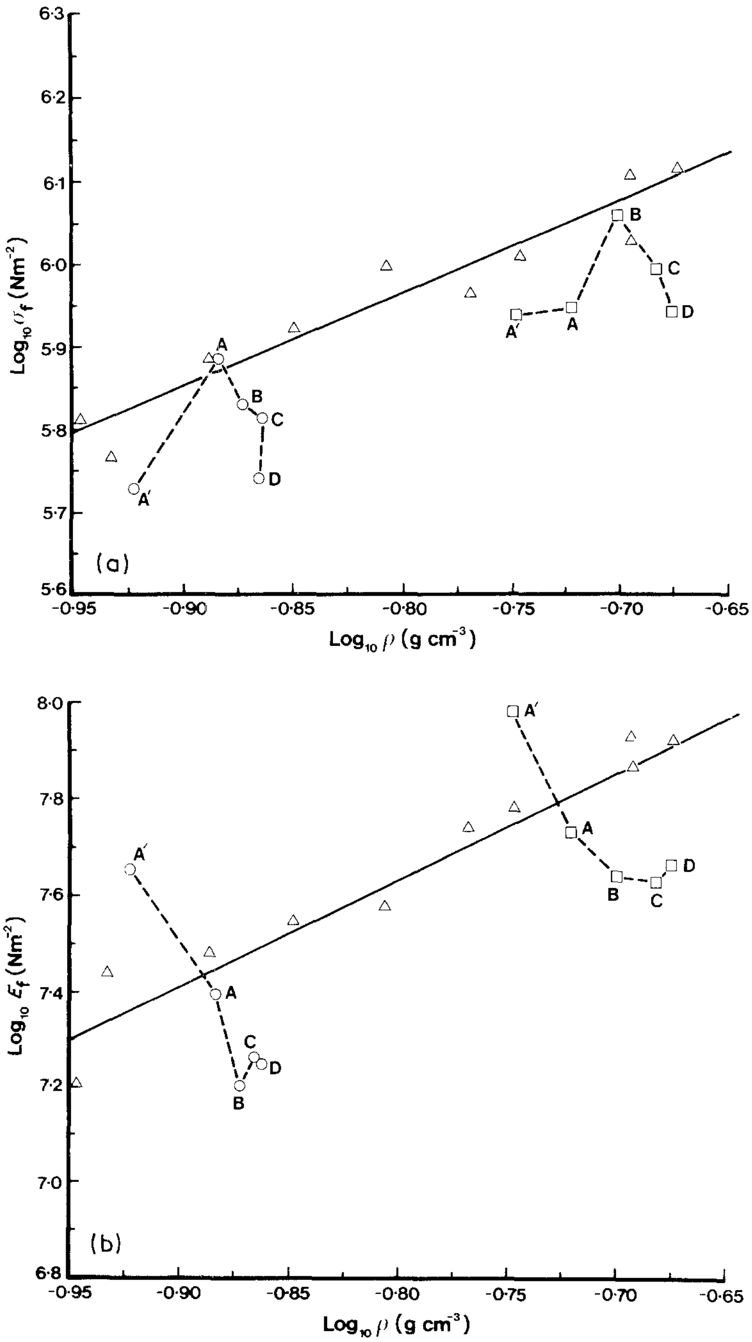

Figure 3 The flexural modulus and strength of wheat starch foams as a function of bulk density. △ Different extrusion conditions. Moisture conditioning at 63% RH for one day; ○, □ moisture conditioning at 100% RH or drying (see Fig. 2)

and drying. The relationship is shown in Fig. 5 for two samples of different starting density (point A). The strength showed a maximum although at a higher level of water addition than the flexural strength. Again the impact data do not fit Equation 4.

4. Discussion

The current mechanical property results have been found to vary with density according to a power law (Equation 4) for foams produced using different extrusion conditions. This is consistent with previous mechanical testing of maize extrudates using impact, flexural, compressive and tensile geometries [3, 4, 11]. Equation 4 is a special case of the general relationship for the deformation of foams derived by Ashby [6, 7]

$$\frac{\sigma}{\sigma_{\mathrm{w}}} = K\left[\frac{\varrho}{\varrho_{\mathrm{w}}}\right]^n \qquad (5)$$

where σ is the mechanical property, ϱ the density of the foam and the subscript w refers to the same properties for the foam wall material. Equation 5 reduces to Equation 4 when the wall properties are constant. Whilst this condition is not necessarily obeyed for extruded foams due to the reactive nature of the extrusion process [1], it nonetheless seems that the factor $\sigma_{\mathrm{w}}/\varrho_{\mathrm{w}}^n$ does not vary significantly with extrusion conditions. The present data of Figs 3 and 4 also indicate that over a limited range of water uptake Equation 4 remains a reasonable description of the mechanical property – density relationship.

The variation of the density by water uptake does however lead to distinct deviation from the simple power law of Equation 4. The origin of the response may be seen by consideration of Equation 5. Since the mass of the foam is the same as that of the wall material Equation 5 may be written

$$\frac{\sigma}{\sigma_{\mathrm{w}}} = K\left[\frac{V_{\mathrm{w}}}{V}\right]^n \qquad (6)$$

where V and V_{w} are the volumes of the foam and cell

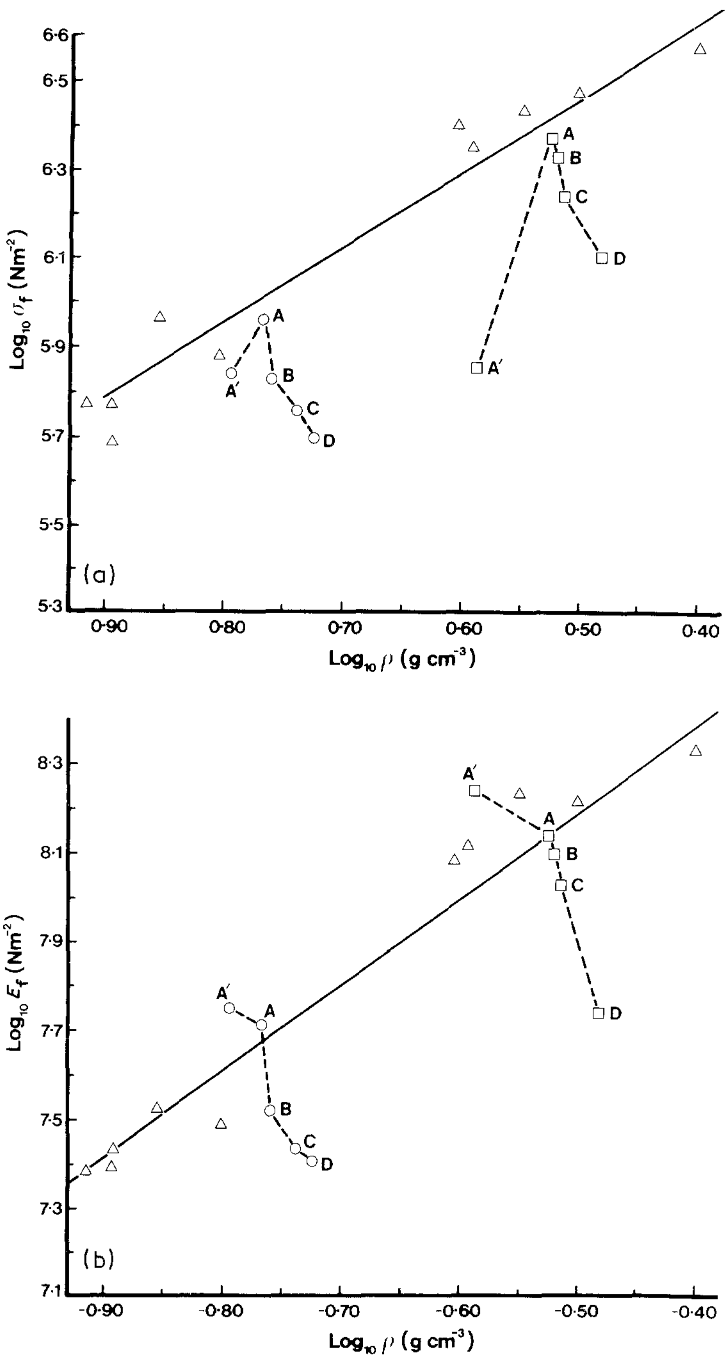

Figure 4 The flexural modulus and strength of wheat flour foams as a function of bulk density. △ Different extrusion conditions Moisture conditioning at 63% RH for one day. ○, □ moisture conditioning at 100% RH or drying (see Fig. 2)

wall material, respectively. The change in V_w/V with water uptake will depend on the swelling of the foam wall material. In the absence of swelling V_w/V will remain constant. For simple square foam cells [6, 7]

$$\frac{V_w}{V} \propto \frac{t^2}{l^2} \quad \text{for open cells}$$

$$\frac{V_w}{V} \propto \frac{t}{l} \quad \text{for closed cells}$$

where l is the cell dimension and t the wall thickness. Since $l \gg t$ an increase in wall thickness and cell size will result in an increase in V_w/V. In terms of Equation 6 σ/σ_w will then increase if swelling occurs. The response of the wall mechanical property term, σ_w is, however, critical in predicting the foam mechanical properties.

The addition of solvents to some polymers is known to result in antiplasticization leading to an increase in strength and stiffness [12, 13]. At greater levels of solvent addition the strength and stiffness decrease as a result of increased molecular mobility. The changes in the tensile strength of polyvinyl chloride have been documented as a function of plasticizer addition [14]. The addition of a solvent progressively lowers the glass transition temperature above which the molecular mobility increases significantly [15]. In a similar way water may act as a plasticizer for biopolymers [16] and the mechanical properties of foods will vary significantly with water content. For example, the Young's modulus of wheat pasta has been shown to decrease markedly above a certain water content [17].

The observed decrease in the foam modulus and strength with increasing bulk density (Figs 3 and 4) may be explained in terms of a decrease in the wall modulus and strength with increasing water content. The rate of mechanical testing is known to affect the material response. For example, transition temperatures have been observed to increase with testing frequency [18]. The impact technique would be expected

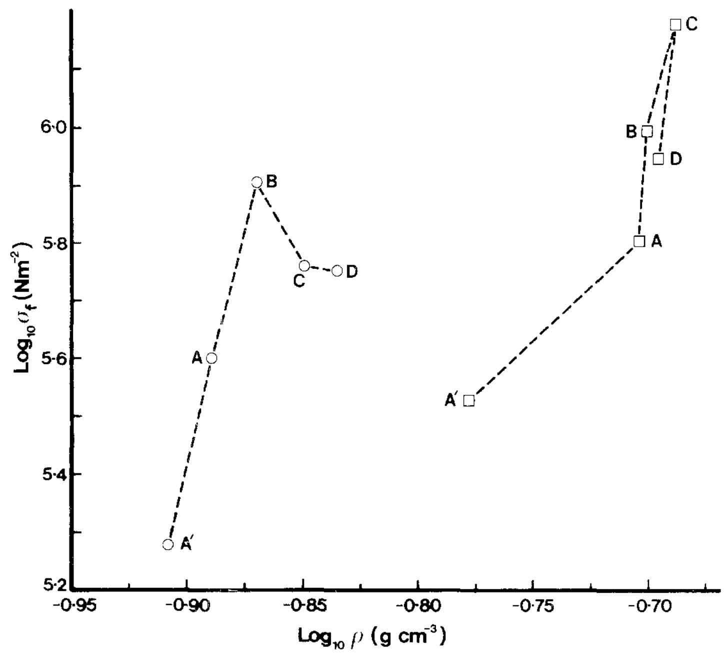

Figure 5 The impact strength of wheat starch foams as a function of bulk density due to conditioning at 100% RH (see Fig. 2).

to shift the glass transition to higher temperatures compared to the flexural test. Equivalently for a constant temperature the transition will occur at a higher water content. A reduction in impact strength would then occur at a higher moisture content compared to the flexural strength. This is consistent with the results in Figs 3 and 5.

5. Conclusion

The flexural strength and modulus of extrusion cooked wheat flour and wheat starch foams have been shown to increase as the power of the bulk density. This is consistent with previous observations where the density has been changed by varying the extrusion conditions. Moisture absorption experiments have shown that these relationships still hold for small density increases (~ 1%) while the further increase of density (~ 10%) may result in a decrease in the mechanical properties. Under impact testing this decrease in mechanical properties occurs at a higher level of water absorption. This behaviour may be described in terms of the plasticization of the foam walls.

References

1. J. M. HARPER, "Extrusion of Foods" (CRC Press. Florida, 1981).
2. W. WIEDMANN and E. STROBEL in "Extrusion Technology for the Food Industry", edited by C. O'Connor (Applied Science, London, 1987) pp 132–69.
3. A. L. HAYTER, P. RICHMOND and A. C. SMITH. *J. Mater. Sci.* **21** (1986) 3729.
4. R. J. HUTCHINSON, G. D. E. SIODLAK and A. C. SMITH, *ibid.* **22** (1987) 3956.
5. E. BAER, "Engineering Design for Plastics" (Chapman and Hall, New York, 1964).
6. M. F. ASHBY. *Acta. Metall.* **14A** (1983) 1755.
7. L. J. GIBSON and M. F. ASHBY, in "Cellular Solids-Structure and Properties" (Pergamon, Oxford, 1988).
8. J. G. BRENNAN, R. JOWITT and A. WILLIAMS, Proceeding 4th International Congress on Food Science and Technology, 1974, p. 130.
9. E. E. KATZ and T. P. LABUZA, *J. Food. Sci.* **46** (1981) 403.
10. A. L. HAYTER, E. H. A. PRESCOTT and A. C. SMITH, *Polym. Test.* **7** (1987) 27.
11. R. J. HUTCHINSON, I. SIMMS and A. C. SMITH. *J. Mater. Sci. Lett.* **7** (1988) 666.
12. R. E. ROBERTSON and C. W. JOYNSON, *J. Appl. Polym. Sci.* **16** (1972) 733.
13. P. J. MAKAREWICZ, G. L. WILKES and Y. BUDNITSKY, *J. Polym. Sci. Polym. Phys. Edn.* **16** (1978) 1545.
14. J. K. SEARS and J. R. DARBY "Technology of Plasticisers", (John Wiley, New York, 1982).
15. P. B. BOWDEN in "The Physics of Glassy Polymers", edited by R. N. Haward (Applied Science, London, 1973) Ch. 5.
16. K. J. ZELEZNAK and R. C. HOSENEY, *Cereal Chem.* **63** (1987) 121.
17. J. ANDRIEU and A. STAMATOPOULOS, *Lebensm-Wiss u. Technol.* **19** (1986) 448.
18. N. G. McCRUM, B. E. READ and G. WILLIAMS "Anelastic and dielectric effects in polymeric solids" (Wiley, London, 1967).

Received 2 August 1988
and accepted 5 January 1989