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Influence of processing variables on the mechanical properties of extruded maize

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Maize was extrusion cooked under different conditions of feed moisture and extruder screw speed to produce foams of different bulk density. The foams were tested in tension, compression and flexure according to British Standards for plastic materials. A power law correlation between mechanical properties and bulk density was used with a density power law index in the range 1.5 to 2.3. This represents a special case of Ashby's treatments of foams where the foam wall properties have not been included. These pore wall properties were a function of processing conditions. A pin identation test was used to obtain localized mechanical properties and indicated the different deformation behaviour of low- and high-density foams together with the greater strength of the foam surface.

1. Introduction

The mechanical properties of foods have often been tested using techniques that are related to plastics test methods [1]. For example, tensile testing equipment forms the basis of tensile, compression and three-point bend tests which are commonly used. These mechanical properties are related to textural characteristics [2].

Solid plastic foams represent a class of materials that has been described by standard test procedures [3]. Solid foams have been characterized by Ashby [4] in terms of their elastic, plastic and fracture deformation.

Most solid foodstuffs are composites and many are foams, e.g. bread. The extrusion cooking process is commonly used to produce brittle foams from starch-based raw materials. The foam is produced from the superheating of water which is included in the feed and is conveyed in a pressure and temperature gradient towards the forming dies [5]. On exit from the dies the pressure falls and the superheated water is vaporized. The combination of bubble nucleation, vapour diffusion and extrudate solidification produces a wide range of foam structures.

The combination of the pore wall properties, which are process dependent, with the foam structure gives a diverse number of mechanical properties. Extrusion-cooked starch foams were tested by Owusu-Ansah *et al.* [6]. They recorded the force–displacement curve in a compression experiment in which the specimen was sheared in a multi-blade (Warner–Bratzler) cell attached to a conventional testing machine.

They related the fine structure of these graphs to the degree of porosity of the foams. Faubion and Hoseney [7] used a compression experiment and a three-point bend test for wheat starch and wheat flour extrusion-cooked foams. Launay and Lisch [8] carried out compression and three-point bend tests on foamed maize extrudates. They measured the slope of the force–displacement plots and calculated a compression modulus and flexural strength and modulus. Extrusion-cooked foams have also been tested at higher deformation rates using impact procedures. Van Zuilichem *et al.* [9] used an Izod test to measure the energy loss in breaking extruded maize samples. Hayter *et al.* [10] used an instrumented pendulum to compress extrusion cooked foams and calculated the resistance to impact for different foam structures.

This paper approaches the evaluation of food foam mechanical properties from the standard procedures used for foam plastics. Compressive, tensile and flexural tests have been carried out on extrusion-cooked maize foams. Complementary data were also obtained using a pin indentor to localize compressive deformation. The results of this study have been compared with the response of synthetic polymer foams. The strengths and moduli obtained in compression, tension and flexure were found to increase with the foam density in accord with results for synthetic polymer foams. The flexural parameters were larger than those for tension and compression as also observed for polymer foams which accords with the greater strength of the foam skin compared with the pore walls.

2. Experimental approach

2.1. Materials

Continuous lengths of the foams were produced using a Baker Perkins MPF 50D co-rotating twin screw extruder. Maize grits (Smiths Flour Mills, Worksop. YG 600) were extruded over a range of moisture contents and screw speeds as given in Table I. Some typical samples are shown in Fig. 1. The bulk density of the foams was measured by the displacement of fine

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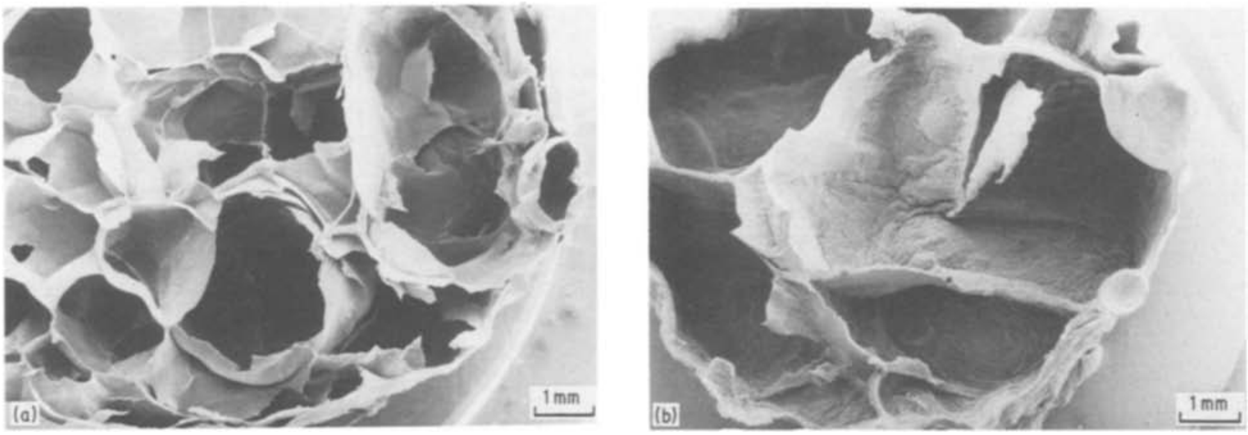


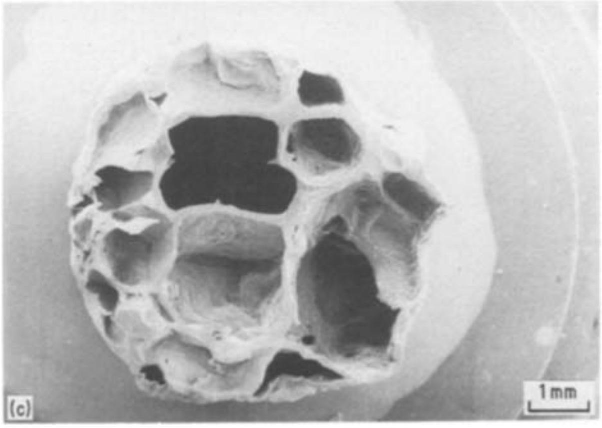


Figure 1 Scanning electron micrographs of extruded maize samples.

	Bulk density ($g\,cm^{-3}$)	Screw speed (r.p.m.)	Moisture content (% d.w.b.)
(a)	0.05	40	23.5
(b)	0.15	30	35.6
(c)	0.30	20	39.7

sand. The dependence of the bulk density on screw speed and feed moisture content is shown in Fig. 2.

2.2. Test procedures

For the majority of the experimental work an Instron TM-M tensometer was used.

The British Standard test method for cellular materials is BS 4370 [3]. This standard refers to the same tests and equations that have been used for unfoamed specimens – BS 2782. The specimen length was maintained constant independent of diameter changes occurring as a function of extrusion conditions.

2.2.1. Compression

Experiments were conducted according to BS 2782, Part 3, Method 345A (1979). The specimen height was 15 mm and the cross-head speed was 5 mm min^{-1}. The

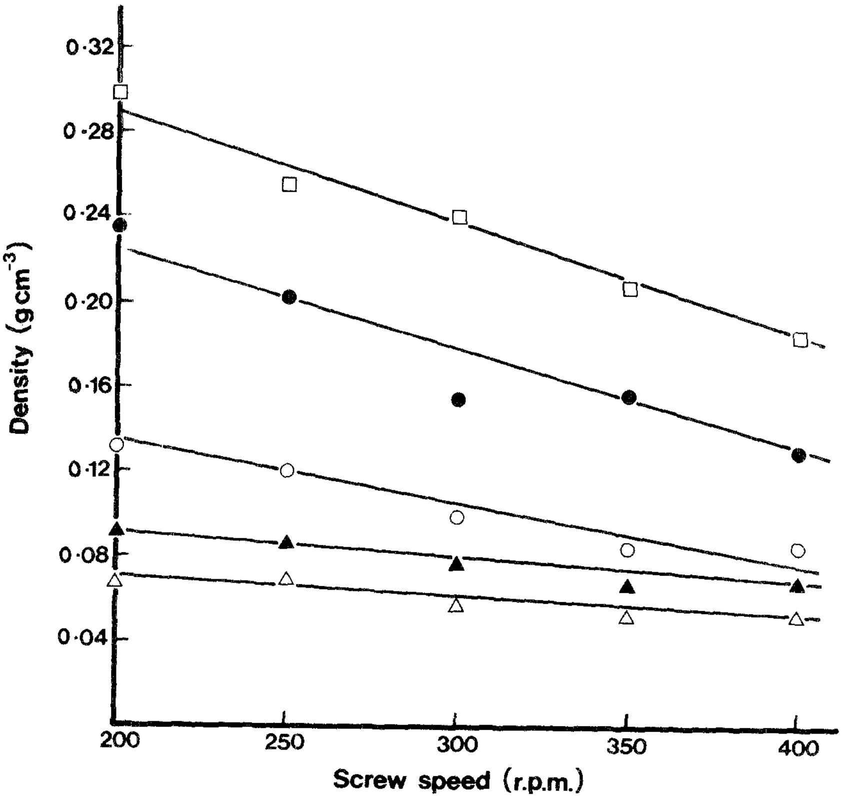
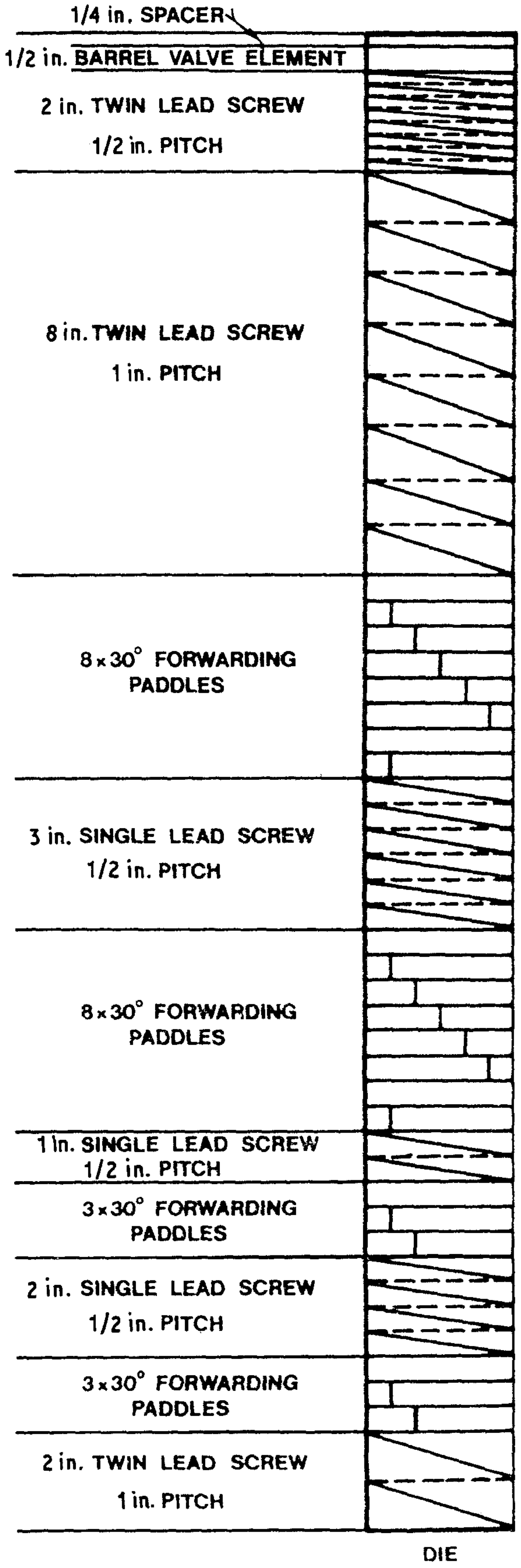


Figure 2 The bulk density of the extrudates as a function of extruder screw speed for different extrusion moistures. Moisture content (% d.w.b.): (□) 39.7; (●) 35.6; (○) 31.5; (▲) 27.5; (△) 23.5.

TABLE I Extruder variables

Feed rate = 50 kg h^{-1}
Temperature profile = 27–52–93–120–120 (°C)
Die size = 2 mm (× 2)
Moisture content (dry weight basis) = 23.5 to 39.7%
Screw speed = 200 to 400 r.p.m.
Screw configuration:



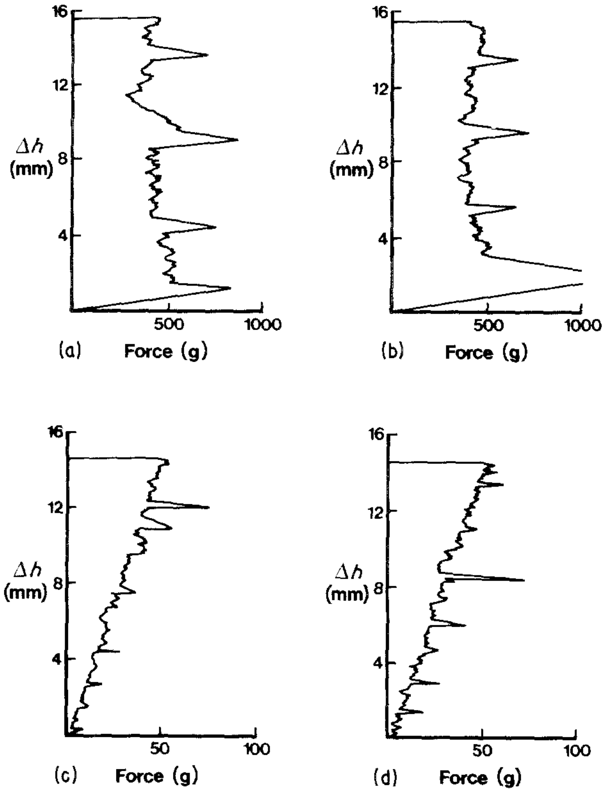


Figure 3 Force against displacement for pin indentation. (a) Specimen bulk density = 0.18 g cm^{-3}, indentation along axis. (b) Specimen bulk density = 0.18 g cm^{-3}, indentation through skin (perpendicular to axis). (c) Specimen bulk density = 0.05 g cm^{-3}, indentation along axis. (d) Specimen bulk density = 0.05 g cm^{-3}, indentation through skin (perpendicular to axis).

samples were cut using a jig based on two parallel razor blades so that the test piece was parallel to within 0.1% of its height.

2.2.2. Flexure

These tests were carried out under BS 2782, Part 3, Method 335A (1978) and Part 10, Method 1005 (1977). The test procedure used the following conditions: specimen length, 150 mm; span, 100 mm; cross-head speed, 5 mm min^{-1}.

2.2.3. Tension

Tensile tests were carried out under BS2782, Part 3, Method 320 (1976), with the following conditions: specimen length, 100 mm; gauge length, 50 mm; cross-head speed, 5 mm min^{-1}. Conventional grips could not be directly used to hold the foam. Sellotape was wound around the specimen ends together with additional binding. The gauge length was taken as the length between the edges of the Sellotape.

2.2.4. Pin indentation

A needle (diameter 0.1 to 0.6 mm) was gripped by a drill chuck and driven into the sample using the Instron. A cross-head speed of 5 mm min^{-1} was used and the sample mounted horizontally and vertically. Typical force–displacement plots are shown in Fig. 3.

3. Results

Strengths and moduli were calculated from the tension, compression and flexure experimental data.

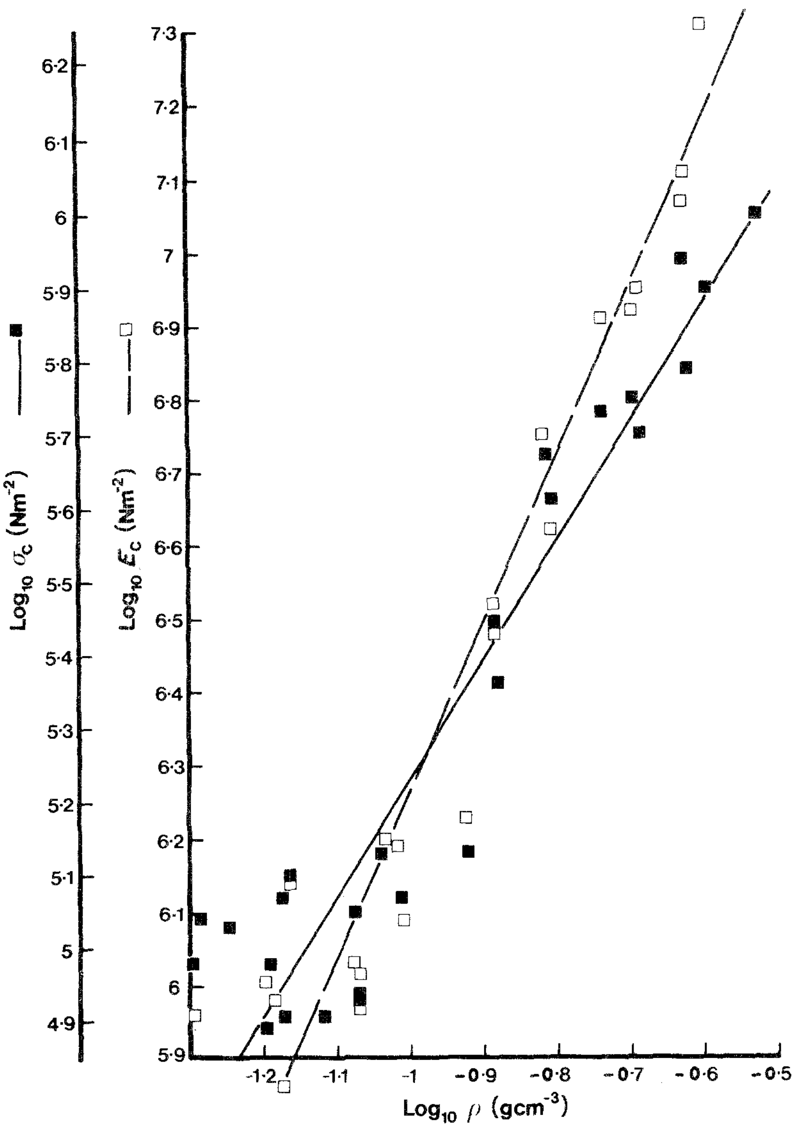


Figure 4 The compression modulus, E_c (□) and strength, σ_c (■) as a function of bulk density.

3.1. Compression

Compressive strength, $\sigma_c = F/A$, where F is the maximum force and A is the original cross-sectional area of the sample.

Compressive modulus, $E_c = (\partial F/\partial L)\ (L/A)$ where $\partial F/\partial L$ is the initial slope of the force–displacement curve and L is the specimen height.

The modulus and strength values have been plotted against the bulk density for all the extruded samples in Fig. 4.

3.2. Flexure

The flexural strength, $\sigma_F = 8FL/\pi d^3$, where F is the maximum force, L is the span and d is the specimen diameter.

The flexural modulus, $E_F = (4L^3/3\pi d^4)\ (\partial F/\partial Y)$ where $\partial F/\partial Y$ is the initial slope of the force–deflection curve.

The bulk density dependence of σ_F and E_F is shown in Fig. 5.

3.3. Tension

Tensile strength, $\sigma_T = F/A$, as defined for compression.

The tensile modulus, $E_T = (\partial F/\partial L)\ (L/A)$ where $\partial F/\partial L$ is the initial slope of the force–displacement curve and L is the gauge length.

The bulk density dependence of σ_T and E_T is shown in Fig. 6.

4. Discussion

The decrease of the bulk density with increasing screw speed and decreasing moisture content (Fig. 2) is in accord with previously published results [8, 11] and with those obtained on flood-fed extruders where the feed rate increased with the screw speed [12].

The data of Figs 4 to 6 show that the tensile, flexural and compression moduli and strengths increase in a similar way with bulk density and that the data for all the samples reduce to a single curve in each case. Similar results and magnitudes have been obtained for foamed plastics [13]. For polystyrene foams a minimum in the flexural modulus was obtained at low densities below the range of the current experiments.

Previous work on extruded food foams has not generally been presented in relation to bulk density, although Hayter *et al.* [10] found that the impact crushing strength of extruded maize foams increased almost proportionately to the bulk density. Owusu-Ansah *et al.* [6] found that the breaking strength of maize starch extrudates obtained using the Warner–Bratzler texture instrument, increased with increasing moisture content. Faubion and Hoseney [7] observed a decrease in strength of wheat starch and wheat flour

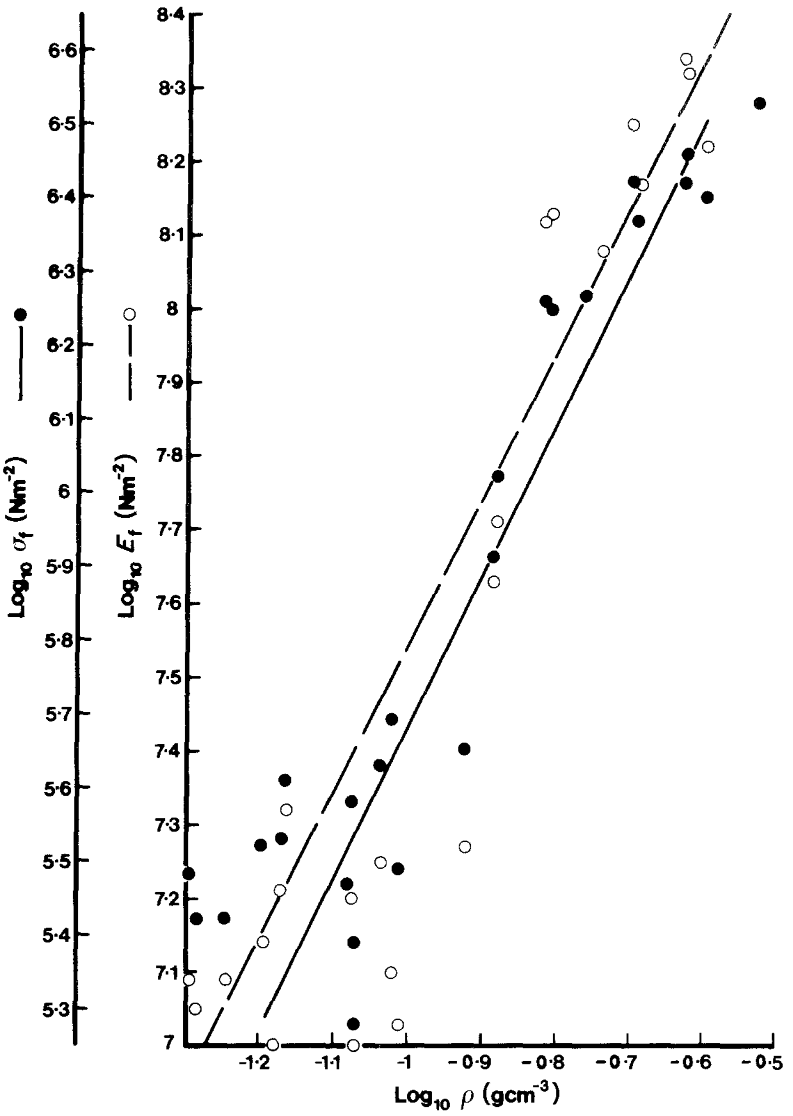


Figure 5 The flexural modulus, E_F (○) and strength, σ_F (●) as a function of bulk density.

extruded foams with increasing extrusion moisture using both Warner–Bratzler and three-point bend experiments. No clear trends were observed in the results of Launay and Lisch [8] with extruded maize. Van Zuilichem *et al.* [9], however, observed an increase in the impact strength of maize extrudates with increasing moisture content. Hayter *et al.* [10] found a similar trend with the impact crushing strength. The present data are in accord with these latter results showing an increase in flexural, tension and compression properties with moisture content. There are, however, no clear precedents for the observed variations of the mechanical properties with screw speed for a constant feed rate.

The flexural strength was found to be approximately three times greater than the compression or tensile strengths while the flexural modulus was 10 to 20 times greater than the moduli in compression and tension. The flexural properties involve tensile and compressive stresses in opposite outer skins. In this context it is interesting that the force required to break the skin of a food foam was significantly larger than that to break an internal pore wall in the case of the high-density sample (Figs 3a, b). The pin penetrated the cell walls without crushing or collapse of the cells. The low-density, more porous foam was, however, broken around the pin. This resulted in a ramped base line of the force–displacement plot corresponding to the build-up of debris around and in front of the pin as it advanced into the foam (Figs. 3c, d).

The general correlation of mechanical properties with a power of the density is a special case of the general equation derived by Ashby [4] for foams:

$$\frac{\sigma}{\sigma_w} \propto \left(\frac{\varrho}{\varrho_w}\right)^n$$

where σ and ϱ are the mechanical property and density of the foam and the subscripts refer to these properties for the pore-wall material. The values of σ_w and ϱ_w are not constant because of the reactive nature of food extrusion, neither may they be measured easily. It would certainly be inappropriate to measure them for unfoamed foods involving very different extrusion conditions. The experiments with pin penetration, although not uniquely measuring pore-wall properties, do indicate the different local strengths of the foams in the cases of different bulk density. It is therefore surprising that as a first approximation the results of Figs. 4 to 6 are consistent with constant values of σ_w and ϱ_w in the above equation. The scatter of the results would indicate that the wall properties need to be taken into account in a more rigorous treatment. The power law indices, n, for the data of Figs. 4 to 6 are given in Table II, together with the

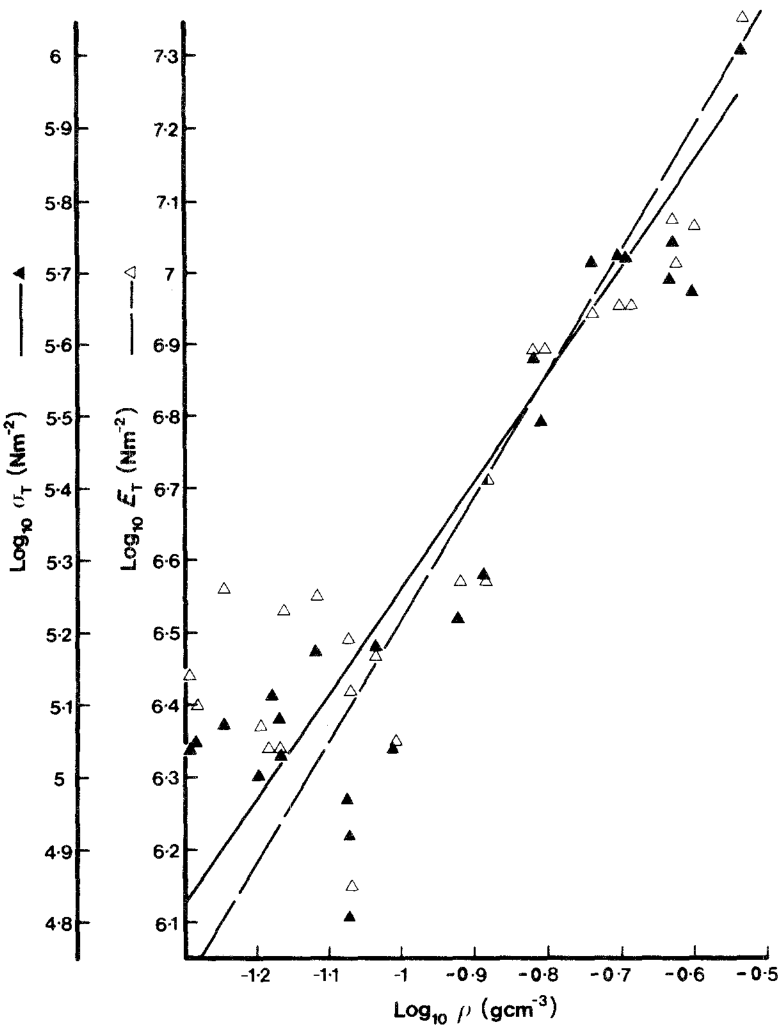


Figure 6 The tensile modulus, E_T (△) and strength, σ_T (▲) as a function of bulk density.

predictions of Ashby for idealized open and closed cell foams. It maybe seen that the value of n is generally greater for the moduli in accord with the Ashby analysis. These data further indicate the widely different textures in terms of mechanical properties and how they may be varied by two of the variables available to extrusion cooking users.

5. Conclusions

The modulus and strength of extrusion-cooked maize foams obtained in tension, compression and flexure increased with the bulk density according to a power law which is an approximation to the Ashby analysis in which the pore wall density and mechanical properties are assumed constant. The power law index was higher for the modulus than the strength as predicted by Ashby. The values were however, closer to the predictions for open cell foams although the foams were observed to comprise closed cells.

TABLE II Power law index values for the equation: $\sigma/\sigma_w \propto (\varrho/\varrho_w)^n$

Modulus	Power law index (n)
Tension	1.7
Compression	2.3
Flexure	2.0
Ashby [4]	2 (open cells), 3 (closed cells)
Strength	**Power law index (n)**
Tension	1.5
Compression	1.6
Flexure	2.0
Ashby [4]	1.5 (open cells), 2 (closed cells)

Pin indentation experiments showed a dependence of the local foam strength on extrusion conditions and a difference between the foam surface and the internal structure which need to be taken into account in a full description of the foam response.

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