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The mechanical properties of extruded food foams

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A pin indentation test has been used to obtain the local mechanical properties and porosity of extruded food foams. These local mechanical properties correlate better with the bulk foam density than more conventional bulk compression data. The Ashby treatment of cellular materials predicts the relationship between mechanical properties and density where they are normalized by the wall material values. However, the foam wall mechanical properties are not currently available for food foams. The pin indentation technique provides an alternative description of the physical properties of these foams.

1. Introduction

The extrusion cooking process has been increasingly adopted in the food industry for the manufacture of a diverse range of products [1]. One of its major uses is in the production of snack-foods and crispbreads from cereals. In this usage the cereal is fed to the extruder in the form of grits or powder together with a low level of water (typically $<20\%$ dry weight basis). The extruder subjects the material to a shear, pressure and temperature history such that the solid undergoes a transition to a viscous "melt". On exit from the dies the superheated water within the melt flashes off as steam leaving a porous, brittle solid of low bulk density. An extensive range of these solid foams is possible through variation of the extruder conditions. Previous work [2–5] has shown the dependence of the bulk density and expansion ratio on the extruder variables. In turn the consumer-perceived properties of extruded solid foams depend on their mechanical properties [6]. Relatively little work has been carried out to obtain the mechanical properties of extruded food foams. The majority of studies has been carried out using techniques based on tensile testing machines. The shear strength of extruded maize starch, wheat starch and wheat flour foams has been measured using a Warner–Bratzler shear cell which deforms the sample between multi-blade platens [7, 8]. Three-point bend tests have also been used [4, 7] to obtain the breaking strength of wheat starch, wheat and maize foams. Van Zuilichem *et al.* [9] used an Izod impact test to obtain the mechanical strength of maize extrudates at higher rates of strain than those obtained in a conventional testing machine. In the majority of the above cases the mechanical property was obtained as a function of a particular extruder variable such as moisture content. Hayter *et al.* [10] used an instrumented pendulum to compress extruded foams and obtained the failure stress at strain rates in the range 20 to 200 $\sec^{-1}$.

In contrast, the mechanical properties of foamed plastics have in general been studied as a function of density. Baer [11] published comprehensive data on plastic foams tested in tension, compression and flexure. Hutchinson *et al.* [12] used a similar approach for maize foams extruded at different screw speeds and moisture contents. They found that the mechanical properties increased with bulk density in a similar way to the data for foamed plastics. Hayter *et al.* [10] found some evidence that the mechanical properties under impact scaled with the bulk density.

The analysis of Ashby [13] for the deformation of cellular solids yields a general equation

$$\left(\frac{\sigma}{\sigma_w}\right) \propto \left(\frac{\varrho}{\varrho_w}\right)^n \qquad (1)$$

where σ is the mechanical property of the foam (e.g. modulus, strength) and ϱ is the foam density. The subscript w refers to the same properties for the foam wall material. Ashby predicted values of n for closed and open cell foams deforming elastically, plastically or by fracture which were verified for various cellular solids. It follows that to a first approximation

$$\sigma \propto \varrho^n \qquad (2)$$

as found experimentally for extruded food foams [10, 12] and earlier for foamed plastics [11].

The present work examines the mechanical properties of a wider range of extruded foams using compression tests and localized pin indentation tests. The latter have been used to obtain the failure stress and modulus of foam cell walls together with estimates of the foam porosity. The data for compression and indentation have been combined in an attempt to use the full Ashby formula (Equation 1) rather than the approximation of Equation 2.

2. Experimental methods

Maize grits and wheat starch were extruded using a co-rotating twin-screw cooking extruder (Baker Perkins MPF 50D, Dow Chemicals, Kings Lynn, UK). Some commercial foamed plastics were also examined. The extruded foams were characterized in terms of their density, pore structure and mechanical properties.

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2.1. Density

The densities of the food foams were calculated from the displacement of fine sand for three samples and a mean value taken. The density of the food foam wall material was measured by the displacement of toluene in a density bottle. Water was used as the displacement medium for the foamed plastic wall material.

2.2. Pore structure

Samples were cut perpendicular to the extrusion direction using a diamond-impregnated wafering saw (Buehler Isomet). Scanning electron microscopy (Philips 501B at 30 kV) was used to examine the foam structures after gold-coating of the samples.

The porosity of the foam sections was calculated from enlarged scanning electron micrographs using a microcomputer-based digitizing tablet. Sufficient sections were examined to count one hundred pores and the mean pore area calculated.

The pore structure was also derived from the results of mechanical testing using pin indentation (Section 2.3.2).

2.3. Mechanical properties

2.3.1. Compression

An Instron 1122 universal testing machine was used to carry out compression tests. Cylindrical samples of 15 mm length were cut using the wafering saw and deformed at a crosshead speed of $5\,\mathrm{mm\,min^{-1}}$. The force–displacement curve was recorded for ten specimens and the failure stress, σ, and modulus, E, calculated using the formulae

$$\sigma = F/A$$

where F is the maximum force and A is the original cross-sectional area of the sample, and

$$E = \sigma/\varepsilon$$

where ε is the strain to break and is defined as $\varepsilon = l/L$ where L is the specimen height and l is the crosshead movement.

2.3.2. Pin indentation

The Instron machine was again used with a pin of diameter 0.58 mm held in a chuck mounted on the

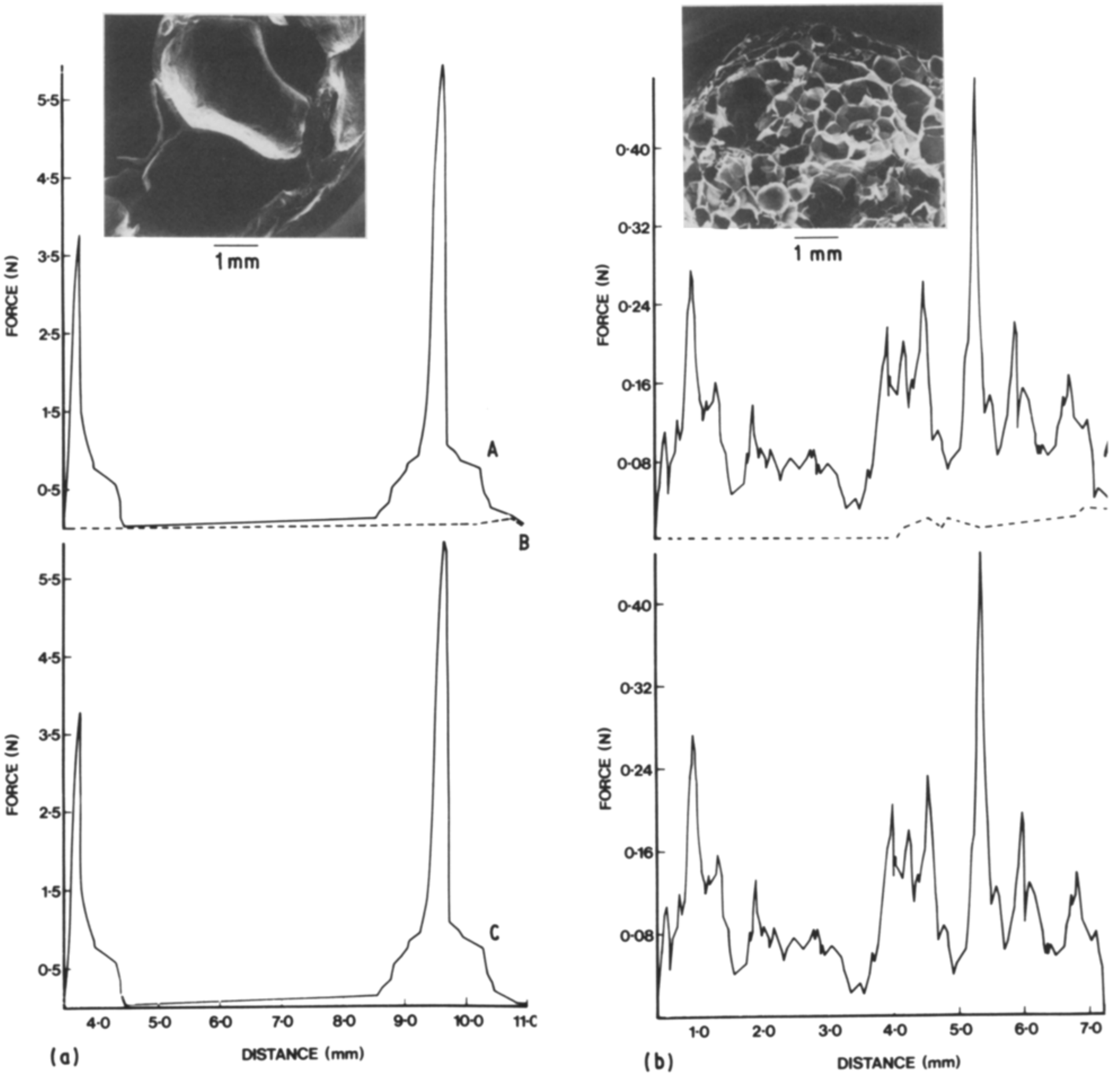

Figure 1 (a, b) The force–displacement plots for pin indentation of two extrusion-cooked maize foams. (A) Pin driven into the specimen, (B) pin withdrawn from the specimen, (C) difference of (A) and (B) to give corrected force–displacement plot.

crosshead. The pin was driven into the foam cylinder parallel to its axis at a crosshead speed of 2 mm min^{-1} and the force–displacement response recorded for five specimens. The form of this dependence varied with each different foam. For some foams it was possible to penetrate successive pore walls such that the hole formed by the pin was clearly shown at the completion of an experiment. In other cases collapse of adjacent walls occurred and debris accumulated around the pin. In the former case the pin test provided an immediate indication of the pore structure of the foam through the rise in force as the pin penetrated successive pore walls (Fig. 1a).

The true force–displacement response was found by subtracting the force to remove the pin from the sample. This is illustrated in Fig. 1b where the baseline of the force–displacement trace (Curve A) is ramped as a result of the accumulation of material round the pin as it penetrates further into the foam. On withdrawing the pin this baseline is isolated (Curve B). The corrected force–displacement curve (Curve C) more closely represents the breakage of successive pore walls.

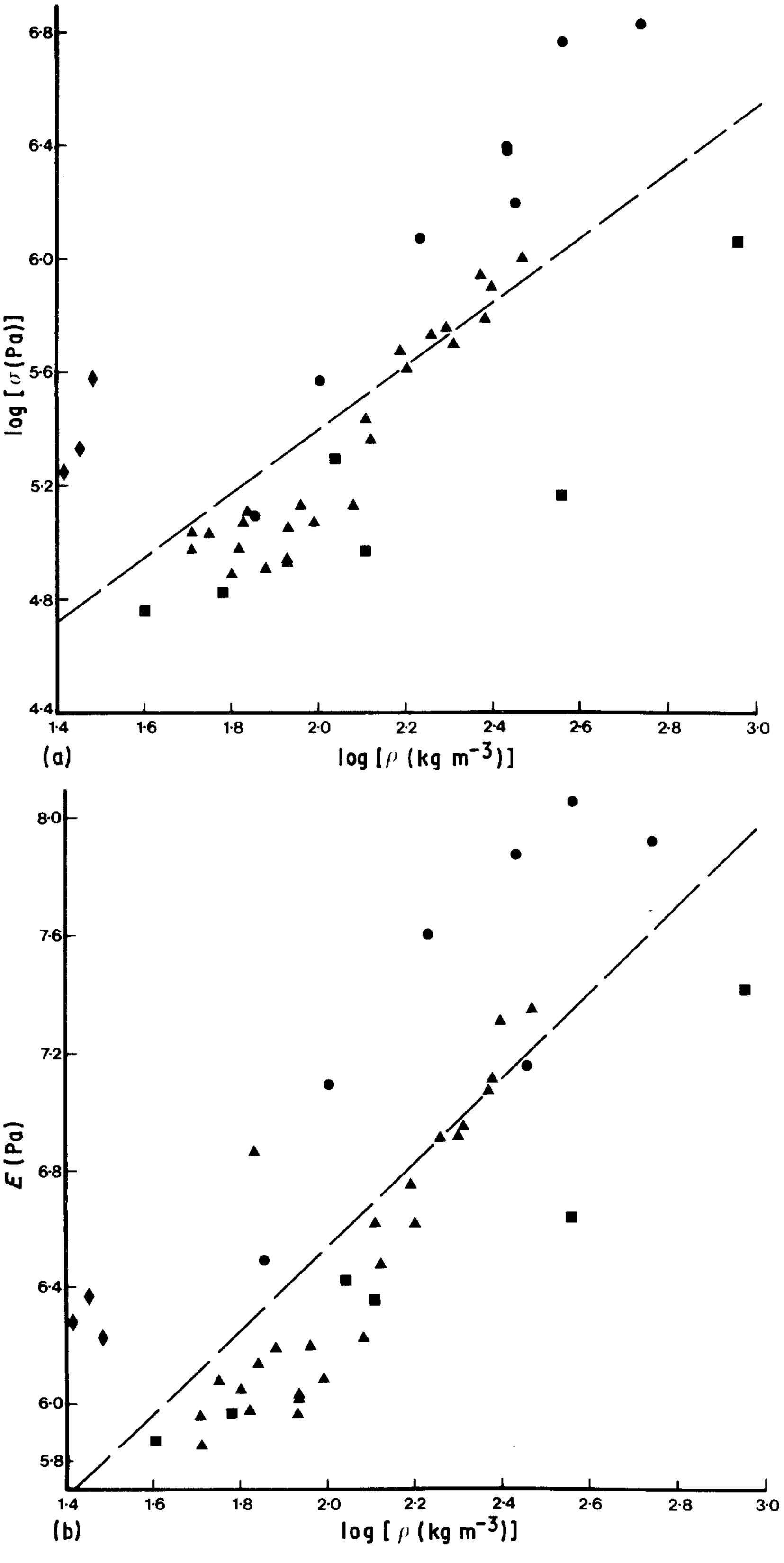

Figure 2 (a, b) The strength (σ) and modulus (*E*) of extrusion-cooked foams obtained in compression as a function of bulk density: (■) maize, (▲) maize (from [12]), (●) wheat starch, (◆) foamed plastic.

The mechanical properties were calculated (i) for the first pore wall and (ii) as the average of the values for all the walls for a penetration distance of approximately 10 mm. The pore structure was also derived from this corrected force–displacement response. The mean distance between the principal force peaks was measured.

The failure stress, σ_w, and modulus, E_w, for the deformation of the pore walls were calculated from the formulae

$$\sigma_w = F/A_p$$

where A_p is the cross-sectional area of the pin, and

$$E_w = \sigma_w/\varepsilon_w$$

where ε_w is the strain to break each wall referenced to the pore size; $\varepsilon_w = l/L_p$ where L_p is the average pore diameter and l is the crosshead movement to break.

3. Results and discussion

3.1. Mechanical testing

The mean moduli and strengths of the extruded foams are plotted logarithmically against the bulk density in Fig. 2. The data of Hutchinson *et al.* [12] obtained under similar testing conditions are also shown. It is clear that the latter results, which were obtained for extruded maize under different conditions of extruder screw speed and moisture content, closely obey Equation 2. The current data obtained under more diverse extrusion conditions show a greater divergence from Equation 2, particularly at low bulk densities. The values of the power-law index, n, (Equation 2) are given in Table I. They are broadly in agreement with the Ashby predictions for open-cell foams. The full Ashby formula (Equation 1) would imply that the data would fall on parallel lines depending on the values of the wall mechanical properties and density. The results for the wall density indicate that although most densities are in the range 1200 to 2000 kg m^{-3} the maize may have a wall density of over 3000 kg m^{-3}, and the foamed plastic walls have a density of 300 kg m^{-3}. This is consistent with some data for maize lying below the line through Hutchinson *et al.*'s [12] results and those for the foamed plastics lying above this line.

The mean moduli and strengths obtained for extruded foams using the pin indentation technique are shown in Fig. 3 as a function of the bulk density. A comparison of the data common to Figs 2 and 3 shows that the mechanical properties from the pin indentation test more closely obey Equation 2. This indicates the use of this type of mechanical test to characterize foam properties. The values of the power-law index n in Equation 2 are given in Table I for the strength and modulus. The value of n is greater for the modulus than for the strength, as predicted by Ashby. The first-wall data are particularly close to the Ashby predictions for closed-cell foams.

The pin indentation test gives information on the mechanical properties of the pore walls although the conditions of deformation are ill-defined. In the absence of knowledge of the mechanical properties of individual pore walls removed from the foams, the values of σ_w and E_w have been taken as indicative of the wall mechanical properties in the Ashby formula (Equation 1). The relative stress and modulus are plotted against the relative density in Fig. 4. It is clear that the data fit to Equation 1 is considerably worse than to Equation 2. This may arise through the inapplicability of the pin indentation test to the pore wall properties. The similar dependence of mechanical properties on density from the two test methods in Figs 2 and 3 implies that the pin test actually relates to the foam properties. It is also interesting to compare the strain rates of the mechanical tests. The compression strain rate, defined as the cross-head speed relative to the sample height, was $5.5 \times 10^{-3}\,\text{sec}^{-1}$ whereas the strain rate for the pin indentation varied from 10 to $92 \times 10^{-3}\,\text{sec}^{-1}$, depending on the pore size.

3.2. Structure

The pin penetration test also gives information on the pore structure of the foams. The mean distance between force peaks was compared with the separation of pore wall intercepts for diameters drawn across a scanning electron micrograph of a foam section. These quantities were plotted against the pore size as derived by drawing round the pores using the digitizing tablet (Fig. 5). While the pore wall intercepts with the diameter are in good accord with the pore size it is clear that the pin penetration test overestimates the number of pore walls. This follows from a lack of filtering of the force events to exclude small or subsidiary peaks in the force–displacement plot. Nevertheless, the approach shows greater potential for pore structure investigation than the derivation of the information from a gross mechanical test on the whole specimen [8].

TABLE I Values of the power law index, n, in Equations 1 and 2

Mechanical property	n (Equation 1) [13]		n (Equation 2)*	Regression coefficient, R^2 (%)
	Open cell	Closed cell		
Compression				
Stress σ	1.5	2	1.1 (1.6)	56
Modulus E	2	3	1.4 (2.3)	62
Pin indentation				
Stress σ_w: first wall			2.3	79
average			2.0	79
Modulus E_w: first wall			2.9	84
average			2.3	80

*The values in parentheses are taken from Hutchinson *et al.* [12].

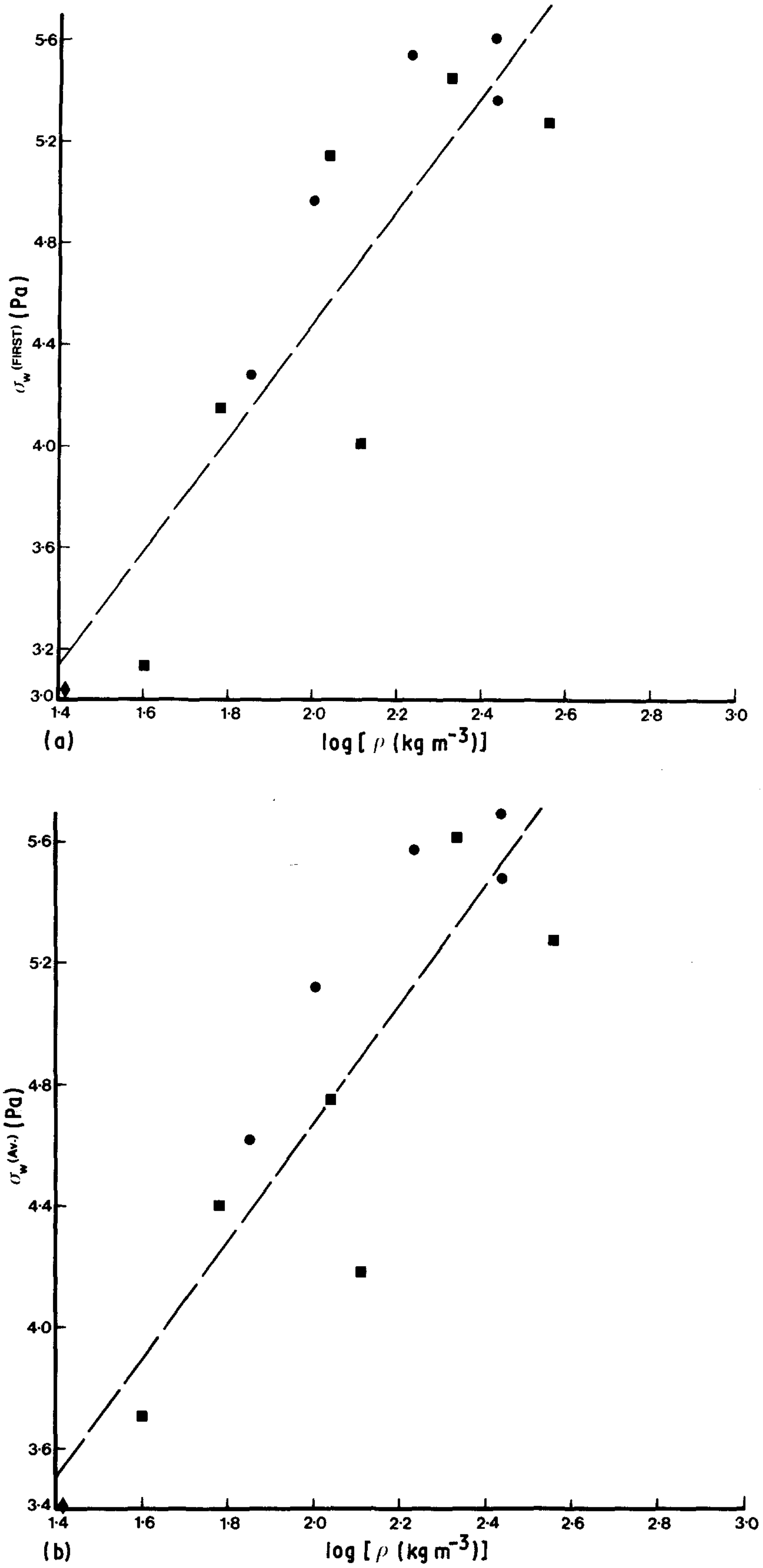

Figure 3 The strength (σ_w) and modulus (E_w) of extrusion-cooked foams obtained by pin indentation as a function of bulk density. Material as shown in Fig. 2: (a) for first pore wall, (b) average of successive pore walls, (c) for first pore wall, (d) average of successive pore walls.

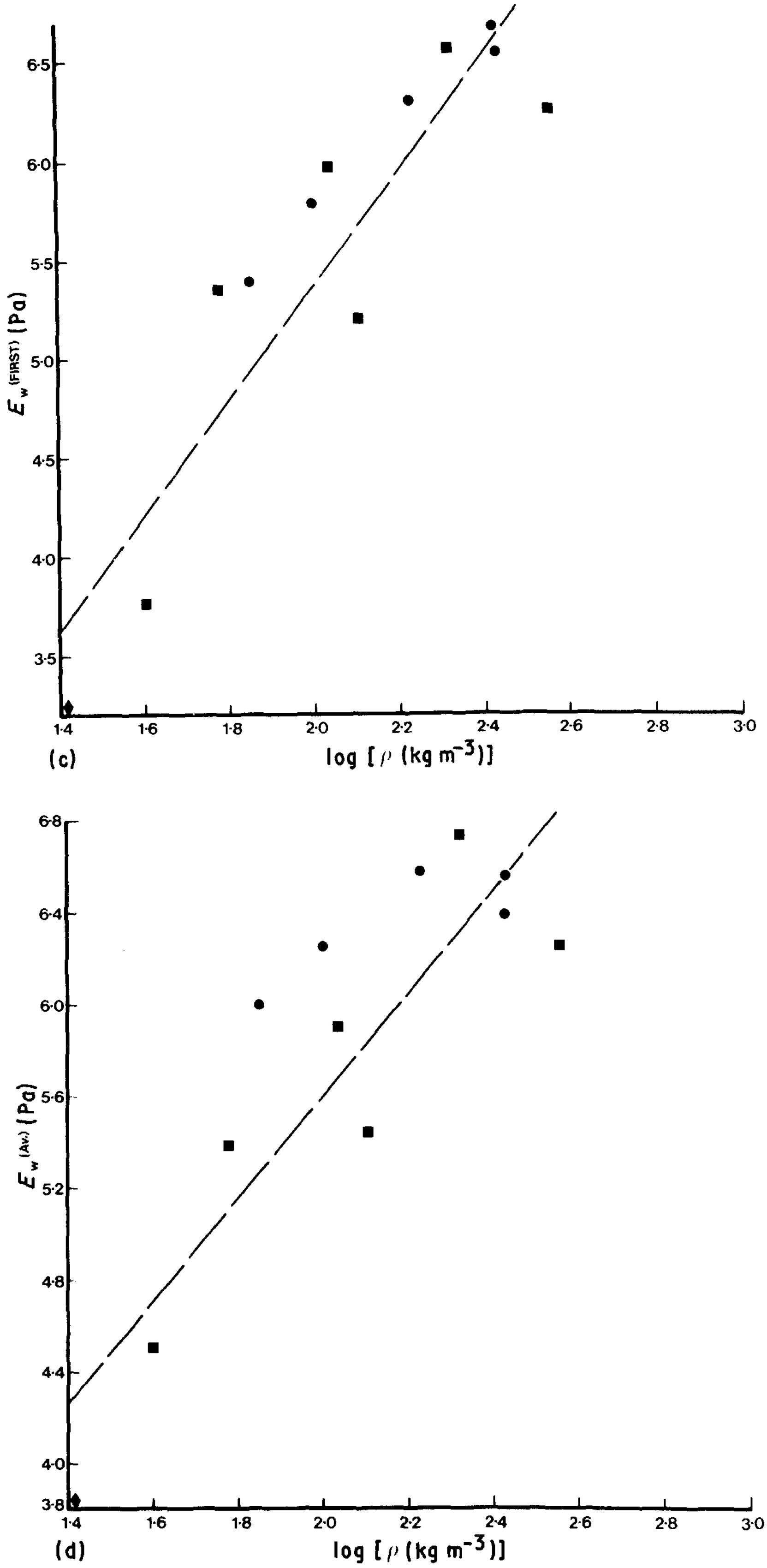

Figure 3 Continued.

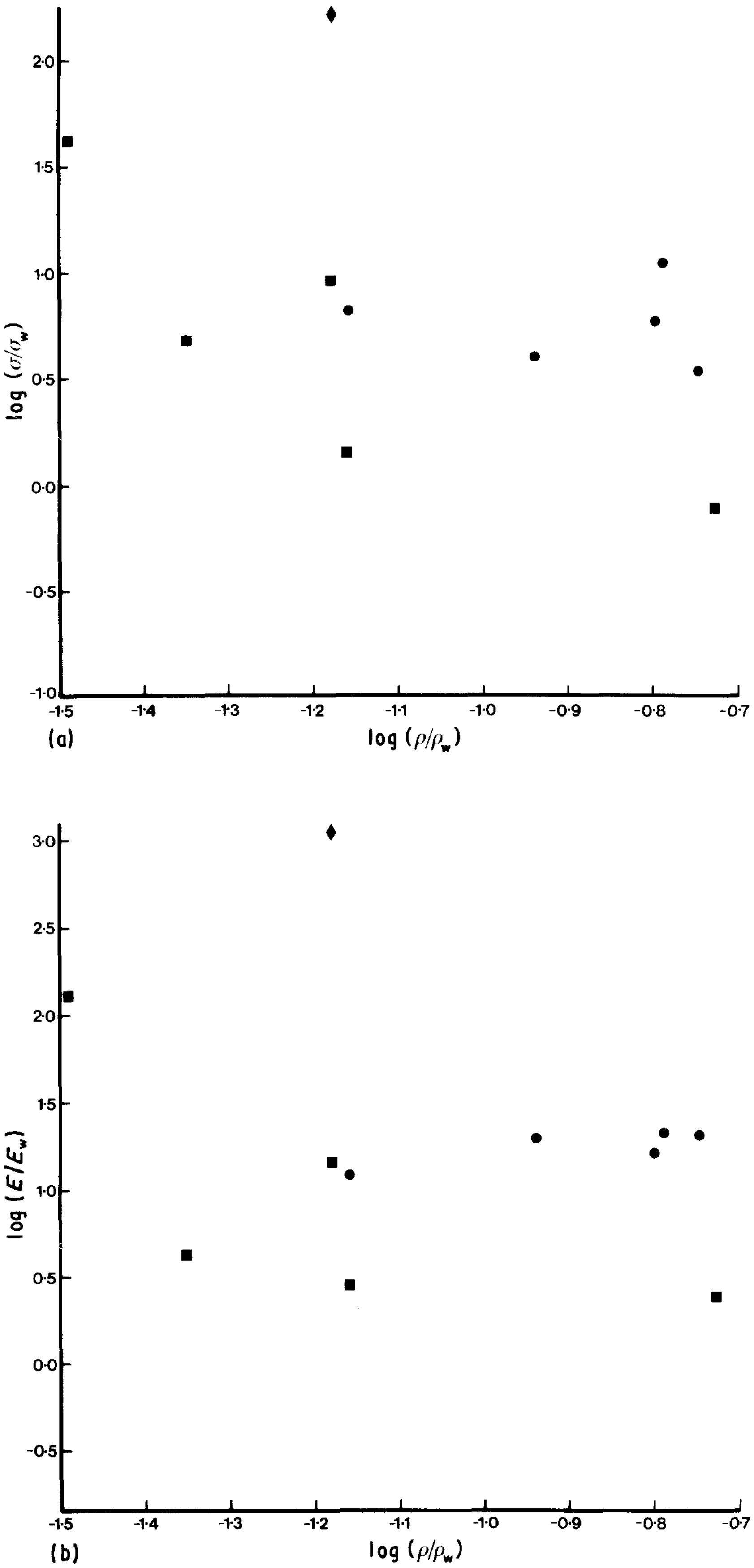

Figure 4 (a, b) The strength and modulus of extrusion-cooked foams in compression relative to their wall properties. The wall mechanical properties were taken from Fig. 3.

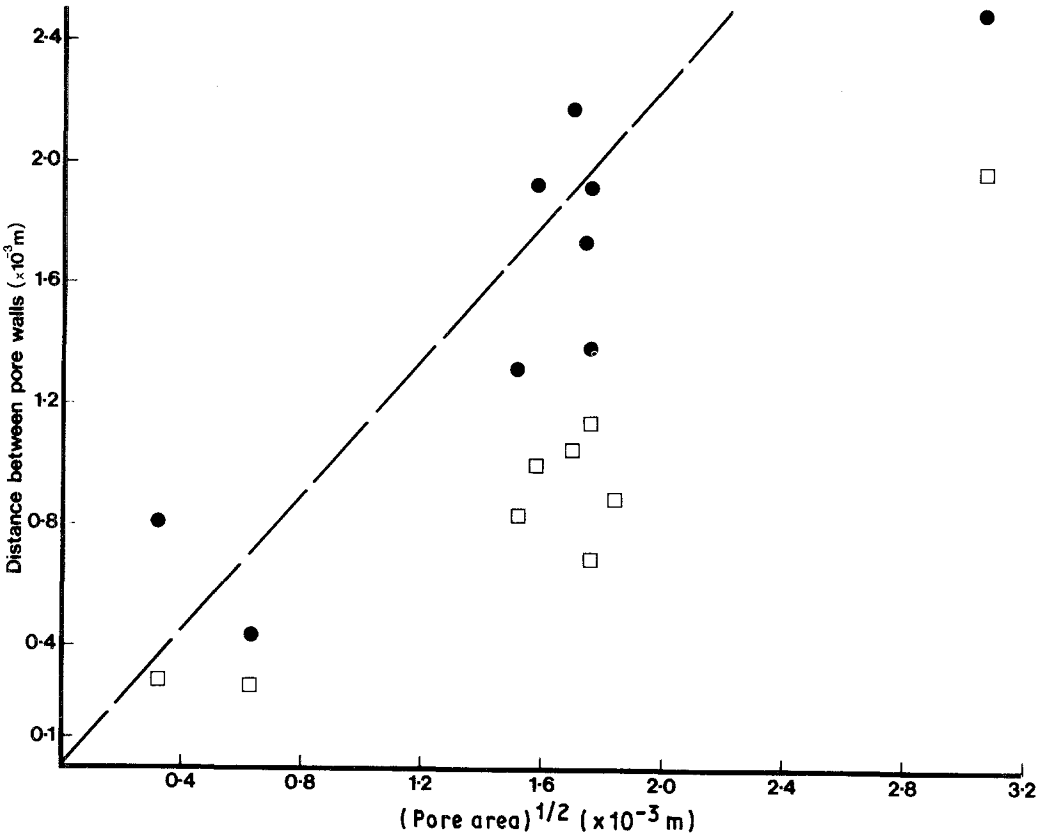

Figure 5 The pore size (derived from the pore area) as a function of the distance between pore walls along a diameter obtained (●) from scanning electron micrography and (□) from indentation using a pin.

4. Conclusions

Results obtained from compression tests on a number of extruded food foams have shown deviation from the simple power-law relationship between mechanical properties and density which had previously been used to describe foams obtained under more restricted extrusion conditons. The Ashby analysis of cellular materials shows that the mechanical properties and density must be normalized by these properties for the wall material. The wall density varies with both material and process conditions, as would be expected for the extrusion of food materials. In an attempt to obtain the wall mechanical properties a pin indentation test has been used. The combination of these measurements gave a poor fit to the Ashby equation. This points to the inapplicability of the pin indentation test for obtaining the pore wall properties, which is to some extent borne out by the dependence of the pin test mechanical properties on the foam density. These pin test data were better described by the density power law than those obtained in conventional compression. The pin indentation approach also gives information on the pore structure of foams from the force–penetration output.

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