

The physical properties of extruded food foams

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The extrusion cooking process has led to the production of many novel foamed foods. Their formation is critically dependent on the processing history and the local conditions at the die. The pore size generally decreases with a decrease in foam bulk density, whilst foamed plastics show the opposite trend. Narrow pore size distributions tend to be associated with foams where the pore size is small compared with the extrudate dimensions. A pendulum impact device has been used to assess the deformation of the different foams as a function of impact energy. The compressive strain increases to a maximum corresponding to the densification of these brittle foams. This contrasts with data for plastic foams.

1. Introduction

Many food products are foamed ranging from creams and meringues to bread and snacks. Foods may comprise a large number of biological molecules such as proteins, polysaccharides and glycerides which in turn constitute a vast range of biological polymers. For example the polysaccharide starch comprises two polymers: (i) amylose, which is a linear molecule of helical conformation and molecular weight of the order of 10^4 , and (ii) amylopectin, a highly branched structure of molecular weight in the region of 10^8 . Maize, a common snack food material, contains approximately 82% starch. Many solid foamed products are structured by the inclusion of air during baking, the release of carbon dioxide or by the loss of water as steam. This paper focuses on some foams produced by extrusion cooking, which is a relatively new means for continuously producing foods using technology similar to that of the plastics industry. For example crispbreads and snack products may be produced by the extrusion cooking of cereals such as maize, rice and wheat with water.

Extrusion cooking subjects the feed material to a combined pressure, temperature and shear history resulting in the transformation of the solid feed to a viscous dough [1]. The extruder is a screw pump which means that mechanical energy is dissipated in conveying this material. The product is then formed by dies and under certain conditions this viscous dough can be foamed. The loss in pressure as the material leaves the die results in the superheated water turning to steam, which diffuses to the atmosphere through the solidifying extrudate. The nature of the foaming process is clearly complex and depends on the interaction of growing pores in a matrix whose properties are changing rapidly. Harmann and Harper [2] described the dependence of the porosity of an extrusion cooked foam on (i) the distribution of water in the viscous material prior to the die, (ii) the material viscosity, and (iii) the normal forces at the die. The latter is responsible for the die swell phenomenon observed in the extrusion of plastics and food materials. Han [3] has given a review of the factors affecting the foaming of

plastics. The pressure and temperature of the melt influence the solubility of gases in the melt, which subsequently affects the foaming process after the die.

Solid foams have been described by Ashby [4]. Two dimensional open and closed cell foams were analysed in their deformation by elastic, plastic and fracture mechanisms. Whilst many examples were given of the elastic and plastic deformation of foams produced from plastic and metals, relatively few data exist for brittle foams. Foamed foods, in particular extrusion cooked foams, have also been poorly studied despite the importance of their textural attributes. Low strain rate deformation tests may yield information on the pore structure of extrusion cooked foams as shown by Owusu-Ansah *et al.* [5]. They recorded the force-displacement in a compression 'texture' experiment and related the fine structure of these graphs to the degree of porosity of extrusion cooked starch foams. Faubion and Hosney [6] have used a compression texture experiment and a three point bend test for wheat starch and flour extrudates. The mechanical properties of foods at high rates of strain may correspond more closely to the sensory property of 'crunchiness' since eating involves high strain rate deformation. Thus Van Zuilichem *et al.* [7] have used an Izod test to measure the energy loss in breaking extruded maize samples, which they termed the breaking strength.

In this paper we have studied starch-based extrusion cooked foams which show a wide range of cellular structures. The foams have been characterized by their pore size distributions and the relative proportions of air and wall materials. An instrumented pendulum technique has been used to compress the foams and obtain information on their resistance to deformation at high strain rates. These data indicate that whilst the resistance to deformation corresponds to the foam density, the details of the foam deformation also depend on the pore structure.

2. Experimental procedure

2.1. Materials

The solid foams were produced using a Baker Perkins MPF 50D co-rotating twin screw extruder. The

TABLE I Extrusion conditions

Foam	Die size (mm)	Temperature profile (°C)	Screw speed	Feed rate (Kg h ⁻¹)	Moisture control (% d.w.b.)	Die Pressure (MPa)	Die temperature (°C)	Drive power (kW)
A	4	27-52-93-140-140	350	40	25	2.4	137	4.0
B	2*	27-52-93-140-140	350	40	25	5.0	147	4.8
C	2	27-52-93-120-100	400	40	17	5.5	147	6.6
D	2	27-52-93-120-120	300	30	47	4.4	116	1.9
E	2	27-52-93-120-120	300	30	39	6.3	113	2.1
F	2	27-52-93-120-120	300	30	32	5.6	130	2.9
G	2	27-52-93-120-120	300	30	24	8.2	138	3.9
H	6	27-52-93-120-120	300	50	27	2.8	124	4.8
I	3	27-43-70-100-100	150	40	35	9.6	100	2.5
J	3	27-43-70-100-100	150	40	35	10.2	103	2.9

*One die insert only.

extrusion conditions are given in Table I for maize (A to G), wheat starch (H) and wheat flour extrusion (I, plain; J, self-raising). The extrusion cooking process independent variables are die size, temperature profile, screw speed, feed rate and extrusion moisture. The process is characterized by measurements of die pressure, die temperature and drive power consumption. Finally, an expanded plastic foam (Foam K) was used for comparison.

2.2. Foam characterization

2.2.1. Structure

The diameter of twenty cut extrudate samples was averaged and the expansion (relative to a die diameter) recorded in Table II. The bulk density of the samples was measured by the displacement of fine sand (Table II).

Sections of extrudate were obtained using a low speed diamond impregnated saw (Buehler Isomet, Illinois, USA). Scanning electron micrographs of the pore structure were obtained with gold coated specimens using a Philips 501B apparatus at 30 kV. Pore size distributions were obtained using a digitizing tablet. This was used to draw one hundred pores from photographs of a necessary number of sections. The average pore size, the number of pores and the pore area relative to the cross section area were also calculated from the digitizing tablet data (Table II).

2.2.2. Mechanical properties

Impact studies on the extruded foams were carried out using an instrumented pendulum (Fig. 1). This device was originally designed and built at the Food Research Institute for the study of dynamic tissue failure in potatoes [8, 9]. A transducer on the axis of the hammer provides a measure of the displacement of the hammer which is monitored as a function of time. This information is plotted using a microcomputer system and may be differentiated to give the speed and deceleration of the pendulum. The energy is adjusted by the initial height of the pendulum hammer. In the present arrangement a crushing test was used with the various foams [10].

The following quantities were calculated for the impact (Table III):

$$\text{Strain} = \frac{x}{d} \quad (1)$$

$$\text{Strain rate} = \frac{x}{dt} \quad (2)$$

$$\text{Resistive stress} = \frac{E}{Ax} \quad (3)$$

where x is the penetration of the hammer into the specimen, d is the specimen diameter, t is the time of penetration, E is the impact energy and A is the cross section area of the hammer. A pendulum head of

TABLE II Pore structure details of the extruded foams

Foam	Expansion	Bulk density (g cm ⁻³)	Average pore area (mm ²)	Number of pores	
				Cross sectional area of sample (mm ⁻²)	Total pore area
				Cross sectional area of sample	Cross sectional area of sample
A	4.0	0.21	9.4	0.1	0.8
B	6.1	0.06	2.3	0.4	0.8
C	5.5	0.04	0.4	1.2	0.5
D	2.2	1.79	0.8	0.4	0.4
E	2.6	0.91	2.5	0.3	0.6
F	3.9	0.36	5.4	0.2	0.9
G	5.3	0.13	5.6	0.2	0.9
H	2.7	0.27	3.5	0.1	0.3
I	2.9	0.38	1.0	0.9	0.9
J	2.6	0.30	0.1	14.8	0.9
K	-	0.03	0.1	17.9	1.0

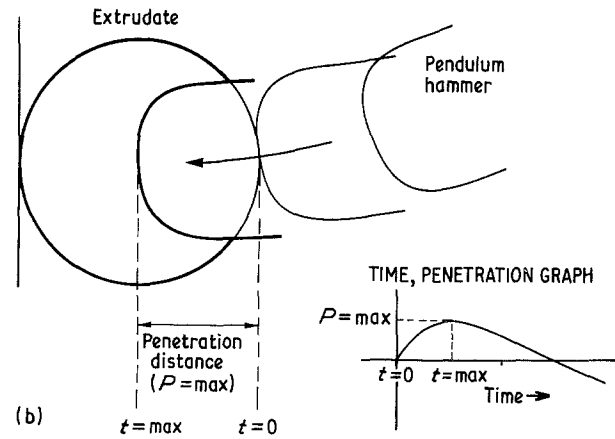
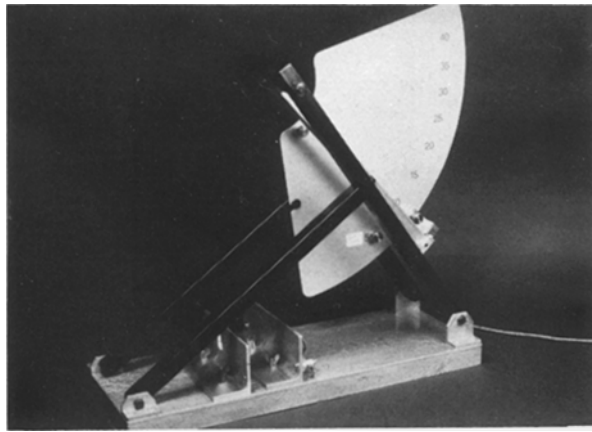


Figure 1 The instrument pendulum used for impact tests on solid foams showing schematically the penetration as a function of time.

diameter 12.5 mm was used in the present experiments.

3. Results

3.1. Foam structure

The scanning electron micrographs of extrudate cross sections are shown in Figs 2 to 4. For constant extrusion conditions, an increase in die size resulted in decreased expansion and increased bulk density. Following the arguments of Harmann and Harper [2] this arises due to the reduction in forces normal to the die at low shear rates and an increase in viscosity under conditions of decreased shear rate and temperature. Following Han [3], lower pressures and temperatures result in a lower solubility of gas in a polymer melt. In the case of water vapour dissolved in a biopolymer melt less expansion would be expected at increased die size. The experimental evidence indicates larger pores with increasing die size (Fig. 2), which is in accord with the arguments of Harmann and Harper [2] who relate a low porosity to a poor distribution of water such as occurs at low mechanical energy input at an increased die aperture. Foam C was a very low density, highly porous maize foam (Fig. 2) which is consistent

with the higher values of die pressure, die temperature and mechanical energy dissipation.

The results obtained by varying extrusion moisture are shown in the extrudates of Fig. 3. With increasing extrusion moisture the expansion decreased and the bulk density increased in agreement with other reported data in the lower moisture range 13 to 17% (dry weight basis) [2]. The die temperature and die pressure decreased with increasing extrusion moisture, consistent with reduced superheating of the water in the extruder die and a consequent decrease in expansion. The present results showed a decrease in pore size with increasing extrusion moisture (foams D to G) whereas Harmann and Harper [2] recorded an increase in pore size. According to their arguments [2] the observed decrease in extruder mechanical energy dissipation with increasing moisture would in fact imply an increased pore size. In the present high moisture extrusion experiments the large reduction in expansion restricts the area over which large pores can exist without the constraint of the surface. This tends to reduce the average pore size.

Owusu-Ansah *et al.* [5] found that the number of air cells increased with expansion for maize starch

TABLE III Mechanical deformation of foams

Foam	Impact energy (mJ)	Strain	Strain rate (sec ⁻¹)	Resistance (× 10 ⁴ Pa)	Bulk Density (g cm ⁻³)
A	39	0.20	43	9	0.21
B	39	0.62	37	4	0.06
C	39	0.54	42	5	0.04
H	39	0.05	36	41	0.27
I	39	0.07	71	53	0.38
K	39	0.07	21	22	0.03
C	81	0.72	64	8	0.04
D	81	0.16	229	93	1.79
E	81	0.15	148	84	0.91
F	81	0.17	64	50	0.36
G	81	0.27	44	23	0.31
H	81	0.09	61	48	0.27
I	81	0.15	111	51	0.38
K	81	0.14	38	25	0.03
H	334	0.22	64	75	0.27
I	334	0.53	138	57	0.38
J	334	0.86	217	39	0.30
K	334	0.28	78	50	0.03

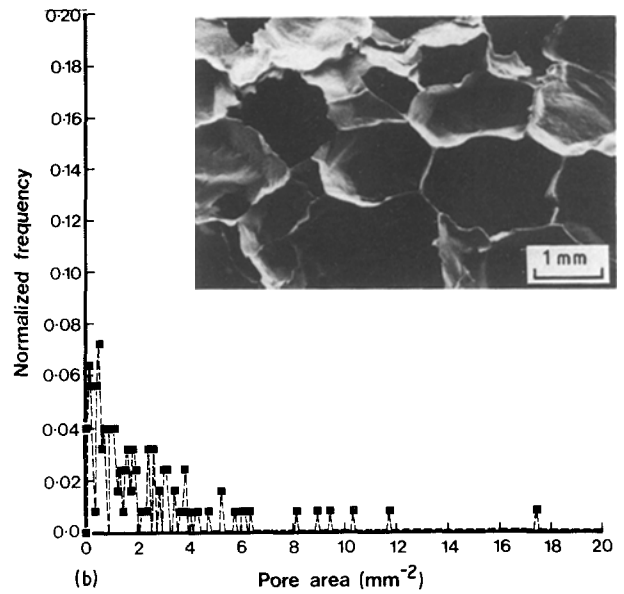
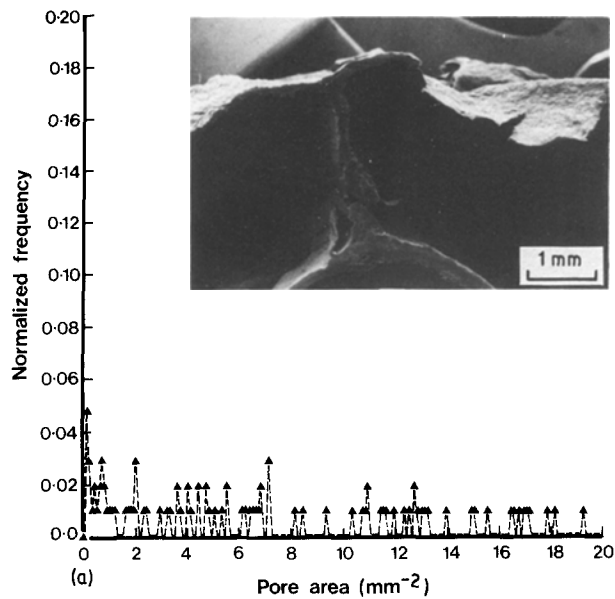
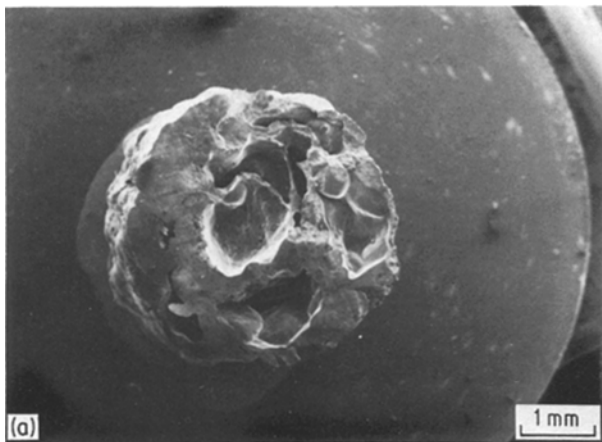
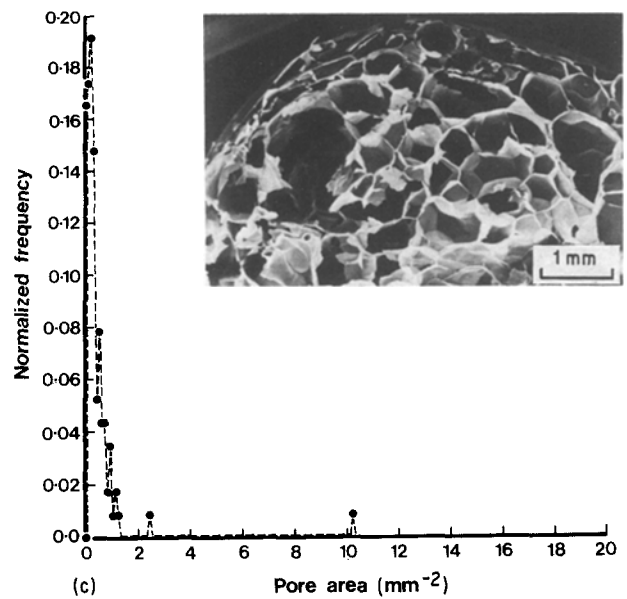


Figure 2 Pore area distributions for maize extrudate cross sections. A scanning electron micrograph of part of a typical section is shown in each case: (a) foam A, (b) foam B, (c) foam C. Extrusion cooking conditions are given in Table I.

extrudates. The present data for maize however show some exceptions to this rule. McIntyre and Anderton [11] found that a small pore size correlated with a high density which is only consistent with the foams D to G. By comparison the starch extrudate has a larger proportion of wall material than any of the maize extrudates A to G (Fig. 4) although the pore size and density are comparable.



While an average pore size has been calculated for the above foam cross sections, the data of Fig. 2 show a considerable variation in the pore size distributions. Foam C, which has the smallest pores, has a very narrow range of pore sizes, whereas foam A is charac-

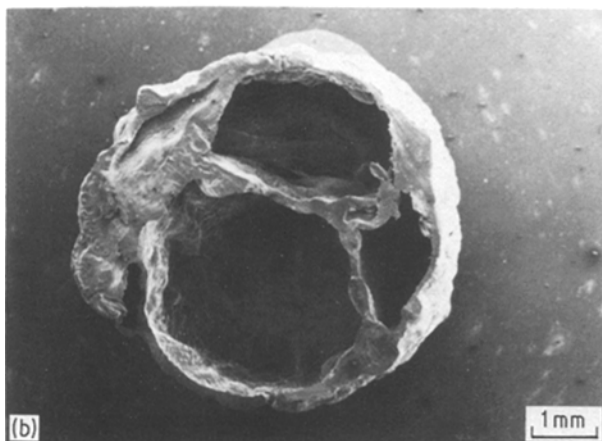
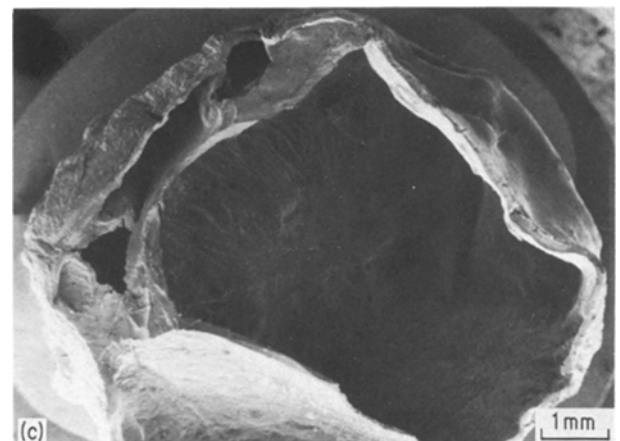


Figure 3 Scanning electron micrographs of part of a typical section for maize extrudates: (a) foam D, (b) foam E, (c) foam F. The extrusion moisture falls from D to F as given in Table I.



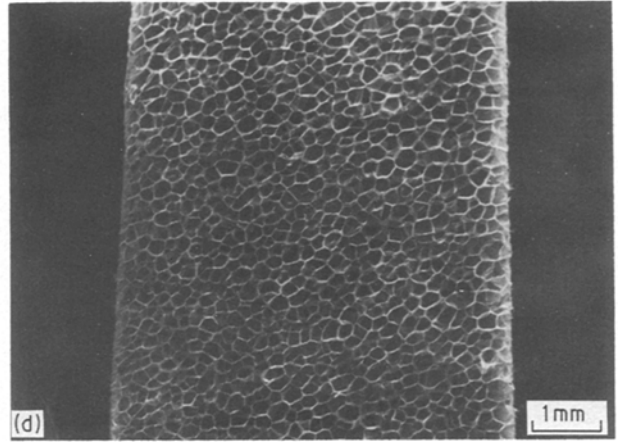
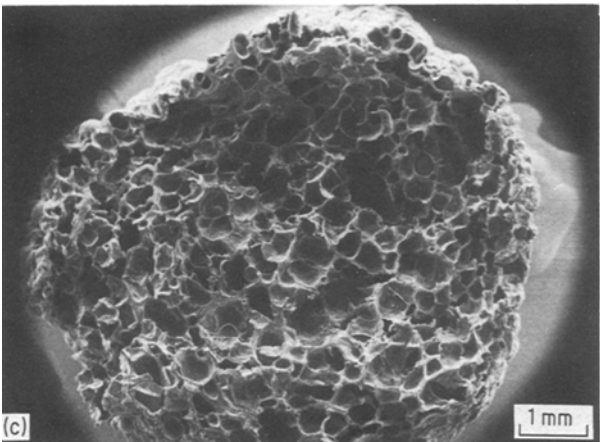
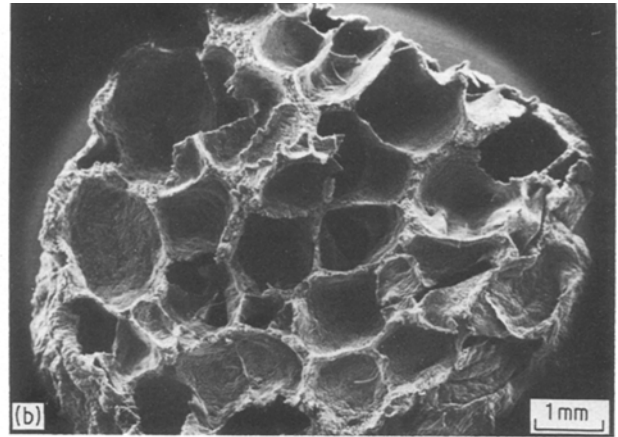
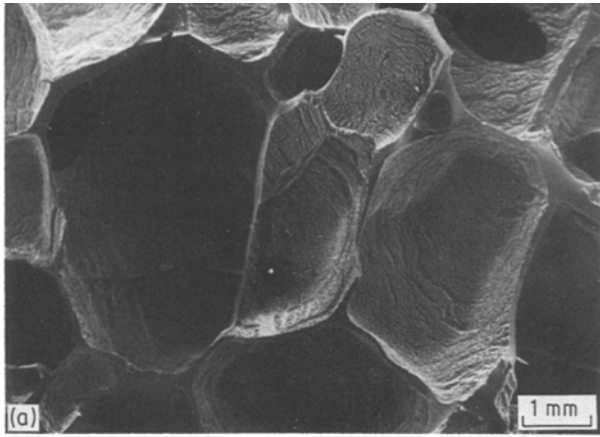


Figure 4 Scanning electron micrographs of a section normal to the axis of the wheat starch and flour extrudates (Table I): (a) foam H, (b) foam I, (c) foam J, (d) foam K.

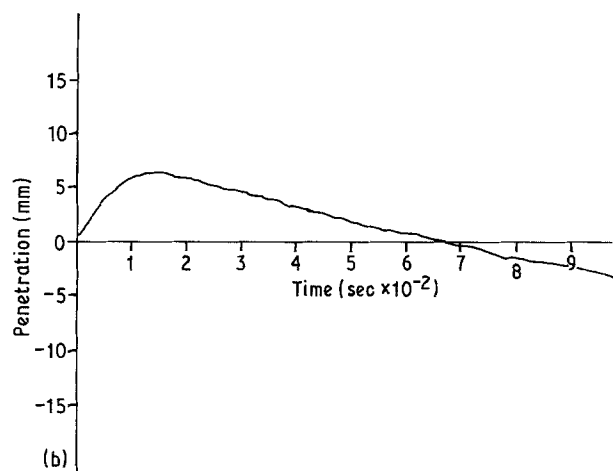
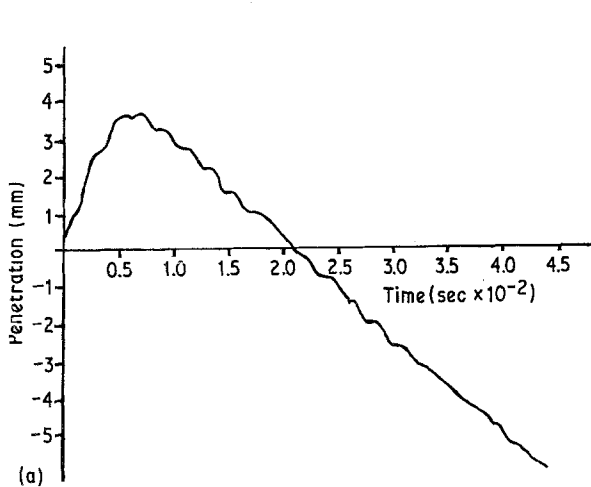
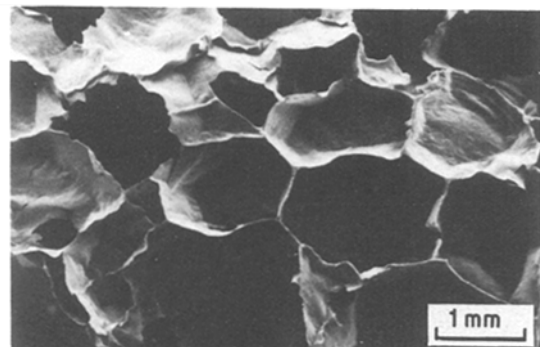
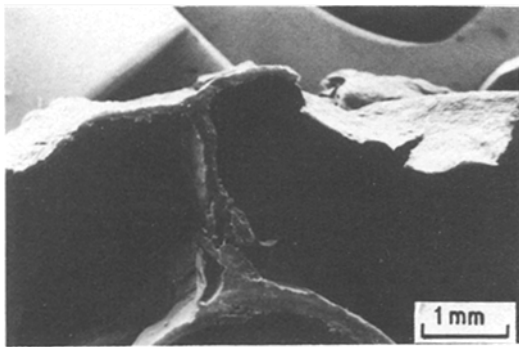


Figure 5 The penetration of the pendulum hammer into maize extrudate foams as a function of time. Impact energy = 39 mJ. (a) foam A, (b) foam B.

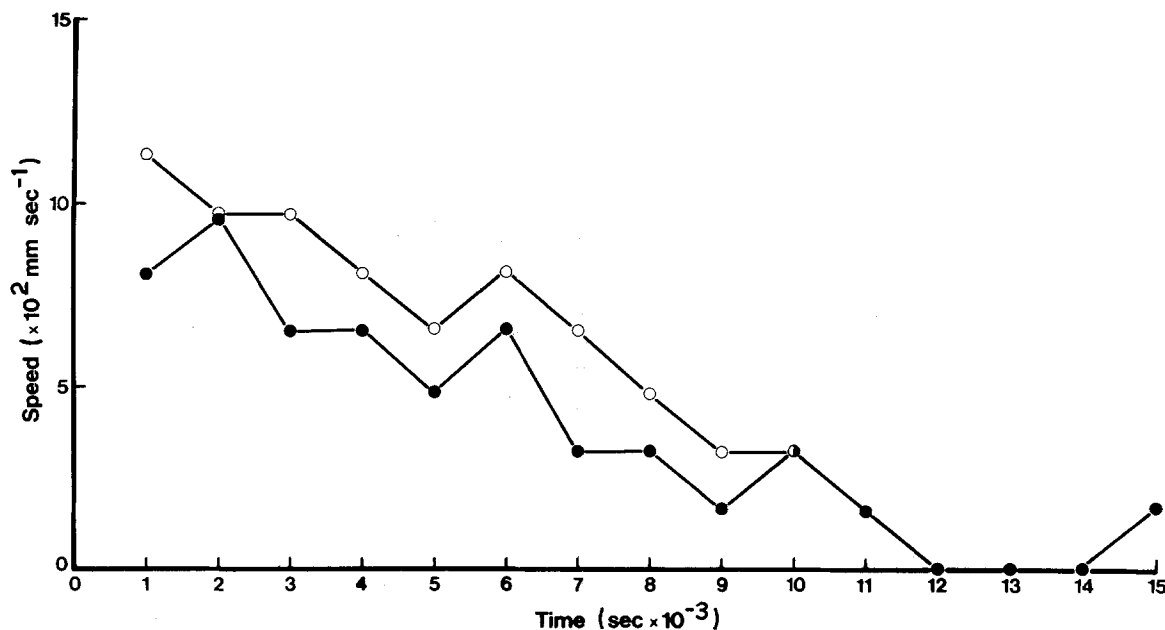


Figure 6 The speed of the pendulum hammer in maize extrudate foam C as a function of time: Impact energy, (●) 39 mJ; (○) 81 mJ.

terized by a broad distribution. The variation of the pore size near the surface indicates that unless the pores are small the surface tends to be surrounded by smaller pores than in the bulk of the foam.

The inclusion of the additives in self-raising flour (J) leads to similar expansion ratios to plain flour (I) corresponding to almost identical die pressures and temperatures. The former comprised many smaller pores, which is consistent with additional pore nucleation sites through both the inclusion of additives and their better distribution at the greater mechanical energy dissipation.

The ratio of the wall volume to sample volume is identical to the ratio of the bulk foam density to the wall material density and may also be related to the ratio of wall area to sample area. For a given cubic cell whose wall is very much thinner than the cell dimension, the density ratio depends on whether the cell is open or closed. For all cases except the starch and plastic foams, a closed cell approximation gave more realistic values of the wall density using the ratios of pore area to sample area given in Table II. Consideration of Figs 2 to 4 shows that all foams comprise closed cells.

3.2. Mechanical properties

Of the maize foams A to C, foam A deformed least, resulting in a high resistance (Table III). The time dependence of penetration into the specimen was irregular for the thick-walled pores of foam A (Fig. 5a). In contrast, foam B had a low resistance to impact and deformed to a large strain, the penetration into the specimen being smooth (Fig. 5b). Foam C responded similarly to foam B; Fig. 6 shows the speed of the hammer at two impact energies. The linear reduction in velocity with time indicates that a constant force may be associated with the crushing and justifies the definition of resistance according to Equation 3. The starch foam (H) showed a much higher resistance and lower strain than maize foams A to C, although

the foam density and pore size were not markedly different. The wall area was, however, much higher for the starch foam. The plastic foam (K) has a similar bulk density to foam C but deformed less, resulting in a greater resistance to impact.

Foams D to G showed a slight decrease in strain with increasing moisture although the strain rate and resistance increased markedly (Table III). For wheat starch, Owusu-Ansah *et al.* [5] found that the breaking strength increased with increasing extrusion moisture in the range 13 to 21% (d.w.b.) although Faubion and Hosney [6] observed a decrease in the breaking strength in three point bending with an extrusion moisture increase from 17 to 24% (d.w.b.).

The resistance and strain of maize foams D to G was comparable with those of the starch, flour and plastic foams at an impact energy of 81 mJ. Maize foam C and the plastic foam K were of least bulk density, although again their resistances were different by a factor of > 3. Foams C, D, I, J and K comprised the smallest pores although their mechanical properties and bulk densities showed large variations.

The starch, flour and plastic foams were compared using an impact energy of 334 mJ which showed that the starch deformed least. Plastic foam K deformed to the same strain as foam B under forty times the impact energy.

The analysis of Ashby [4] for two dimensional foams indicates that the strain increases to a maximum value corresponding to complete densification whether the foam deforms by elastic, plastic or fracture modes. The current energy range was not sufficient to cause complete densification for the plastic foam (K) (Fig. 7). The data for the low resistance maize foams B and C (Table III) show that the strain increased more rapidly with impact energy. The wheat flour (I) and starch (H) extrudates showed a rapid increase of strain at an impact energy of ~0.6 J (Fig. 7) which corresponds to fracture of the specimens instead of the local densification which occurred at lower impact energies.

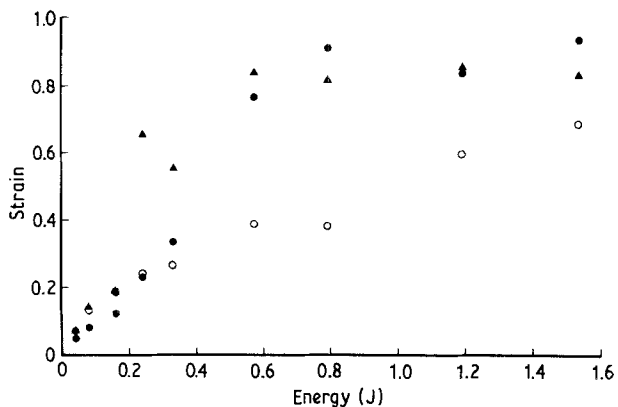


Figure 7 The strain of deformation of starch, wheat flour and plastic foam extrudates as a function of the impact energy. ○ plastic foam; ●, starch; ▲, wheat flour.

Although the hammer did not reach the back plate (strain of unity), it is clear that the impact energy may be dissipated in kinetic energy of the fragments. The onset of gross fracture of the sample is a regime of behaviour that is better studied by other experimental arrangements such as the Charpy or Izod geometries. It is also clear from Table III that the strain rate of impact increases with impact energy. This would be expected since in the simplest case of a constant deceleration (Fig. 6) the strain rate is proportional to the square root of the impact energy.

The analysis of two dimensional foams by Ashby [4] showed that the mechanical property of a foam is constant for strains in the range 0.05 to 0.8, the latter corresponding to densification. The present data are consistent with this result provided that the mode of deformation is by local crushing and not by gross fracture. The resistance stress, σ , at low strains (above 0.05) is plotted against the foam bulk density, ρ , in Fig. 8 using logarithmic axes. The data showed an approximately linear relationship:

$$\sigma \propto \rho^{1.1} \quad (4)$$

which is consistent with the general relationship

$$\left(\frac{\sigma}{\sigma_b}\right) \propto \left(\frac{\rho}{\rho_b}\right)^n \quad (5)$$

used by Ashby [4] for the mechanical properties of elastic, plastic and brittle foams. It is noteworthy that a greater range of mechanical properties may be obtained from maize than from its constituent starch. For crushing of brittle foams Ashby's two-dimensional analysis predicts $n = 1.5$ for open cell foams and $n = 2$ for closed cell foams. For three dimensional, irregular foams deviations from these analyses would be expected and Equation 5 would apply locally within these foams. Ashby found relatively little literature for crushing of brittle foams but the data were consistent with an open cell two dimensional structure (i.e. $n = 1.5$) For plastic and metal foams σ_b and ρ_b are generally identified with the isotropic bulk values. For food foams the values of σ_b and ρ_b are not known. The value of ρ_b depends on the nature of the processing history in which various reactions may occur, typically taking on values in the range 900 to 1300 Kg m⁻³ for

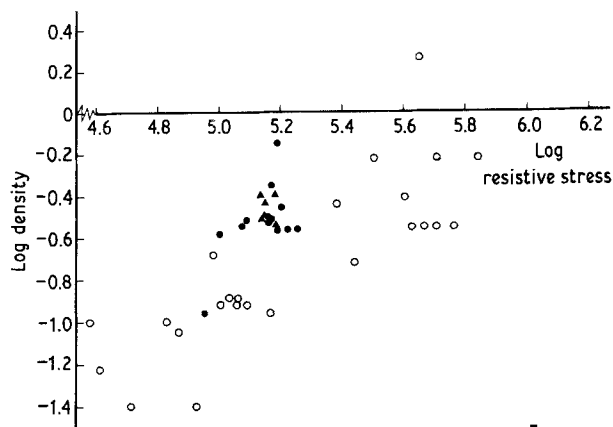


Figure 8 The resistive stress (Equation 4) as a function of the foam bulk density on logarithmic axes. ○, maize grits; ●, wheat starch; ▲, maize starch; ■ plastic foam.

unfoamed maize. Measurements of ρ_b and σ_b for the various food foams would allow fitting of the data to Equation 5. It is however clear that the mechanical property and the density vary within each foam specimen.

4. Conclusions

The results of structural and mechanical characterization of some food foams show the diverse properties compared with many synthetic foams. The expansion increased with increasing die pressure and die temperature. The porosity of the foam as judged by the number of pores or the pore size is not uniquely related to the expansion or the mechanical work input as indicated by some previously published results. The influence of the foam surface is apparent in foams of large pores giving rise to small pores near the surface layer. The pore size distribution tends to be narrower when the foam pores are small relative to the specimen size. The resistance of the maize foams to crushing was less than that of starch, wheat flour or plastic foams for the same impact energy, irrespective of density or pore characteristics. This indicates the influence of the wall properties which are not easily characterized and which depend on processing history.

The strain of extrusion cooked foams increased with impact energy reaching a maximum value corresponding to gross fracture of the specimens. Plastic foams require much more energy to deform to the same extent and no maximum strain was observed in the present experiments. At low strains the resistance increased almost linearly with bulk density with the exception of the plastic foam. Further characterization of the wall material is needed to find how the normalized stress scales with the normalized density for food foams. The effect of the pore size distribution is to cause local variations in the relative density. Complementary investigations of the fracture toughness would enable direct numerical comparison with other solid foams, at the same time simulating another aspect of their texture.

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