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Anisotropic polyurethane foam with Poisson's ratio greater than 1

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Anisotropic polymer foams have been prepared, which exhibit a Poisson's ratio exceeding 1, and ratios of longitudinal to transverse stiffness exceeding 50. The foams are as much as 20 times stiffer in the longitudinal direction than the foams from which they were derived. The transformation process involved applying to open-cell polyurethane foam an axial strain of 25 to 45%, at a temperature above the softening point, followed by cooling under axial strain.

1. Introduction

A cellular material is one made up of an interconnected network of solid struts or plates which form edges and faces of cells. It may be viewed as a composite consisting of a solid phase and empty space or a fluid phase such as air. Cellular solids have served structural roles in nature as honeycombs, bone and coral skeletons, for millions of years. Synthetic cellular solids have been developed only recently for various applications, and their potential is far from exhausted. Cellular solids, depending on microstructure, can be very efficient in terms of optimizing strength and stiffness with respect to weight. Foam materials have often been called "nature's equivalent of the I-beam" [1], and are commonly employed in cushioning, insulating, padding and packing, and as the core for stiff, lightweight sandwich panels. Further development of cellular solids may be pursued based on control of the microstructure.

Poisson's ratio is one of the mechanical properties of a material: it is defined as the negative of the lateral strain divided by the axial strain for a bar under axial load. All commonly known cellular materials (natural as well as synthetic), have a convex cell shape and exhibit a positive Poisson's ratio, typically 0.3 ± 0.1 for synthetic foams nearly zero for cork [2]. Moreover, ordinary materials without pores also exhibit positive Poisson's ratios, e.g. 0.5 for rubbers, 0.33 for aluminium, and 0.27 for most steels. Such materials undergo a lateral contraction in response to an axial stretch, and a lateral expansion when subjected to axial compression.

The theoretical allowable range of Poisson's ratio for isotropic materials in three dimensions is -1 to 0.5 as demonstrated by energy arguments [3]. An isotropic material with negative Poisson's ratio, however, was not believed to exist until recent work by Lakes [4]. The fabrication was achieved through a transformation of the cell structure from a convex polyhedral shape to a concave shape. These types of foam samples having a negative Poisson's ratio have been termed "re-entrant" due to their macrostructural appearance and behaviour. Prior experiments in preparing and studying re-entrant polyurethane foam (Scott industrial foam) [4, 5, 6], silicone rubber foam [5] and metal foam [4, 5, 7] dealt with open-cell foam. Different techniques were used for each of these materials.

In this study, Poisson's ratios exceeding one were achieved, combined with substantial anisotropy in stiffness. This behaviour was achieved by transforming the foam to achieve a permanent axial deformation via a combination of heat treatment and stretch. Scott Industrial foam was used; it is similar to the foam used in earlier studies of creation of negative Poisson's ratio foam [4, 5, 6].

2. Experimental procedure

2.1. Rationale

The Scott Industrial foam used in this study is a green polyurethane foam which has on average 65 pores per inch (p.p.i). Foam of this type, both 65 p.p.i and 25 p.p.i were used successfully in earlier transformations which gave rise to negative Poisson's ratio foam [4]. In particular, a minimum value of ν (-0.7) was achieved by transformation using a triaxial permanent compression procedure at 170 °C for 17 min [6]. Based on the kind of nonlinearity observed in the conventional (as-received) foam, it was considered likely that large Poisson's ratio values, greater than one, could be achieved by a different sort of transformation process involving tension rather than triaxial compression. Specifically, in conventional Scott Industrial foam, Poisson's ratio ν increases rapidly under $25 \sim 45\%$ tensile strain, with a maximum of $\nu = 0.55$ at $\varepsilon = 45\%$ [6]. Any further increase in strain results in a gradual decrease in Poisson's ratio from its peak value. It was therefore decided to produce permanent transformation strain from $25 \sim 45\%$, since

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this region in the nonlinear behaviour [6] produces a rapid change in Poisson's ratio with increasing strain.

2.2. Materials

Polyurethane foam [Scott Industrial foam of density $\rho = 0.03\text{gcm}^{-3}$, 65 pores per inch (p.p.i) corresponding to l (length of cell rib) = 0.4 ± 0.03mm], was obtained from Foamade Industries, Auburn Hills, MI, USA. The foam is reticulated with an open cell structure. The foam was provided in 2m lengths with a 5×5cm square cross-section. This material was then cut into lengths for specimens. We remark that the density of the solid polyurethane phase is $\rho_s = 1.05 \sim 1.25\ \text{g cm}^{-3}$ [8]. The specimens were made geometrically similar so that changes in strain rate with time would be similar for all samples.

2.3. Specimen preparation

The foam samples were cut into bars with dimensions of $5 \times 5 \times 30$ cm. Holes were punched through two opposite sides of the foam, 5 cm from each end. Two rods of 12.7 mm diameter were pushed through these holes and the specimen was mounted, under tension, to a constant-strain jig. The oven was preheated to 30 °C higher than the predetermined temperature (170°C) to compensate for a drop in temperature due to placement of the test jig. The samples were heated to a temperature in the range of $165 \sim 175$ °C (measured via a mercury thermometer) for 17 min, as described in earlier studies of negative Poisson's ratio materials [4, 6]. The foam was then cooled to room temperature and the permanent strain was evaluated from dimensional measurements with a micrometer.

2.4. Mechanical testing

Studies of elastic behaviour in tension and compression were performed on specimens with four values of initial permanent axial strain: 0% (conventional or control), 25%, 35%, and 45%. Following procedures similar to those used in a prior study of conventional and re-entrant foam [6], the present foams were studied over a range of testing strains. Three experiments with each strain value of foam were performed.

Fiduciary marks were made for displacement evaluation using a fine, indelible marker near the centre of each specimen; the marks were made sufficiently far from the ends that the strain field would be uniform by virtue of Saint Venant's principle. These gauge lines were drawn in the middle of one side of the specimen; 4 cm apart in the longitudinal direction and 2 cm apart in the transverse direction. Another set of lines for use in measuring both longitudinal and transverse strains was drawn on an adjacent face of the sample. Incremental differences in the spacing of the gauge lines were measured to calculate longitudinal and transverse strains to infer Poisson's ratio of the foam. The top of each marked line was used as a reference point for measurement to minimize error. Although the measurements were taken with care, the results showed errors at small strains. This can be attributed in part to the limiting resolution of one's eye (0.1 mm) in comparison with the size of the open cell structure of the foam specimen and in part the size of the ink marks. The calculated Poisson's ratio values had higher error for lower strain due to uncertainty in measured displacement; these errors were plotted as error bars in Fig. 1.

In tension studies, increments of 1 cm of axial displacement were applied, with dead weights suspended from the end of the specimen, until the specimen failed. Dimensional measurements of longitudinal and axial displacements based on the fiduciary marks described above were taken for each increment. Engineering stress–strain curves were plotted from the load–displacement data. Compression studies were also conducted with dead weights, using 15-cm long test sections cut from the middle of the sample. All sections were made geometrically similar so that any Euler buckling would occur at the same stress. The load giving rise to buckling was considered as the critical buckling load and the corresponding strain was calculated from the inferred Young's modulus. Measurements were terminated when any observable buckling or inhomogeneous deformation occured.

The modulus of elasticity of the material at small strains can be taken as the tangent modulus, E_t. In the tensile tests, several data points were obtained for each sample's stress–strain curve. The tangent modulus, E_t, was taken between the origin and the first data point. The secant modulus, E_s, was found as the slope between the origin and the last data point. For small deformation range available in transverse specimens, data acquisition for tangent modulus was difficult due to a decrease of relative resolution. This problem was solved by using a polynomial function for curve fitting. Each stress–strain curve was considered as a quadratic function $\sigma = E_t\varepsilon + A\varepsilon^2$ and the value E_t from the curve fit was used as tangent modulus.

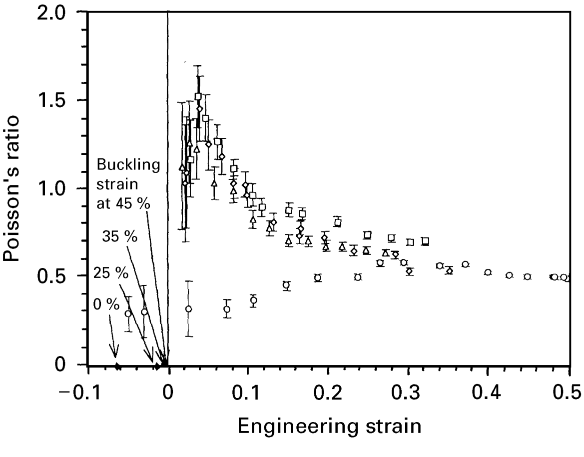

Figure 1 Poisson's ratio versus engineering strain for control and transformed Scott Industrial foam samples; solid diamond represents internal buckling strain; Poisson's ratio not measured. Circles, squares, diamonds and triangles represent permanent strain values of 0% (control), 25%, 35%, and 45%, respectively.

2.5. SEM evaluation of foams

Structure of specimens of foam were examined via scanning electron microscopy (SEM) at a magnification of ×80. A Hitachi "Nature" SEM (Model No. S-2460N at Central Electron Microscopy Research Facility) was used for the study; this instrument allows a variable pressure inside the specimen chamber. An accelerating voltage of 3 keV was used to take micrographs of the samples which were sputter-coated with Au–Pd.

3. Results and Discussion

The Poisson's ratios versus engineering strain for the control and transformed foam samples with 25, 35 and 45% permanent axial strains are plotted in Fig.1. Results for both adjacent lateral surfaces of samples agree within the error bars. Therefore only data points from one surface are plotted in Fig.1 to reduce the complexity of the figure. The control specimens exhibit a Poisson's ratio near 0.3 for small tensile strain. Poisson's ratio exceeds, then approaches, a value of 0.5 in tension at large strain. A Poisson's ratio of greater than 0.5 does not violate any physical laws, but is a consequence of anisotropic behaviour due to the large strains causing alignment of cell ribs. The transformed foam samples exhibit large Poisson's ratios near 1.1 for small tensile strains. At large strain, Poisson's ratio for control as well as transformed foam approached a value of about 0.6. A maximum value of Poisson's ratio was observed at a strain value around 0.04. Failure of the foam was by tearing near the supports. Where no error bars are visible in Fig.1, the uncertainty is smaller than the size of the data point.

The Poisson's ratio in the transverse (perpendicular to the load used to create permanent axial deformation) direction was difficult to measure owing to the smaller size of these specimens. Large tensile strains were needed in these tests since the transverse specimens were small, so that displacement for a given strain was smaller than in the case of the larger longitudinal specimens. Transverse plane Poisson's ratio values of transformed foam were measured to be approximately 1.5 at an axial strain of 0.5; by contrast the Poisson's ratio of the control material at the same large strain was 0.5. The Poisson's ratio of the control material in the transverse plane was identical to the Poisson's ratio in longitudinal tests, confirming the isotropy of the control (unprocessed) foam.

Buckling in compression is an internal buckling (Fig. 2) associated with inhomogeneous deformation rather than Euler column buckling, and this buckling was observed even in very short specimens. Compressive strain for buckling decreases with increasing permanent strain of transformation. This behaviour can be explained by the increase in stiffness of samples transformed at higher permanent strains. The stiffness increase is due to cell rib alignment, but the collapse strength, governed by cell rib buckling, does not change much; consequently the strain associated with material buckling decreases with transformation permanent strain. Band instability due to microbuckling has been seen previously in the plateau region of conventional (control) foams [9]. Although those bands were of low contrast, presently observed specimen buckling is more macroscopic and more easily observable.

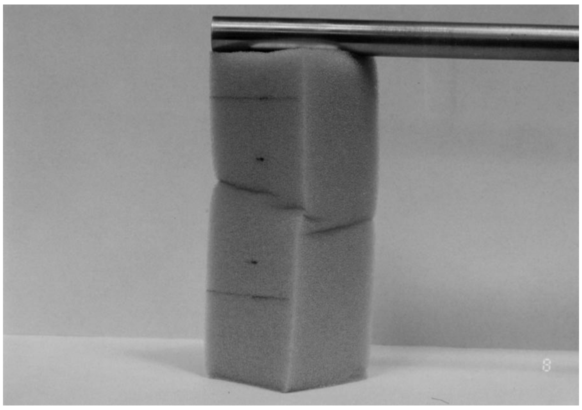

Figure 2 Demonstration of the buckling in the transformed Scott foam under compression.

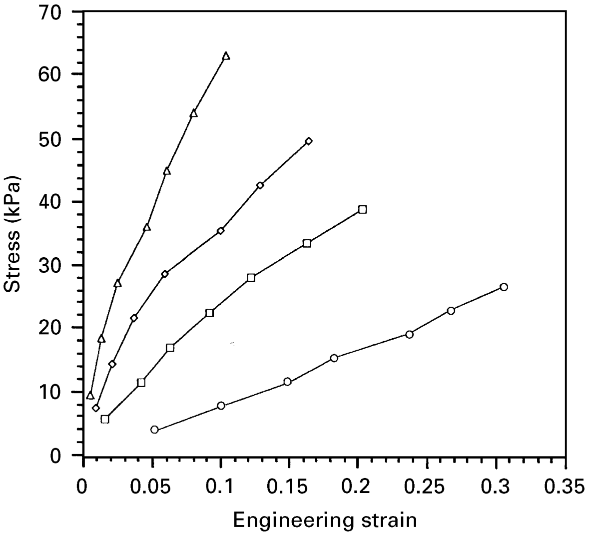

Figure 3 Engineering stress versus strain curve for control and transformed Scott foam samples in longitudinal direction. Circles, squares, diamonds and triangles represent permanent strain values of 0% (control), 25%, 35%, and 45%, respectively.

Stress–strain curves for load in the longitudinal (permanently strained) direction are plotted in Fig. 3. Specimens with higher degrees of permanent strain, exhibited a higher stiffness and a lower strain value at failure. This phenomenon may be due to the fact that the highly stretched foam was already near the limitation of maximum strain for the foam material. Longitudinal tangent moduli, E_t, and secant moduli, E_s, are plotted versus permanent transformation strain in Fig. 4. The longitudinal tangent modulus increases rapidly with the larger permanent strain values. These results, as inferred from the previous graph, show that the foam becomes stiffer in the axial (strained-tensional) direction as the permanent strain value of transformation increases.

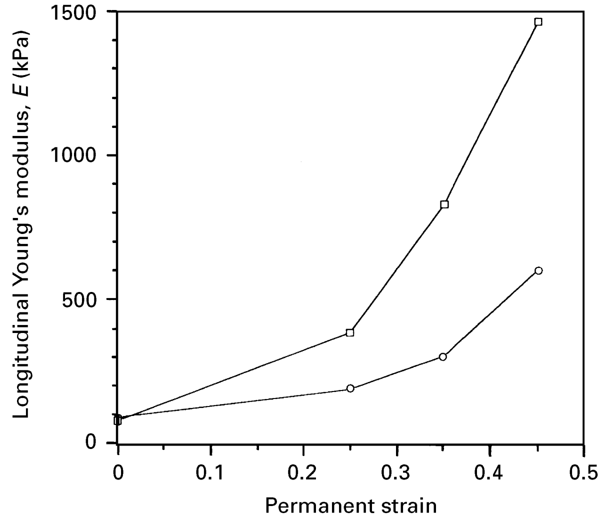

Figure 4 Longitudinal Young's modulus versus permanent strain for control and transformed Scott foam samples. Circles and squares represent secant and tangent modulus, respectively.

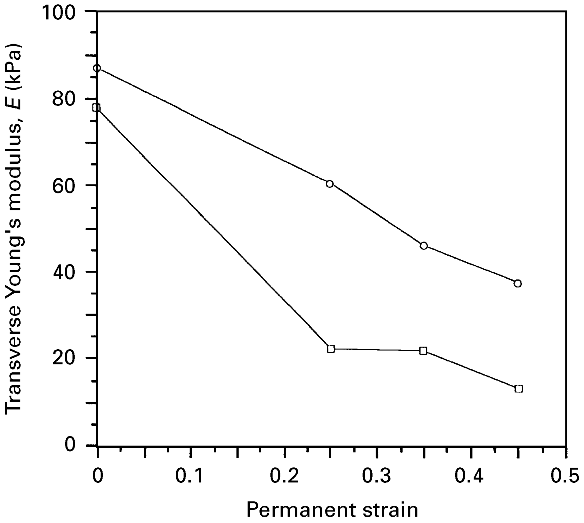

Figure 6 Transverse Young's modulus versus permanent strain for control and transformed Scott foam samples. Circles and squares represent secant and tangent modulus, respectively.

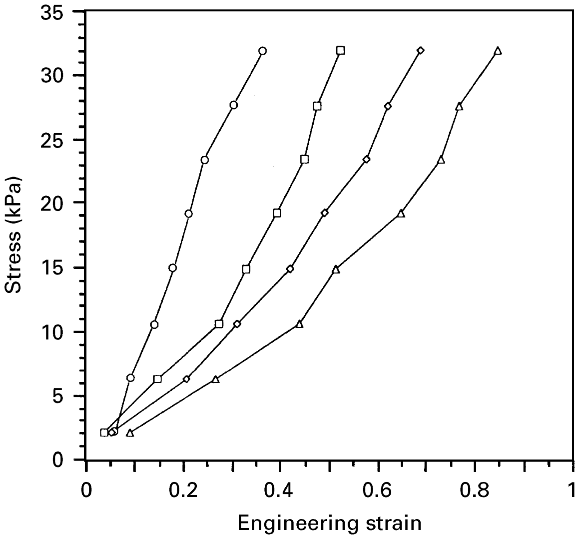

Figure 5 Engineering stress versus strain curve for control and transformed Scott foam samples in transverse direction. Circles, squares, diamonds and triangles represent permanent strain values of 0% (control), 25%, 35%, and 45%, respectively.

Fig. 5 shows the engineering stress–strain curves for tests measuring transverse sections of control and transformed foams. The transformed foam is anisotropic: it is much stiffer in the longitudinal direction than it is in the transverse direction, as can be seen by comparing with Fig. 3. Secant and tangent moduli for the transverse direction calculated from the data in the previous graph are displayed in Fig. 6. Both moduli rapidly decrease with higher values of permanent strain in the transformed foams. The transformed foam is considerably more compliant for tension in transverse directions than for the longitudinal direction (the direction of the permanent stretch).

Fig. 7 shows a micrograph of a control foam sample. The cells in this foam are rather round and symmetrical. It can be observed that cell ribs have a triangular cross-section. In comparison to the cellular structure in the control foam, the ribs of the transformed foam are elongated and aligned, as shown in Fig. 8. This structure accounts for the stiffness and small strain range observed in highly transformed specimens, since aligned ribs deform by stretching more than by realignment and bending. Moreover, the structure revealed by SEM is consistent with the observed elastic anisotropy.

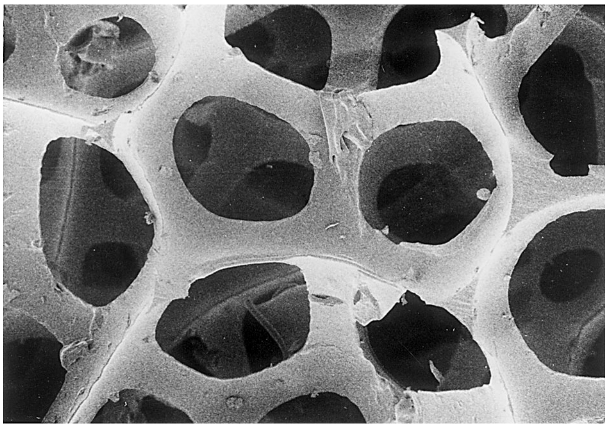

Figure 7 Scanning electron micrograph of conventional Scott Industrial foam. Magnification ×80, accelerating voltage 3 keV.

Foams which were transformed by permanent uniaxial stretching exhibited increased axial stiffness (by as much as a factor of 20), larger Poisson's ratio in excess of 1, and orientation of the microstructure. Poisson's ratios exceeding 1/2 are permissible in anisotropic materials. Indeed, hexagonal honeycombs can exhibit Poisson's ratio of 1, and if they have oriented hexagonal cells, greater than 1, in certain directions [2].

Materials with $\nu > 1/2$ in both transverse directions have been termed "stretch densifying" in the terminology of Baughman and Galvao [10], who found certain (anisotropic) crystals to exhibit such a property. The present foams exhibit a controllable stretch-densifying property, achieved by processing. The present anisotropic foams are in contrast to the re-entrant foams

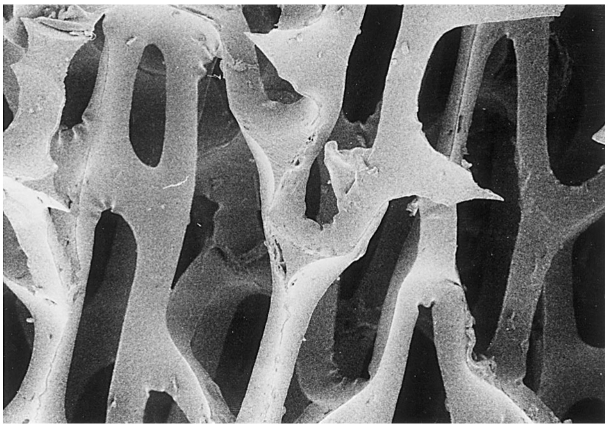

Figure 8 Scanning electron micrograph of transformed Scott Industrial foam, 45% permanent strain, Magnification × 80, accelerating voltage 3 keV.

developed by one of the authors [4]; those foams were produced by triaxial permanent compression, and they exhibited reduced Young's modulus, negative Poisson's ratio, and an isotropic re-entrant microstructure.

4. Conclusions

1. The Poisson's ratio of transformed foam was about 1.1 at small tensile strain, increasing to around 1.5 at a strain of 0.04, then decreasing to about 0.6 at large strain.

2. Compression experiments at small loads disclosed an internal banding form of buckling in transformed foams.

3. The transformed foam is stiffer in the axial (strained-tensional) direction, by a factor of up to 20, and it is more compliant in the transverse direction than the control foam.

4. Transformed polyurethane foam exhibits structural alignment of the cell ribs. This structure accounts for the mechanical anisotropy observed in highly transformed specimens.

Acknowledgements

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