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Foams as 3D perforated systems: An analysis of their Poisson's ratios under compression

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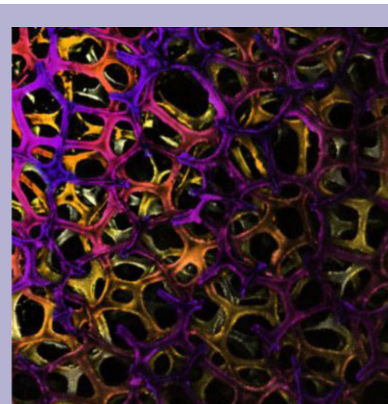
Using experimental data, it is shown that the Poisson's ratios of standard (untreated) open cell polyurethane foam vary when loading in different loading directions, since foam is inherently asymmetric and anisotropic. The loading direction which is in plane orthogonal to the rise direction of the foam constantly exhibited the most negative Poisson's ratio across foam samples of different types, even at moderate compressive strains. It was also shown that although the foam may become auxetic at very high values of compressive strain, it shows an incremental negative Poisson's ratio at moderate compressive strains. The results obtained are discussed in light of the deformation mechanisms, which have been proposed in literature to explain negative Poisson's ratios in foams. The effects of changing loading direction on the mechanical response of the foam are highlighted.



An image of the symmetrical face of a foam cube, taken using a confocal microscope at 4× magnification.

1 Introduction Sparked by the pioneering work of Lakes [1], Wojciechowski [2], and Evans [3], auxetics have attracted an increasing interest over the past decades [4–11]. Auxetic materials present the counter intuitive property of expanding laterally when a uniaxial load is applied, that is, they have a negative Poisson's ratio (PR) [12–14], where the PR is the negative ratio of the transverse and axial strains. This particular property imparts numerous advantageous characteristics to auxetic materials, including higher indentation resistance, which increases applicability in products such as body armor [15], and pores which dilate upon the application of stress, which makes the materials perfect for use in smart filters and bandages [16–19]. In addition, auxetic materials, as opposed to conventional materials, are also known to form domed structures readily (synclastic curvature). In fact, improved mattresses and cushioning structures could ideally be constructed of auxetic materials such as auxetic foams [20–22]. Composite materials, which exhibit auxetic behaviour have also been proposed [23, 24].

Foams have been a significant contributor to the development of the field of auxetic materials [2], and have been the subject of numerous extensive studies. Auxetic foams can be produced by treating 'normal foams' (i.e. as produced by most manufacturers) using specific thermo-mechanical [1] or chemo-mechanical [25] treatment methods. Auxetic foams have also been the subject of deformation mechanism studies [26].

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Standard polymeric foam has been shown to exhibit slight auxetic behaviour at high compressive strains [27–31]. Such behaviour, as in all auxetic materials, is expected to be the result of a scale independent [3, 32] combination of geometrical conformations, together with specific deformation mechanisms. The exact structure and deformation mechanism of foam remains a topic of hot debate. Foam, which can be considered as a three-dimensional cellular solid defined as a set of ligaments connected through joints, has been modelled via numerous techniques including numerical techniques [33–36], tomography [36, 37] and prototyping [38]. Alternatively, these structures may be defined as a series of perforations or voids in a continuous solid volume [39–42]. It has already been shown that treating an idealized cellular solid as a three-dimensional arrangement of voids is sufficient to accurately predict the physical characteristics of that solid [40]. We propose that foam can also be studied in this manner, with the important difference that the voids in a normal foam solid are elongated, rather than being spherical.

During the manufacturing process of open cell foams carbon dioxide normally forms at nucleation sites. This, coupled with the internal stresses caused by the foam mold, causes the voids inside the foam structure to become asymmetric, as they adopt an elongated shape. [43] This makes foam highly anisotropic [44]. An idealized model of the foam structure is presented in Fig. 1a.

This inherent asymmetry causes the six faces a foam block to belong to one of two distinct face types. Four of the cube faces exhibit elongated elliptical pores, whereas the two remaining faces exhibit more circular pores. The four faces with elliptical pores will be referred to as the rise faces. The other two faces, which have circular pores, will be referred to as the symmetrical faces. The elliptical shape of the pores in the rise faces gives these faces asymmetric properties. In fact, these faces can be loaded in two directions: parallel to the elongation (parallel to the rise direction), or orthogonally to the elongation. The loading direction, which is in-plane orthogonal to the rise direction will be referred to as the transverse loading direction. The differences between the faces and loading directions have been summarized in Fig. 1b. Furthermore, a photograph taken using a confocal microscope, which clearly illustrates the shape of the foam structures, has been provided in Fig. 1c.

Previous studies on untreated foams have either reported the PR going to zero [45, 46], or being slightly negative [27–30]. The results presented here resolve the differences between these studies by proposing that the discrepancies are probably attributable to the fact that the effect of the loading direction was not considered in the previous studies. We also show that the loading direction of a foam cube was found to have a much greater influence on its PR than other intrinsic properties of the sample, such as its nominal number of pores per inch (PPI), or chemical composition. Finally, we explain this behaviour by providing a probable mechanistic interpretation.

2 Experiments and calculations

Foam samples were cut into 5 cm cubes using a worktop thermo-cutter. Three faces on each cube were marked consistently with eight marks for pattern recognition, as required for analysis through the MessPhysik Video-Extensometer software.

Subsequent measurements were performed by tracking these markings. Three measurements of the width of the foam face, and one measurement of the length of the same face were performed during the compression experiments.

The three width measurements were averaged into a single value after ensuring that all the three individual

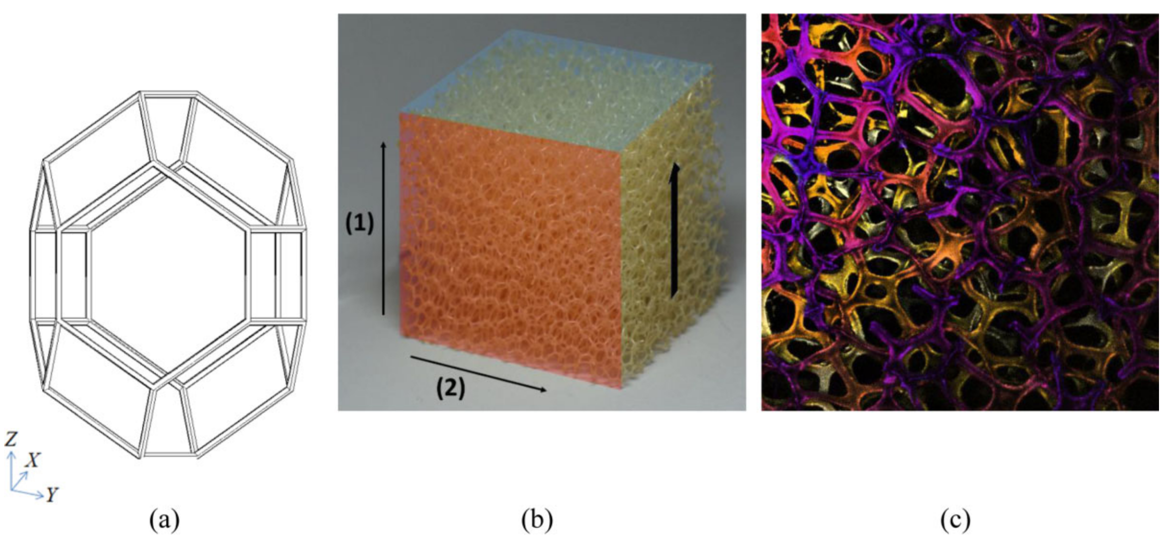

Figure 1 (a) An example of an idealized model of the elongated voids in real foams. (b) A photograph of a foam sample cube. One of the rise faces is shown in red. The symmetrical face is shaded blue. The large black arrow indicates the rise direction. The rise (1) and transverse loading (2) directions are shown by the thin arrows. (c) An image of the symmetrical face of a foam cube, taken using a confocal microscope at 4× magnification.

readings followed the same trend. Black coloured foams were marked with white markings and light coloured foams were marked with black markings. The three faces were chosen in such a way that they all had one corner of the foam cube in common. This ensured that compression tests were performed once for each of the three possible loading directions. The identities of the faces were determined by observing the elongation of the foam cells visually.

The samples were loaded into a Testometric Tensile Loading machine, using compressive plates. The foam blocks were compressed at a constant rate of 5 mm min^{-1} up till 75% axial strain. Transverse and axial lengths of the foam were measured using an appropriately calibrated MessPhysik Video-Extensometer. The tests were repeated three times for each face, for a total of nine tests per foam cube.

During the compression experiment, length and width readings were taken every 0.2 s. Axial strain, transverse strains and PRs were then calculated for each of these data-points.

The overall PR at 75% axial strain was calculated as follows:

$$\nu = -\left(\frac{w_{75} - w_{\mathrm{o}}}{w_{\mathrm{o}}}\right) \cdot \left(\frac{h_{\mathrm{o}}}{h_{75} - h_{\mathrm{o}}}\right), \quad (1)$$

where w_{75} is the width at 75% axial strain, w_{o} is the original width, h_{75} is the height at 75% axial strain, and h_{o} is the original height.

The transition point was taken to be the first significant observation of a decrease in transverse strain (compared to the previous readings) as the axial strain continued to decrease. The PR from transition point to 75% axial strain was calculated as follows:

$$\nu = -\left(\frac{w_{75} - w_{\mathrm{TP}}}{w_{\mathrm{TP}}}\right) \cdot \left(\frac{h_{\mathrm{TP}}}{h_{75} - h_{\mathrm{TP}}}\right), \quad (2)$$

where w_{TP} is the width at the transition point, and h_{TP} is the height at the transition point.

3 Results and discussion

3.1 Mechanical testing As expected, upon application of low compressive axial strain the standard foams tested started to expand laterally, that is, acting in a conventional manner. At higher axial compression a transition point was encountered beyond which the foam started to contract as the compressive strain increased, implying a negative incremental PR. By the end of the experiment at 75% axial strain in compression, all the foam samples tested presented negative transverse strains, and therefore a negative overall PR, for at least one loading direction. This implies that the instantaneous PR of the foam decreased as the compressive axial strain increased. Furthermore, standard open cell polyurethane foam may exhibit auxetic behaviour even at moderate compressive strains for specific loading conditions.

The general trend in behaviour observed is exemplified in Fig. 2, while a table listing numerical results is given in Table 1. Further results, which are not significantly different from those presented in Table 1 are listed in the Supporting Information. Part of the results in Table 1 are illustrated in Fig. 3.

An analysis of Fig. 3 shows that even though the observed behaviour during compression did vary with the nominal PPI of the foam, there seemed to be no linear correlation or overall trend. This will be the subject of further studies. There also seemed to be no discernible overall difference in behaviour between the chemical compositions of the foam samples (Table 1 and Supporting Information).

On the other hand, the direction of loading of the foam samples was shown to have significant effects on the resulting measured parameters. For each of the three different loading directions, measurably different PRs were observed for each of the corresponding faces, even though in each of the faces the transition point was encountered between 20 and 30% axial compression.

In all the experiments performed, loading in the transverse direction caused the highest degree of auxetic behaviour. Inversely, the rise loading direction constantly expressed the least negative (or most positive) PR, and the latest transitions from conventional to auxetic behaviour. The symmetrical face was found to have values between those encountered for the rise and the transverse loading directions. When considering the average transition point of the foam, the transverse loading direction showed an inclination to present auxetic behaviour at lower values of axial compressive strains (Table 1).

The average overall PR for loading in the transverse direction was found to be −0.050, with the most negative

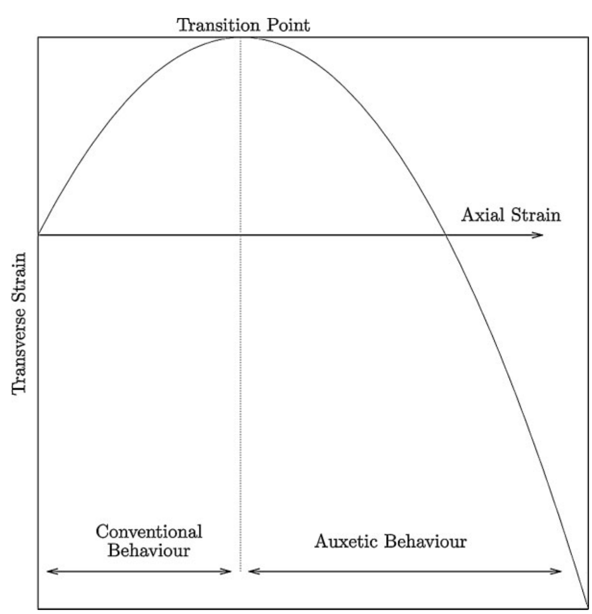

Figure 2 A simplified strain–strain graph, given here for illustration purposes. The direction of the x-axis is inverted.

Table 1 Parameters measured for five foam samples, separated by the PPI of the sample and the compression direction. Each data point is the average value of three compression experiments. Numbers in brackets are the calculated standard deviations for the different repeats of the same experiment.

foam	PPI	loading direction[a]	overall PR at 75% axial strain	transition point (axial strain)	PR from TP[b] to 75% axial strain
ester	10	rise	0.006	−0.201	−0.044
			(0.008)	(0.017)	(0.005)
		trans.	−0.044	−0.200	−0.086
			(0.004)	(0.006)	(0.003)
		symm.	−0.036	−0.276	−0.082
			(0.005)	(0.015)	(0.006)
	18	rise	0.011	−0.285	−0.063
			(0.022)	(0.005)	(0.010)
		trans.	−0.033	−0.240	−0.080
			(0.004)	(0.007)	(0.004)
		symm.	−0.006	−0.271	−0.055
			(0.006)	(0.004)	(0.001)
	30	rise	0.024	−0.266	−0.040
			(0.006)	(0.015)	(0.002)
		trans.	−0.055	−0.200	−0.097
			(0.004)	(0.004)	(0.004)
		symm.	−0.042	−0.229	−0.098
			(0.006)	(0.005)	(0.009)
	38	rise	−0.009	−0.230	−0.065
			(0.006)	(0.007)	(0.002)
		trans.	−0.045	−0.247	−0.093
			(0.005)	(0.008)	(0.002)
		symm.	−0.002	−0.246	−0.053
			(0.006)	(0.009)	(0.002)
	40	rise	0.003	−0.268	−0.055
			(0.010)	(0.018)	(0.008)
		trans.	−0.045	−0.215	−0.091
			(0.008)	(0.009)	(0.007)
		symm.	−0.021	−0.253	−0.062
			(0.002)	(0.011)	(0.003)
ether	30	rise	0.050	−0.416	−0.017
			(0.009)	(0.101)	(0.011)
		trans.	−0.051	−0.209	−0.085
			(0.005)	(0.002)	(0.002)
		symm.	−0.039	−0.253	−0.078
			(0.007)	(0.020)	(0.003)
	50	rise	0.023	−0.291	−0.039
			(0.008)	(0.015)	(0.003)
		trans.	−0.035	−0.252	−0.077
			(0.005)	(0.012)	(0.003)
		symm.	−0.023	−0.284	−0.066
			(0.007)	(0.012)	(0.003)

[a]"trans." stands for the transverse loading direction and "symm." stands for loading the symmetrical face.
[b]TP stands for Transition Point.

value being that of −0.055 for the PPI 30 polyester foam. Conversely, the average overall PR for loading in the rise direction was positive, with a value of 0.016. The overall PR when loading the symmetrical face was once again negative at 75% strain, with an intermediate value of −0.030. The transverse loading direction constantly exhibited the most negative incremental PR, with the most negative value being that of −0.097.

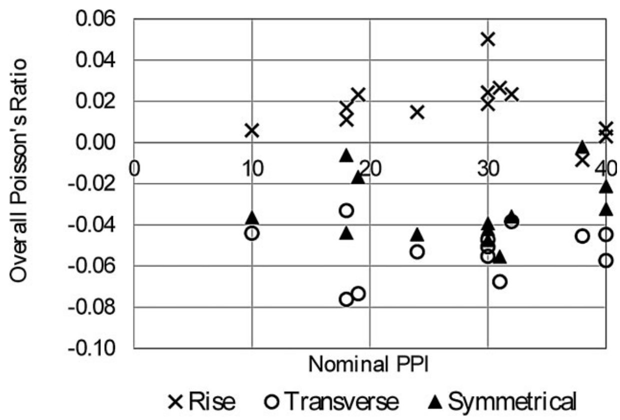

Figure 3 A plot of the PR calculated at 75% axial strain in compression versus the nominal PPI of the foam samples. Note that the least negative ratios are obtained for the rise loading direction, while the most negative values are obtained for the transverse loading direction.

These findings are corroborated by the findings of Babaee et al. [40], who have studied idealized 3D voids. Babaee et al. have shown that the properties of idealized auxetic 3D structures may be switched or fine-tuned just by applying a stimulus to alter their initial architecture.

3.2 A discussion on deformation mechanisms As shown previously in Fig. 1a, the apices of the elongated voids are denser in plastic material, making them rigid when compared to the rest of the structure. Simultaneously, a ring of plastic material forms roughly around the equator of the elongated voids. When compressed, the foam may start to deform by bending of the ribs, acting in a conventional manner. However, beyond a certain threshold, the ribs around the void adopt a re-entrant conformation. Compressing such a conformation further would induce the elongated void to pull itself in, leading to the observed incrementally negative PR. This mechanism is different from that proposed by Babaee et al. [40] for a hypothetical 3D structure. Alternatively, the observed auxetic behaviour may be caused by the apices of the elongated cells rotating in response to the additional compressive strain. This behaviour, which is similar to the rotating mechanism [47] acting out-of-plane, would induce the cell to curl in on itself, again leading to auxetic character. This mechanism is analogous to that being proposed by Shen et al. [39], who show that a perforated material containing perfect 3D voids deforms by a rotating cubes mechanism to give a negative Poisson's ratio.

Both these studies [39, 40] were based on idealized solids. A recent paper by Taylor et al. [48] has shown, both through modelling and through experiment, that periodic 2D geometries with an alternating pattern of elongated pores can exhibit negative Poisson's ratios, the extent of which can be tuned by the degree of elongation of the pores. These findings further corroborate the results presented here.

Furthermore, real foams also have numerous imperfections. The ratio between the size of their apices and the size of their ligaments also tends to be larger compared to idealized solids. This inevitably leads to their measured PR being quite different from that of the idealized structures.

Before concluding, it is important to emphasise that although this finding that standard foam may exhibit auxetic characteristics at moderate compression conditions, the known processes for the manufacturing of auxetic foam do not become redundant since some applications could require foams with auxetic properties, which are manifested in tension or at very low compressive strains. Furthermore, it is important to note that the foams produced from these conversion methods are normally more auxetic than the standard foams under compression. It should also be highlighted that the results presented here postulate a powerful link between the cell growth during the manufacturing process of the foam, and the mechanical properties it exhibits. Therefore, by slightly altering the manufacturing process, the characteristics of the foam could be changed drastically. Even though untreated foams exhibit only slightly negative PRs, this should still stimulate research into the manufacturing procedure of 'normal foams'. Such research would be greatly facilitated by the unequivocal determination of the mechanism (or mechanisms) of deformation of untreated foams.

4 Conclusions The results of this study have shown that standard open cell polyurethane foam may exhibit auxetic behaviour even at moderate compressive strains for specific loading conditions. This could have great implications from a commercial point of view since it implies that the benefits one normally associates with auxeticity may be imparted by standard foams without the need of expensive pre-treatments.

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Supporting Information

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