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Auxetic Foams for Sport Safety Applications

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Abstract

Auxetic materials offer potential to be applied to sports safety equipment. This work reports quasi-static and impact testing of auxetic open-cell polyurethane foam - fabricated with a compression and heat treatment process - in comparison to its conventional counterpart. The foam was compressed to 70% of its original dimension along each dimension during the conversion process. Quasi-static compression testing confirmed the converted foam to be auxetic, with a Poisson's ratio of -0.08. Impact testing was performed for energies up to 5.6 J with an instrumented drop rig and high-speed video. Peak accelerations were ~3 times lower for the auxetic foams, because they prevented bottoming. This work has shown further potential for auxetic foam to be applied to sports safety devices. Future work should look to optimise foam selection and the conversion process, while comparing auxetic foam with existing materials and products.

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Keywords: Impact, protection, sport, Poisson's ratio, material

1. Introduction

Sports equipment designed to prevent the injuries that arise from impact events usually carries out aspects of energy attenuation and load distribution, while limiting accelerations and forces. These safety devices can include personal protective equipment or crash barriers, with foams often serving as the energy absorbing component [1]. The performance of these safety devices is typically assessed by simulating an impact and measuring their ability to reduce peak acceleration and/or force. Auxetic foams are innovative materials - with a negative Poisson's ratio - that

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offer potential for sport safety devices with better conformability, superior energy absorption and reduced thickness [2].

Previous work investigating the application of auxetic foams to sports equipment has focused on quasi-static characterisation [2] and low-energy impact performance [3]. The aim of this work is to further investigate the application of auxetic foams to sports safety devices. This paper will assess the ability of auxetic foam to attenuate peak acceleration for a range of impact energies, and discuss its potential applications for sport safety equipment.

2. Methods

Auxetic foam - fabricated by converting open-cell foam with a compression and heat treatment process [2-4] – was investigated alongside its conventional counterpart. Quasi-static compression was performed in a uniaxial test machine and Poisson's ratios were obtained by filming marks applied to the front face of the sample and then measuring their positions in the footage. A drop rig was used for impact testing, with performance based on the ability of the samples to attenuate impact acceleration. The adopted methodology was similar to that used by Allen et al. [3].

The starting foam was reticulated open-cell polyurethane, with 30 pores in^{-1} and a density of 26-32 kg/m^3 (Custom Foams, R30FR). To facilitate the conversion process a 143 x 143 x 143 mm foam sample was placed inside a lubricated compression mould of size 100 x 100 x 100 mm to achieve a tri-axial compression with a Linear Compression Ratio (LCR) of 0.7. LCR is defined as the ratio of the compressed to initial dimension. The mould was then put in an oven at 180°C for 30 minutes, following which the foam was removed and stretched gently by hand at room temperature. The foam was then returned to the mould and placed back into the oven for another 30 minutes. The process was repeated for a final time with the oven temperature reduced to 100°C for 30 minutes. Following conversion, the outer faces of the sample were removed to produce a 90 x 90 x 90 mm cuboid, which was then cut into three 30 x 90 x 90 mm samples. The density of the converted foam was 76–93 kg/m^3, comparable to the ethylene vinyl acetate copolymer foams typically used in football shin protectors [5]. Three unconverted samples of the same size were also cut from a monolith with the rise direction through the thickness.

Quasi-static compression was performed on the samples in a uniaxial test machine (Instron 3369, 50 kN load cell). Each cuboid was compressed to 50% strain at a rate of 10 mm/min, with load and extension recorded at 10 Hz. Young's modulus was obtained from linear regression of the mean stress-strain data up to 5% compression. The tests were filmed with a camera (JVC Everio Full HD) at a resolution of 1920 x 1080 pixels. The footage was used to locate temporal positions of four pin heads in the front face of the sample, using a bespoke tracking software utilising MATLAB (MathWorks). Poisson's ratios were obtained from linear regression of the mean true strain-strain data up to 5% compressive strain.

Impact tests were performed with a bespoke drop rig, fitted with a 2.27 kg cylindrical dropper with a flat face measuring 115 mm in diameter (Figure 1). Drop heights increased from 0.10-0.25 m in 0.05 m increments, providing impact energies of ~2-6 J. Each sample was tested once at each height. The dropper was fitted with a wireless accelerometer (Analog Devices, ADXL001-500) recording at 50,000 Hz, providing acceleration-time data for each impact (DTS SLICEWare Version 1.08.0475). The impacts were also filmed with a high-speed camera (Vision Research, Phantom V4.3) at 10,000 Hz, with a resolution of 448 x 128 pixels and exposure time of 97 µs. The footage was used to identify the frames corresponding to the start and end of contact between the sample and dropper, and the maximum deformation. Aligning peak acceleration with maximum deformation allowed the start and end of contact to be identified in the acceleration-time traces. The footage was also used to measure maximum deformation of the samples.

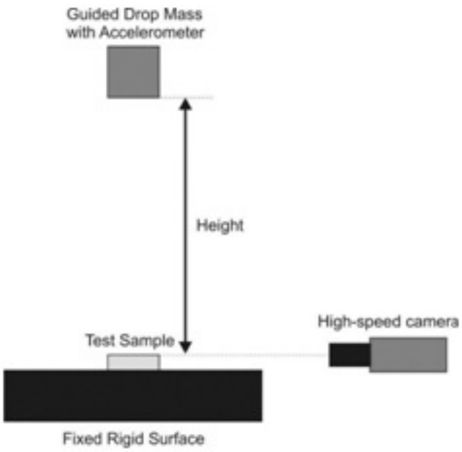

Figure 1 Experimental setup for impact testing

3. Results

Figure 2a shows the conventional foam exhibited classic foam stress-strain behaviour under quasi-static compression [6], with a relatively linear stress-strain relationship up to ~5% compression followed by a plateau region. The Young's modulus of the converted foam was around a quarter of its conventional counterpart and the corresponding stress-strain data remained relatively linear with no plateau region, in agreement with previous work on foams undergoing a similar conversion process [2-4]. Figure 2b shows quasi-static strain-strain data. The conventional foam had a Poisson's ratio of 0.43 and the converted foam was confirmed to be auxetic with a Poisson's ratio of -0.08. Note, the compressive stress-strain behavior of the converted foam shown in Figure 2a, confirmed to be auxetic in Figure 2b, cannot be generalised to all other auxetic structures. For example, simple cubic three-dimensional auxetic metamaterials display compressive stress-strain behavior similar to that of the unconverted (conventional) foam in Figure 2a [7].

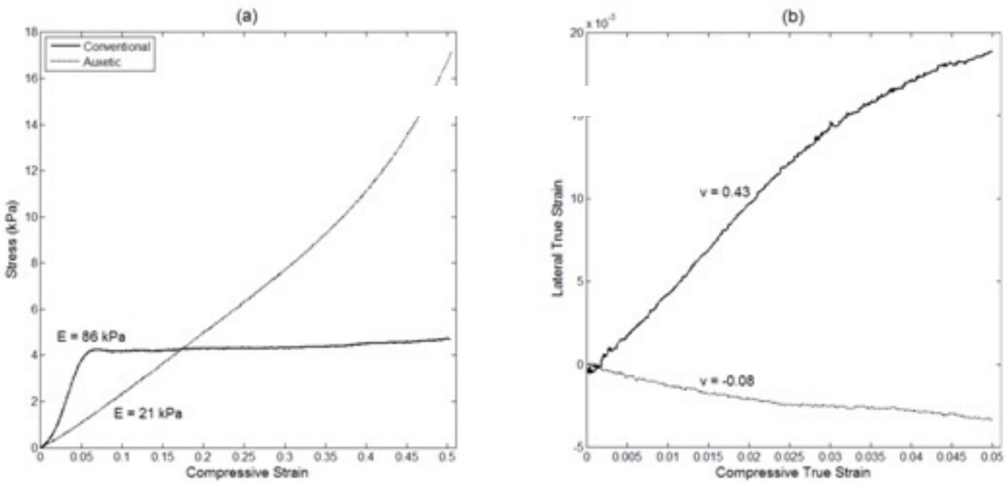

Figure 2 Mean quasi-static compression results for conventional and auxetic foam, a) stress-strain and b) true strain-strain up to 5% true compressive strain.

Figure 3 shows sample acceleration-time traces for impact energies of 2.2 and 5.6 J. Temporal accelerations increased with impact energy and contact times decreased. Acceleration-time traces for the axuetic foam had lower and less pronounced peaks.

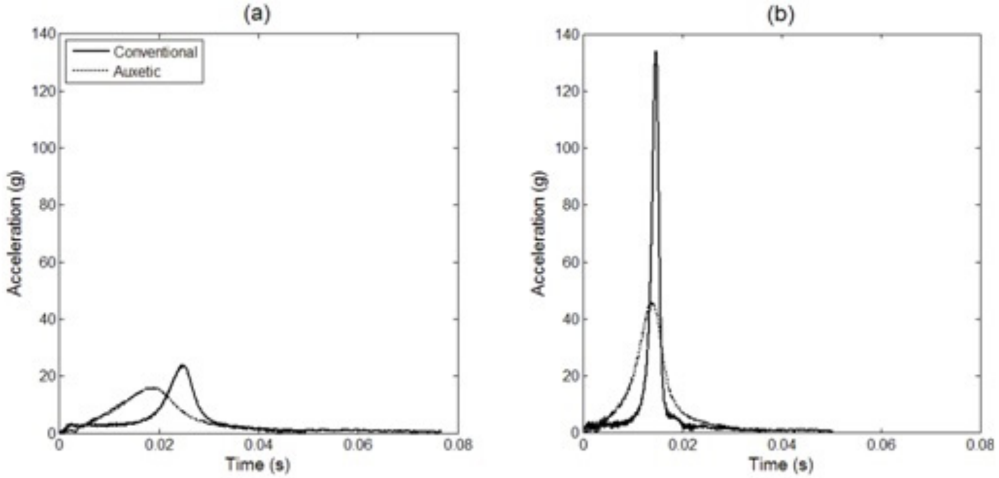

Figure 3 Acceleration-time data from impact testing, a) 2.2 J and b) 5.6 J.

Figure 4 shows peak accelerations normalised to the value obtained for the conventional foam at the lowest impact energy. At the lowest impact energy, peak accelerations were similar for both foams. Peak accelerations increased with impact energy, but the increase was significantly less pronounced for the auxetic foam. The higher energy impacts on the auxetic foams had substantially lower peak accelerations.

Figure 5 shows considerably higher maximum compressive strains for the conventional foam, with the images in Figure 5 showing these samples "bottoming out" for all but the lowest energy impact.

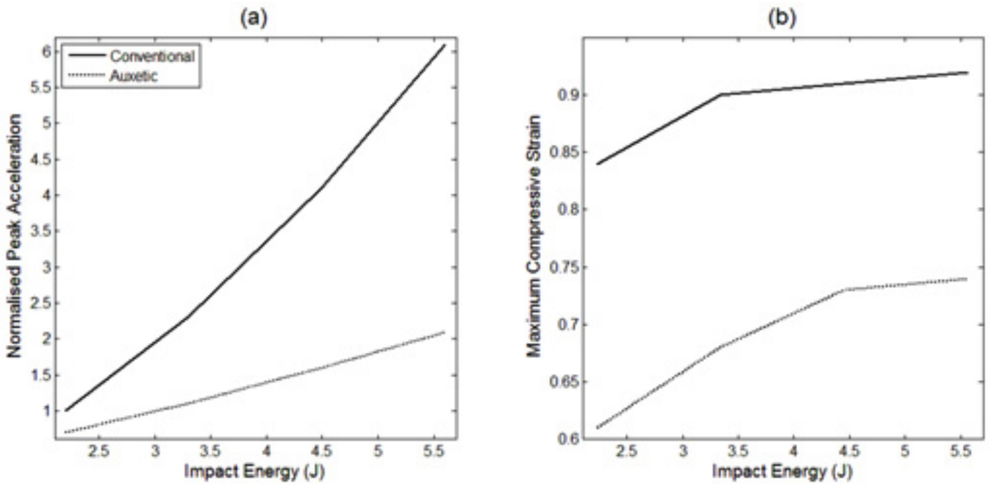

Figure 4 Impact testing results for conventional and auxetic foam, a) Peak acceleration normalised to 22 g, the value obtained for the conventional foam at the lowest impact energy and b) Maximum compressive strain.

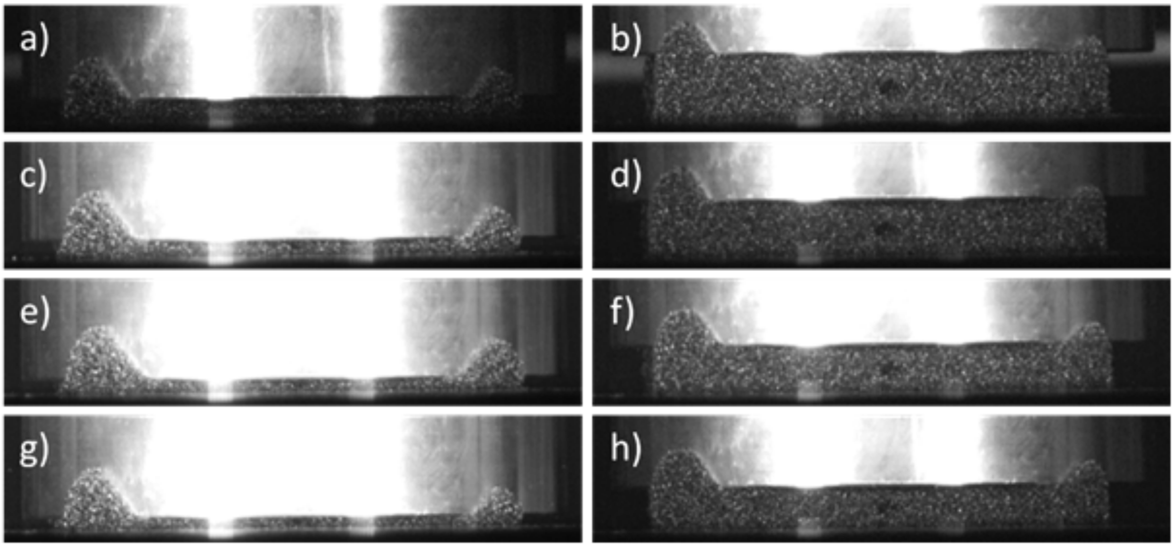

Figure 5 Images from the high-speed camera showing maximum deformation, a) conventional at 2.2 J, b) auxetic at 2.2 J, c) conventional at 3.3 J, d) auxetic at 3.3 J, e) conventional at 4.5 J, f) auxetic at 4.5 J, g) conventional at 5.6 J, h) auxetic at 5.6 J

4. Discussion

Peak accelerations were ~3 times lower for auxetic foam in comparison to its conventional counterpart. Similar peak accelerations were observed for both foams at the lowest impact energy of 2.2 J, but the auxetic samples performed better as impact energy increased to the maximum of 5.6 J. The auxetic foam performed better because it deformed less during impact, preventing the high accelerations observed when the conventional samples bottomed out. Quasi-static compression confirmed different stress-strain relationships for the two foams. The auxetic foam resisted cell-wall buckling with an almost linear stress-strain profile, which is likely to be why these samples deformed less during impact.

Poisson's ratio for the auxetic foam was -0.08, which is lower than values reported by Allen et. al. [3], but higher than those reported elsewhere [2, 8-11]. The Poisson's ratio of foam - following a compression and heat treatment process - is influenced by a number of factors, including the composition and porosity of the candidate foam, the level of compression applied and the cooking temperature and time [4, 8,9]. Future work will investigate conversion methodologies to further our understanding to how best to minimise Poisson's ratio.

The work presented here has indicated further potential for auxetic foam to be applied to sports safety equipment, although further research is required. Auxetic foam considerably outperformed its conventional counterpart, but it is not yet known how it can be best applied to sports safety equipment. Further work needs to compare auxetic foam against current materials and products, while also investigating transmitted energy for higher impact speeds and for repeated impact loading. There is also a need for larger auxetic samples, particularly if crash barriers are to be investigated or if prototype protective equipment is to be produced. Further work will, therefore, not only look to optimise foam selection, but also investigate methodologies for producing large samples of auxetic foam. Further work will also investigate the effect of adding a shell, as previous work showed auxetic foam to considerably outperform its conventional counterpart when a concentrated impact load was applied to samples covered with a semi-rigid sheet [3].

5. Conclusion

Peak accelerations were considerably lower for auxetic foam in comparison to its conventional counterpart, for impact energies up to 5.6 J. The auxetic foam performed better because it prevented bottoming out. Further work should aim to optimise both foam selection and the conversion process for sport safety, and compare performance against current materials and products. This investigation has further identified that auxetic foams have potential to be applied to sport safety devices, such as body armour or crash barriers.

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