Investigation on the Compressive Properties of Auxetic Foams Under Different Loading Rates

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Abstract

Auxetic materials or materials with a negative Poisson's ratio have a great potential to be used in many industries because of their specific mechanical properties such as high stiffness and strength with significant weight saving. In this paper, the effect of various parameters of the fabrication process on the microstructure of a Polyurethane auxetic foam was investigated. Moreover, the compression behavior of this foam in different situations, from quasi-static to high strain rate loading, was studied comprehensively. Results indicated that 70% volume reduction, being heated to 180 centigrade degrees and kept at that temperature for one hour and forty-five minutes could maximize the auxeticity of the foam. Microscopic images demonstrated that the foam structure cells were transformed from honeycomb to re-entrant, causing the Poisson's ratio to become negative. With increasing the re-entrant cells, the auxeticity of the foam increased which leads to increasing the absorbed energy in quasi-static compression up to 443%, and in high strain rate loading up to 617%.

Keywords: Negative Poisson's ratio, Polyurethane auxetic foam, Quasi-static Compression, Low-velocity impact, Split Hopkinson Pressure Bar.

Introduction

Over the three decades, the development of designing in engineering structures and technology in industries such as aircraft, automotive, and sports industries has led to the widespread use of new types of light-weight materials with better mechanical properties than conventional ones. Scientists study on new materials with high stiffness, low specific weight, and low-cost of manufacturing. In isotropic materials, elastic properties are expressed by the two main parameters, namely Young's modulus and the Poisson's ratio. The Poisson's ratio is typically between 0.25 and 0.35 in ordinary materials and 0.5 for soft elastic materials. Lakes [1] first fabricated materials with a negative Poisson's ratio by applying volumetric compression and temperature to polyurethane foam. This material is called "auxetic" with Greek roots meaning "what becomes bigger". Evans [2] attributed this phenomenon to materials with a negative Poisson's ratio to the foam structure. He asserted that the structure of the cells in conventional polyurethane foam was honeycomb, which becomes re-entrant after applying the mentioned thermo-mechanical process. Evans and Alderson [3] published a scanning electron micrograph of two conventional Polyurethane and auxetic Polyurethane foams structures, which perfectly matched the announced schematic structure. Chiang [4] made auxetic foam by compressing ordinary PVC foam in three directions and performing heat treatment on it. The total volume reduction in the foam was approximately 50% from its original volume, but its local volume decreased by 75% in certain parts of the foam during this process. In the same year, Alderson et al. [5] made two types of flat and curved auxetic foam sheets by applying uniaxial compression on a normal specimen, which was then heated and cooled. The curved auxetic foam was made by placing the foam between two plates and then applying a bending force to it, which in other stages, resembles a completely flat foam, being subjected to heat treatment only in a few steps. Jiang et al. [6] developed a particular type of auxetic composite by multiple layers of auxetic foam as fibers and Polyurethane as a matrix by injection, heating, and cooling. Lee and Zang [7] found an optimal method to produce Polyurethane auxetic foams through ordinary ones. Underhill [8] subjected three different sizes of Polyurethane foam to compressive and thermal stresses. All the three types of foam became auxetic once the compression ratio reached 2. The maximum Poisson's ratio (-0.16) belonged to the tiniest cavity size, which occurred at a density coefficient of 3.2. Yao et al. [9] examined the fabrication and behavior of auxetic shape memory composite foam. The foam was made with soft Polyurethane foam as a matrix and memory epoxy resin as a functional phase. Fan et al. [10] developed a new method based on the SPC method to prepare auxetic polymer foam for use in structures. The presence of water vapor between cells was reported as an important factor that result in the negative Poisson's ratio of the foam. Webber [11] developed a novel two-stage processing route for the production of auxetic microporous ultra-high molecular weight Polyethylene. This new method was more versatile than the previously established three-stage processing route. Scarpa and Pastorino [12] performed a quasi-static compression test on the conventional and auxetic foam, and showed that the stress-strain diagram of auxetic foam is very different with that of the conventional Polyurethane foam. This research provided a model for detecting the cell failure behavior of auxetic foam since the sides of the cell were bent. Ravirala [13] developed auxetic Polypropylene fibers based on the thermal processing route. The auxetic PP films were produced at 159 °C with a screw speed of 1.05 $rad.s^{-1}$ and 0.0225 $m.s^{-1}$, were found to have low strain (<0.1%) Poisson's ratios of ν_{xy}=-1.12 and ν_{yx}=-0.77. Alderson [14] produced a novel processing route to create auxetic polymers. At low strains, $\nu = -0.32$, was the largest negative value measured in this work.

As it is clear, the mechanical properties of materials are completely related to the material's microstructure; thus, these properties can be controlled by changing the microstructure of the material. Using the two parameters of heating times and temperature, control the intruded structure and consequently the amount of auxeticity in the foam. In previous studies, researchers created an auxetic structure in the foam using a specific temperature without changing it, but they ignored the effect of different temperatures and heating times on the final structure. In this study, the optimal structure was determined applying different heating times and examining different microstructures obtained using microscopic images. To confirm the optimal structure, different tests were performed on the specimens. Although, some previous works have studied the mechanical behavior of the auxetic foams, there is no comprehensive paper investigating the energy absorption properties of these materials under various types of loading. In this research, the drop hammer test on the auxetic foam was performed in order to study the amount of energy absorption. Moreover, a uniaxial tensile test and a quasi-static compression test were performed to obtain the properties of the foam to find the optimal structure between the fabricated samples. Furthermore, the microstructure-associated mechanical properties of each group were investigated, and the relationship between the heating time and the obtained microstructure was studied. Finally, the Split Hopkinson pressure bar test was performed on the auxetic and the non-auxetic foams to investigate their behavior at high strain rates. A comprehensive discussion was carried out through the following sections. It was hoped that the auxetic foam obtained in this scientific research has higher mechanical properties, higher energy absorption, and lower manufacturing costs compared to previous specimens.

Fabrication and Test of Specimens

Polyurethane foam refers to a group of foams made of a combination and through the reaction of a certain amount of Polyol and Isocyanate. Soft Polyurethane foam has high flexibility and low tensile strength due to having an open cell structure with airflow through the cells. It is also resistant to various solvents and has a low heat conductivity and good sound absorption properties. In this research, Polyol and Isocyanate were initially mixed in a 1:2 ratio and poured into a mold to form a foam, which was cut into 70×70×35 mm^3 pieces at the end of drying. By averaging the 20 samples from different parts of the foam, the density of the foam was 88.5 kg/m^3 using the ASTM D3574 standard. The foams were compressed into 50×50×30 mm^3 steel molds and then subjected to 180 °C in an oven at various times. This temperature was obtained experimentally as the softening temperature of foam.

Different heating temperatures and heating times are required to make auxetic foam with different densities and properties. These values must be obtained experimentally for each foam. For the foam used in this study, it was concluded that if the foam is heated in the oven for less than 1 hour, after cooling and leaving the mold, the structure of its cells will not change, and it will return to its original size. In addition, if the foam is subjected to a temperature more than 1 hour and 45 minutes, the foam bonds will burn and lose their properties.

In order to achieve the optimal time to make the best foam with an auxetic structure, according to Table 1, the foams were divided into four groups of three specimens, that for each of them, the conventional Polyurethane foam subjected to 180 °C for 1 hour, 1 hour, and 15 minutes, 1 hour and 30 minutes, and 1 hour and 45 minutes in the oven. The cool-down time of the foam in the mold after the heating step is very important; because, once the foam was extracted from the mold after about 4 hours, it lost its auxetic properties and returned to its original size in the experiment. But, the foam did not lose its auxetic properties when it was cooled for more than 15 hours in the mold at room temperature. Therefore, foam rest time is a pivotal factor in the auxetic process of polyurethane foam. The foam structure was examined under a microscope after removing foams from the mold to confirm the auxetic structure.

Table 1. Process data regarding the four groups of auxetic foams

Foam group	Heating time	Temperature	Rest time
AU 1	1 hour	180°C	15 hours
AU 2	1 hour and 15 minutes	180°C	15 hours
AU 3	1 hour and 30 minutes	180°C	15 hours
AU 4	1 hour and 45 minutes	180°C	15 hours

For the evaluation of the mechanical properties of the foams and drawing a comparison of different groups of them, they were subjected to various tests. According to ASTM D3574 for the tensile test, 25×135×10 mm^3 specimens were prepared. Subsequently, as Figure 1 depicts, it was placed in the tensile testing machine and then pulled at a speed of 30 mm/min by the device's jaws at room temperature. The Poisson's ratio diagram was obtained in terms of the strain from this test for the sample of conventional and auxetic foams.

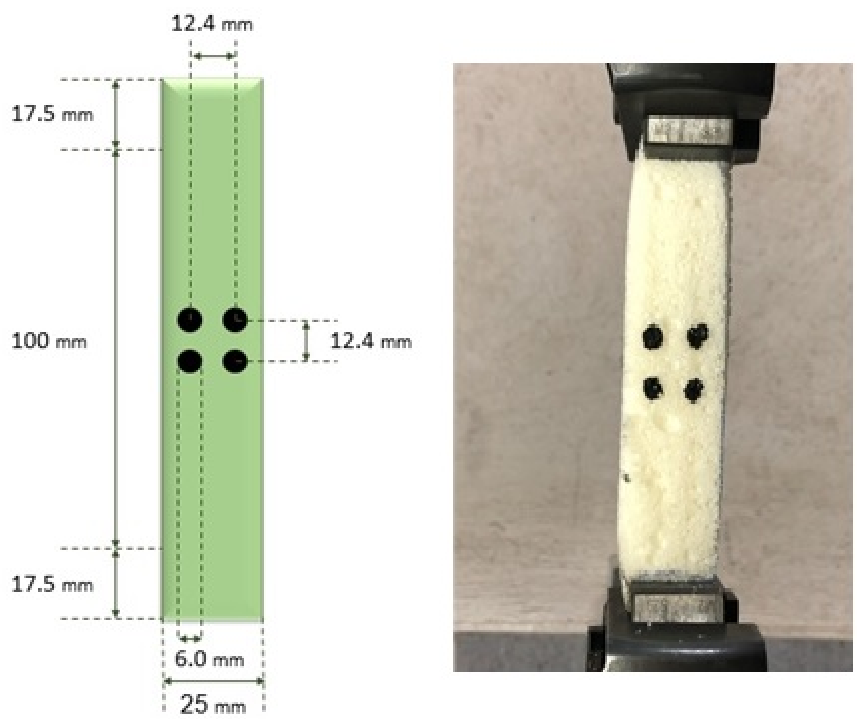

Figure. 1. Conventional Polyurethane foam subjected to tensile test

Afterwards, a compressive uniaxial quasi-static test was performed on the specimen with dimensions of $50 \times 50 \times 25 mm^3$ at the rate of 50 mm/min (Figure 2-a). Besides the uniaxial tests, triaxial quasi-static test was performed on the specimens, to check the effect of other sides' compression. Some specimens with the same size were prepared for the drop hammer test. Moreover, a weight with mass of 9 kg fell on the specimen at room temperature from a height of 20 cm (Figure 2-b) for investigation of low-velocity impact on the foams. The output of this test was the acceleration-time curve.

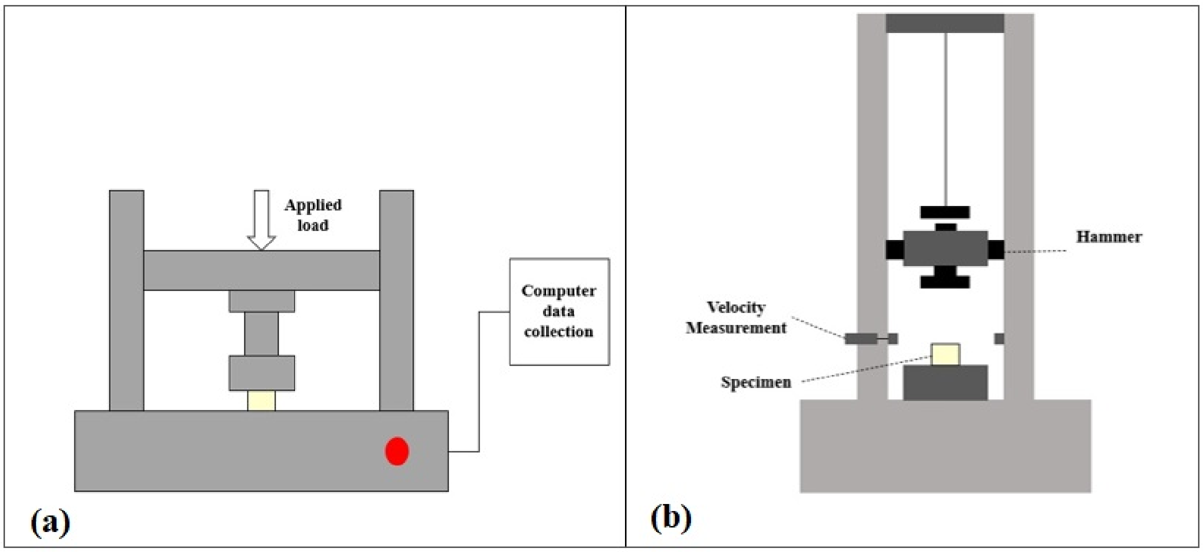

Figure. 2. Auxetic foam subjected to (a) uniaxial quasi-static test, (b) drop hammer impact test

The Split Hopkinson Pressure Bar (SHPB) test was carried out to evaluate the foam behavior at high strain rates. This device worked by applying pressure to the input bar on which an elastic pressure wave was created (Figure 3). In the interface of the input bar and the sample, some parts of the wave were reflected as a tensile wave, and other parts were transmitted to the main sample as a pressure wave. This was also true for the interface of the sample and output bar. The wave signals in these two bars were recorded by strain gauges connected to two bars connected to a multi-channel oscilloscope. The scale of the recorded output voltages was in millivolts; therefore, these voltages were amplified via an amplifier. To conduct this test, a specimen with dimensions of $10 \times 10 \times 5$ mm^3 was prepared and subjected to three strain rates of 685 s^{-1}, 939 s^{-1}, and 1472 s^{-1}. They were tested at each strain rate. Thus, the repeatability of the test could be observed. The strain, stress, and strain rate of each specimen can be found by the transmitted and reflected wave signals in Equations 1-3 [15].

$$\varepsilon(t) = \int \dot{\varepsilon}\,(\tau)d\tau \qquad (1)$$

$$\sigma_s(t) = \frac{A_0^2 E_0}{A_s^2}\,\varepsilon_T(t) \qquad (2)$$

$$\dot{\varepsilon_s}(t) = -\frac{2C_0}{l_s}\,\varepsilon_R(t) \qquad (3)$$

where $C_0 = \sqrt{E/\rho}$ is the wave speed of the input bar, $l_s$is the length of the specimen,ε_R is the reflected strain signal, $\varepsilon(t)$ is the transmitted signal, E_0 is the elastic modulus of the bars, and A_0 and A_s represent the cross-sectional area of the output bar and specimen, respectively.

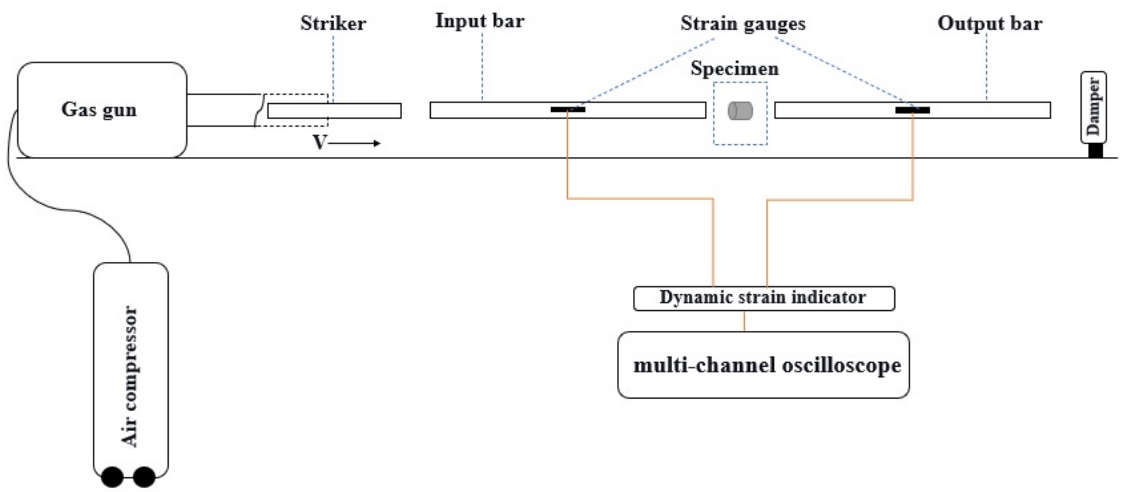

Fig. 3. Split Hopkinson Pressure Bar Schematic sketch

Results and Discussion

A) Changes in the foam structure

After fabrication, the microstructure of each specimen group was examined under a microscope; the results are reported in this section. Blue lines around each foam cell indicate the honeycomb microstructure. Once a specimen was exposed to a temperature of 180 °C for 50 minutes and then cooled in the mold at the room temperature for 15 hours, no change in the structure of the foam cells was observed.

Figure 4-a shows the specimen group of AU1 heated in180 °C temperature for 1 hour in the oven and then cooled for 15 hours at the room temperature. In this figure, the red lines represent re-entrant structures formed by heating and volumetric compression. These structures are attributed to the auxetic property in the foams. Accordingly, the number of re-entrant cells increased in the

structure, and only a small number of them still retained their honeycomb structure. Similar to the previous samples, the percentage of re-entrant cells decreased from the specimen edge down to the center.

Figure 4-b demonstrates the exposed specimen AU2 heated for 1 hour and 15 minutes in 180 °C temperature inside the oven. As seen in the figure, the number of the cells with re-entrant structure increased compared to that in the AU1 specimen, yet a small number of cells retained their honeycomb structure. Additionally, as in the previous specimen, the number of re-entrant cells decreased when approaching the center of the specimen.

Figure 4-c illustrates the specimen AU3 heated for 1 hour and 30 minutes in 180°C temperature inside the oven which was then cooled for 15 hours at the room temperature. As it is clear, the number of re-entrant cells are is higher than that of the AU2 group, and a few cells retained their honeycomb structure.

Figure 4-d shows the specimen in the AU4 group heated in the oven for 1 hour and 45 minutes at 180 °C temperature and then cooled in 15 hours at room temperature. As could be seen, the number of the cells with re-entrant structures is higher than that of the previous specimen, and the cells with honeycomb structures are not observed. In addition, the number of the cells with re-entrant structure did not decrease by approaching the center of the specimen as they have relatively steady auxetic properties in the whole specimen with a good approximation.

Comparing all the figures, it is concluded that further heating of specimens results in more re-entrant cells. This behavior was predictable since as a result of a longer heating time, the walls of the cells have more time for collapse and being re-entrant. The specimen in group AU4 was selected as the optimum specimen owing to have more re-entrant cells in its structure. The effect of getting re-entrant on the mechanical properties of the foam is discussed in the next sections.

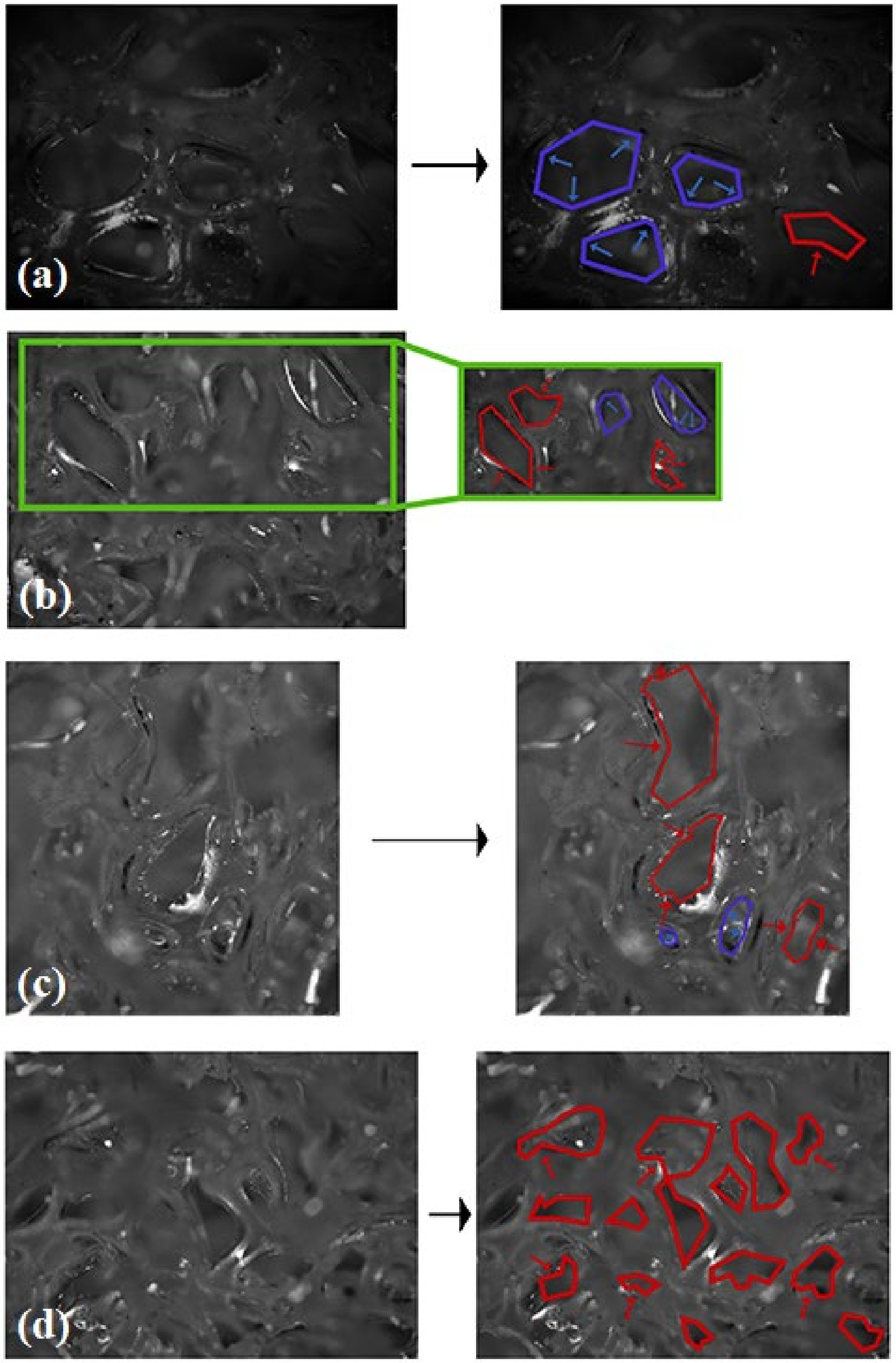

Figure. 4. Microstructure near the center of the sample (a) AU1 foams with the heating time of 1 hour, (b) AU2 foams with the heating time of 1 hour and 15 minutes, (c) AU3 foams with the heating time of 1 hour and 30 minutes, (d) AU4 foams with the heating time of 1 hour and 45 minutes

B) Tensile properties of the foam

To perform the tensile test, due to the optimality of the AU4 specimen, this sample was tested and compared with the conventional Polyurethane foam. The displacement in the transverse and longitudinal directions was determined in the tensile test. The strain field was obtained in the direction of loading and transverse direction related to the central part of the specimen using Digital Image Correlation (DIC). The detected points shown in Figure 1 were used to measure the displacement changes and obtaining the equivalent strains. Based on the definition of$\nu_{xy} = -\varepsilon_y/\varepsilon_x$, the Poisson's ratio was obtained at any moment by dividing the strain in the transverse direction to the longitudinal direction of the specimen. Figure 5-a exhibits the negative Poisson's ratio (increasing the width of the specimen during stretching) in the auxetic specimen; meanwhile, Figure 5-b shows the positive Poisson's ratio (decrease in the specimen width during the tensile test).

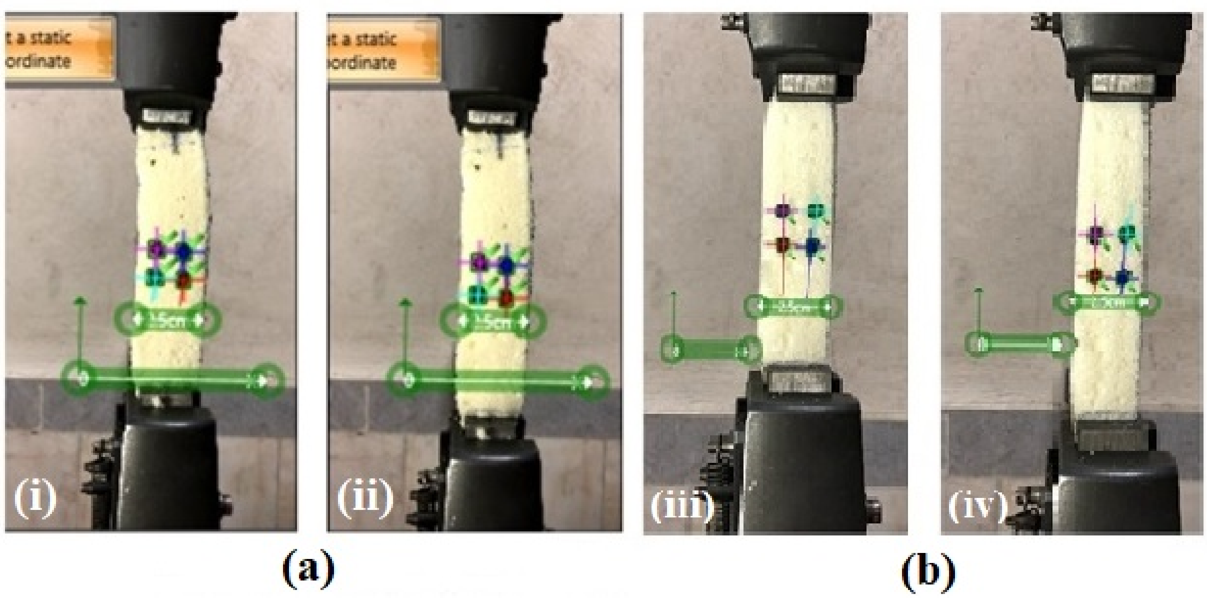

Figure. 5. (a) Auxetic foam in early stages of the test, (i) strain=0, (ii) strain=20% (b) Conventional foam in early stages of the test, (iii) strain=0, (iv) strain=30%

The Poisson's ratio-strain curve based on the results is shown in Figure 6, according to which the negative Poisson's ratio initially increases by increasing the strain. The maximum negative Poisson's ratio of the auxetic specimen which is -0.097 is belonged to strain 24.01%, and the negative Poisson's ratio decreased with an increase in the strain after this point. From the strain of 42.1%, when the specimen reached its initial size, until the fracture point, the Poisson’s ratio was observed to be positive. In addition, it should be noted that the average Poisson's ratio of the conventional specimen was about 0.387.

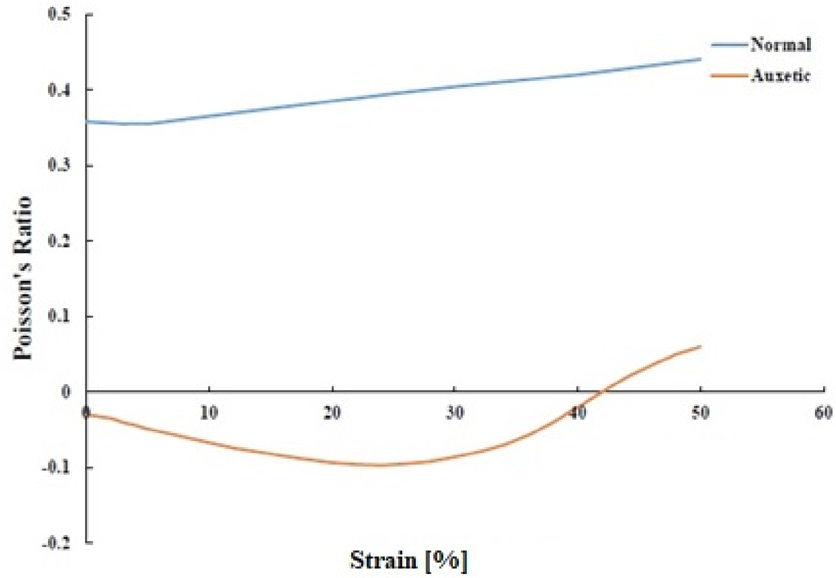

Figure. 6. In-plane Poisson's ratio of the conventional and auxetic foams

Figure 7 shows the load-displacement curve in both conventional and auxetic Polyurethane foam subjected to uniaxial tensile loading. As could be seen, the modulus of elasticity of the auxetic foam is approximately 150 % more than that of the normal foam. Furthermore, the fracture force in auxetic foam is about 10 N (50.5%) more than the fracture force in conventional Polyurethane foam.

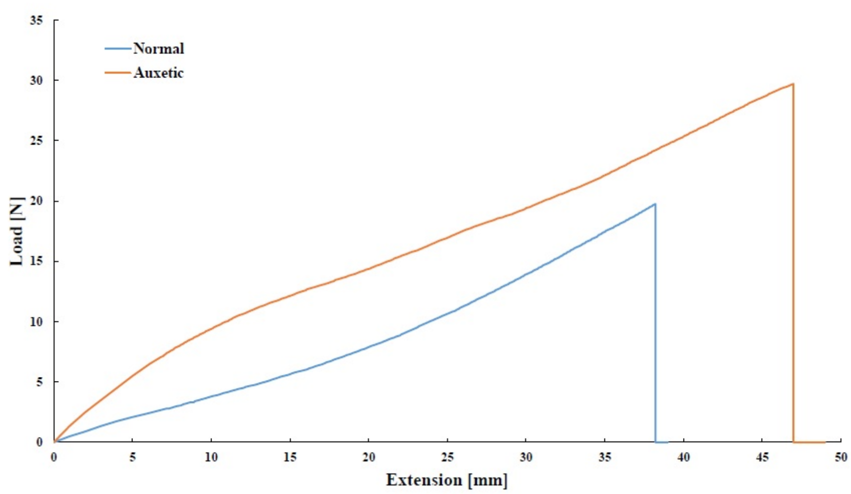

Figure. 7. Uniaxial tensile load-deformation curve of the conventional and auxetic foam

C) Compressive properties of the foam

C-1) Quasi-static

The results of the quasi-static test at a speed of 50 mm/min are shown in Figures 8 and 9. As mentioned previously, to examine the accuracy of the test, three specimens were fabricated and tested from each group of the samples. The load-displacement diagrams in Figure 8 confirm the reproducibility of the samples.

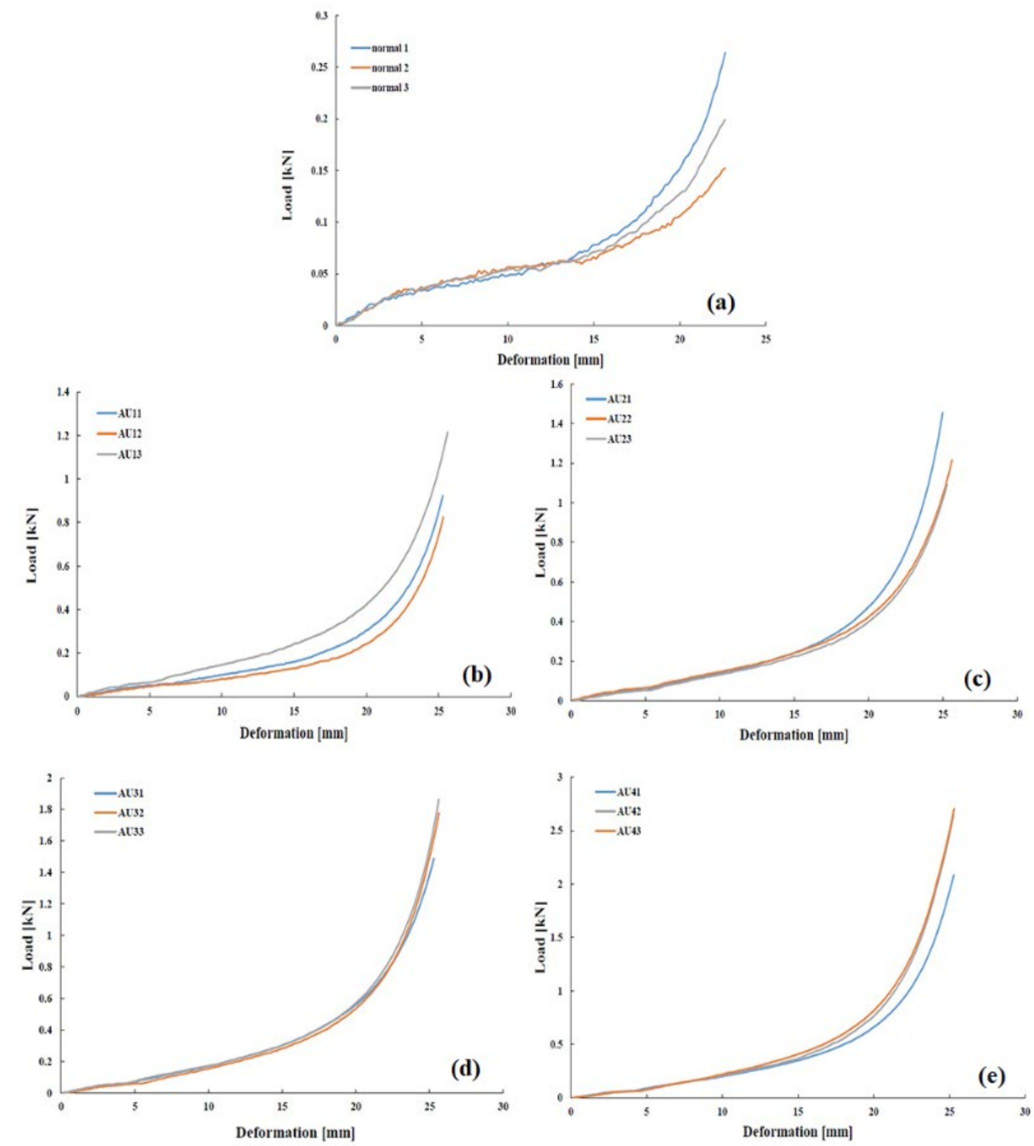

Figure. 8. Load-displacement curves for (a) conventional foams (b) AU1 foams (c) AU2 foams (d) AU3 foams (e) AU4 foams

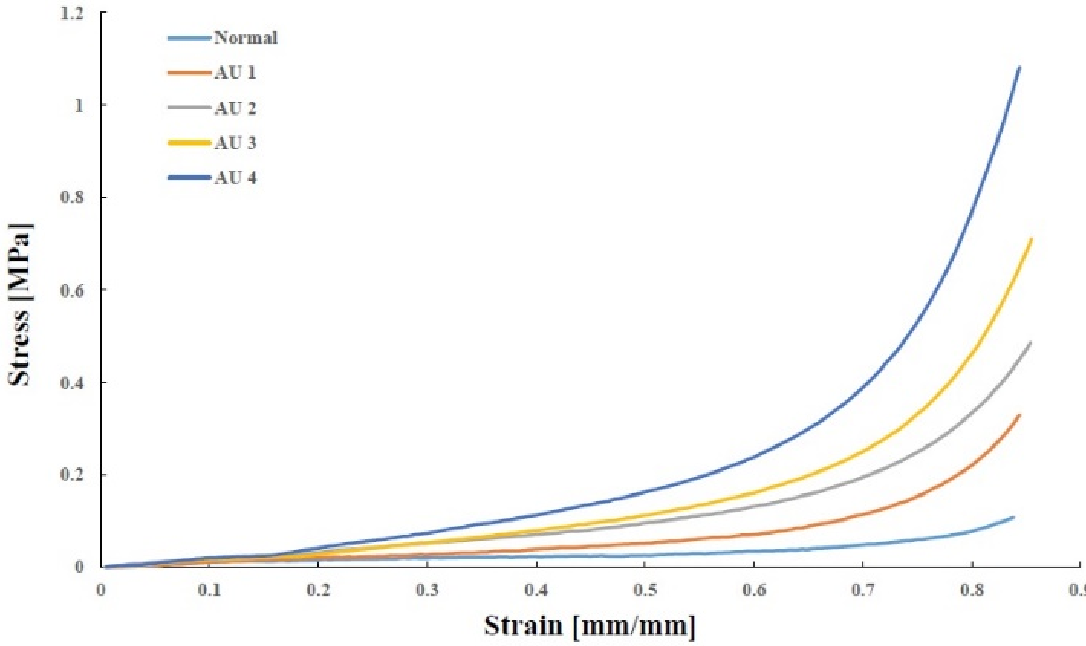

Figure. 9. Quasi-static stress-strain curves of the specimens of the normal and auxetic foams.

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Generally, the stress-strain curve of foam is divided into three parts: (a) the linear elastic region, (b) the plateau region (steady stress), and (c) the densification region. In the first region, the compressive stress increases linearly with a rise in the strain. It is founded that the more the auxetic property, the smaller the linear elastic region. The stress does not increase significantly by strain in the second region. Therefore, this region is also called steady stress is formed by buckling at the cell boundary. Finally, due to the closure of the cells in the foam, after the plateau area, the graph entered the third area, where the compressive stress increases rapidly relative to the strain. Figure 9 depicts that the behavior of all types of the foams had the same trend and all the foams were similar concerning their size. Meanwhile, the conventional Polyurethane foam had the minimum compressive performance in comparison with the others. According to the results in Table 2, the linear elastic and plateau regions of the foam became shorter with an increase in its auxeticity. However, the level of stress values became higher. The reason is that in conventional foams and foams with less auxeticity, the number of re-entrant microstructures is lower, as a result of which they are more flexible than foams with further auxeticity. Accordingly, they were further deformed with a lower compressive strength. Due to the higher compressive strength of the AU4 auxetic foams, it is expected that the amount of energy absorption in this specimen at the same strain be significantly higher than the conventional Polyurethane foam. The average energy absorption values for each group of specimens up to strain value of 0.7 are reported in Table 2, indicating that the auxetic foam (AU4) absorbed energy by 443 % more than the conventional foam.

Table 2. The range of the mechanical properties in each group of foams under quasi-static test

Foam group	linear elastic region	plateau region	Energy Absorption (J)
conventional foam	0 - 0.201	0.201 - 0.758	0.0160
AU 1	0 - 0.181	0.181 - 0.682	0.0290
AU 2	0 - 0.174	0.174 - 0.595	0.0503
AU 3	0 - 0.161	0.161 - 0.437	0.0582
AU 4	0 - 0.153	0.153 - 0.392	0.0870

C-2) Uniaxial vs triaxial

According to Figure 10, by comparing the results of uniaxial and triaxial quasi-static compression tests in auxetic foams, it is clear that the results and curves of these two tests are consistent on account of non-buckling of the cell-walls during compression. In contrast, the results of these two tests were not similar to the conventional foam because of the buckling of the sample. In fact, the walls of the mold in the triaxial test did not allow the conventional foam to bulge; therefore, so the force between the foam and the wall caused an increase in the stress. On the other hand, the auxetic foam did not bulge because of the negative Poisson's ratio; thus, so the force of interaction between the foam and the wall of the mold did not affect the compression significantly.

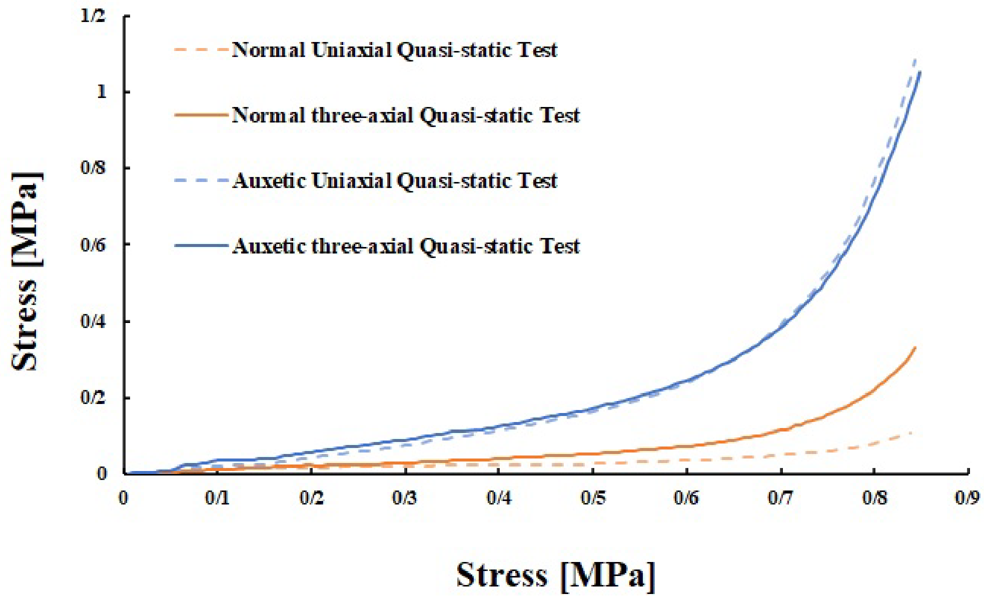

Figure. 10. Uniaxial and triaxial quasi-static stress-strain curve of the normal and auxetic specimens

C-3) Low-velocity impact

As it was mentioned in the previous part, the output of the low-velocity impact test was the acceleration-time curve. This curve was converted into a force-displacement curve at the impact moment. Finally, a stress-strain curve was obtained, which is illustrated in Figure 11. Similar to the quasi-static tests, all the three parts of the typical foam in compression (linear elastic part, plateau, and densification) were obvious; the range of the regions are listed in Table 3. AU4 was considered to have the highest strength among the others and according to the results, the lowest amount of strength belonged to the non-auxetic foam. It should be noted that, the amount of increase in the strength of the auxetic foams in the impact tests was more than that in the quasi-static tests; this implies the benefit of auxetic foams for use in impact energy absorbers. Based on this curve, the energy absorption in the auxetic specimens was significantly higher than that in the conventional Polyurethane foam in a same strain. These values are exhibited in Table 3 for the strain of 0.7.

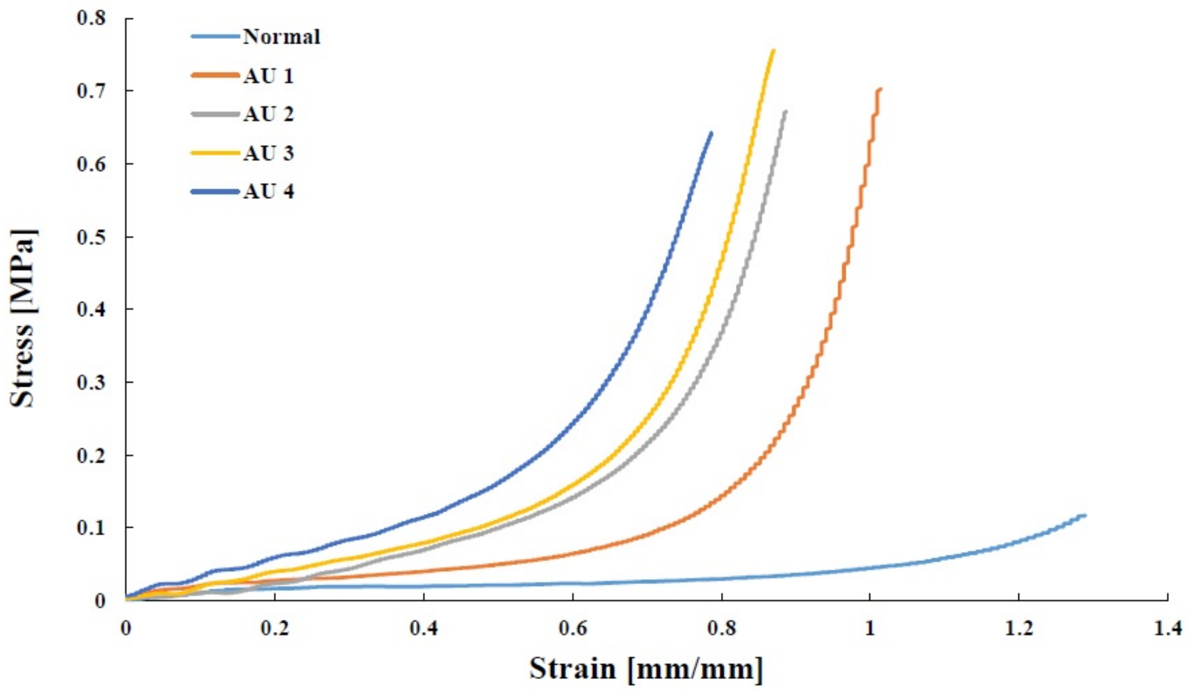

Figure. 11. Low-velocity impact stress-strain curve of the specimens with different specimens.

Table 3. The range of the mechanical properties in each group of foams under low-velocity impact test

Foam group	linear elastic region	plateau region	Energy Absorption (J)
conventional foam	0 - 0.307	0.307 - 0.833	0.0123
AU 1	0 - 0.241	0.241 - 0.487	0.0281
AU 2	0 - 0.223	0.223 - 0.249	0.0497
AU 3	0 - 0.158	0.158 - 0.182	0.0601
AU 4	0 - 0.120	0.120 - 0.164	0.0882

C-4) Split Hopkinson Pressure Bar

Given the relationships mentioned in the previous section, Figure 12 depicts the stress-strain curve of the split Hopkinson Pressure Bar (SHPB) test for analyzing the behavior of the optimum auxetic foam (AU4) for the three strain rates of 685, 940, and 1472 s^{-1}.

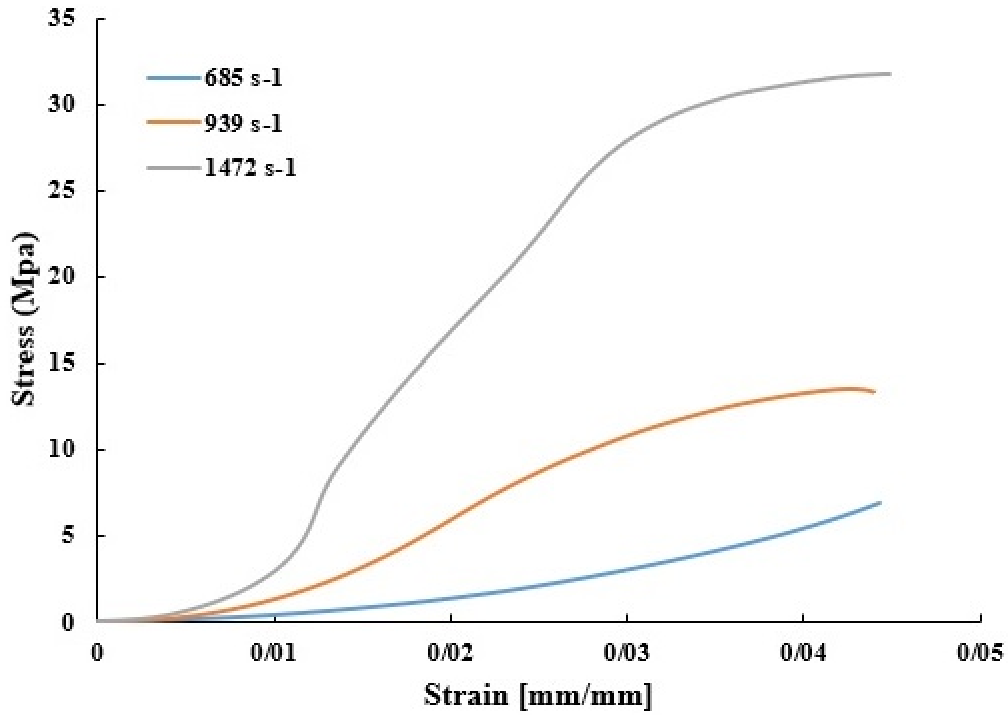

Figure. 12. High strain rate stress-strain curve of the specimens with the optimum auxetic structure

Figure 12 shows different stress-strain curves in various strain rates of AU4 specimens. Note that due to the high flexibility of the convectional foam, SHPB setting could not capture the results of this foam. Hence, the results are only for the AU4 group. In the AU4 group, with an increase in the strain rate, the stress was also enhanced. The compressive strength at higher strain rates (10^3 s^{-1}) was found to be markedly higher than that of quasi-static (10^{-3} s^{-1}) and low-velocity impact (10^0 s^{-1}) loading.

Conclusion

The present research primarily investigated the manufacturing technique of auxetic Polyurethane foam and the effective parameters in the process. The temperature of 180°C was experimentally determined as the softening temperature of the foam, and the foams were divided into four groups based on the heating time. Experimentally, the cooling time in the mold was estimated to be 15 hours at the room temperature. The structure of the foam cells in each specimen group and the number of the re-entrant cells in the center and near the edges were examined under a microscope in order to achieve the optimal structure of the auxetic foam. The number of the re-entrant cells was higher in the specimen AU4 which was exposed to a longer heating time in comparison with those of other groups. Tensile test, uniaxial and triaxial quasi-static compression tests, drop hammer test, and Split Hopkinson Pressure Bar test were performed on the conventional Polyurethane and auxetic Polyurethane foam specimens to study the mechanical properties of the foams. By comparing the test results, it could be concluded that the AU4 specimen, as the optimum specimen, had a higher tensile strength, higher compressive strength, and 443% further energy absorption compared to the conventional foam.

Conflict of Interest

The authors declare that they have no conflict of interest.

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