Design and development of Auxetic materials for defence applications

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

Of
BACHELOR OF TECHNOLOGY
In
MECHANICAL ENGINEERING

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CANDIDATES'DECLARATION

We hereby declare that the project entitled **"Design and development of Auxetic foam for defence applications"** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in 'Mechanical Engineering' completed under the supervision of **Dr. I. A. Palani, Associate professor, Mechanical Engineering,** IIT Indore is an authentic work.

Further, we declare that we have not submitted this work for the award of any other degree elsewhere.

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CERTIFICATE by BTP Guide

It is certified that the above statement made by the students is correct to the best of my knowledge.

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Preface

This report on "**Design and development of Auxetic foam for defence applications**" is prepared under the guidance of **Dr. I. A. Palani.**

Through this report we have tried to give details of fabrication process and potential application of Auxetic foam which has been fabricated from readily and economically available normal PU foam in the market and have tried to cover every aspect of the fabrication process, if the process is technically sound and feasible.

We have tried to the best of our abilities and knowledge to explain the content in a lucid manner. We have also added flow diagrams and figures to make it more illustrative.

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It is their help and support, due to which we were able to complete the design and technical report. Without their support this report would not have been possible.

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Abstract

Defense appliances and protection devices have always been applying foams for effective cushioning and absorbing impact energy. But these still have wide scope for further improvements considering comfort of using them, effectiveness and cost associated with fabricating them. This research aims at fabricating the Polyurethane foam with Auxetic properties developed in it and applying it in the devices used for protection and defense like recoil pads and gun butts; Auxetic foam finds apposite application here due to its inherent and special properties like increased density, increased tensile strength by 40%.

In contrast to conventionally available materials which have positive Poisson's ratio, the Auxetic foams exhibit negative valued Poisson's ratio. With a thermo-mechanical process, the normal Polyurethane foam was transformed into Auxetic foam. To check the change in the microstructure of the foam which is inherent to the Auxetic behavior, pictures were taken on the optical microscope. The Poisson's ratio was calculated using the images captured during tensile test with the displacement of the marked points on the sample. MATLAB image processing tool was used to calculate this Poisson's ratio which was -0.72.

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Chapter1.INTRODUCTION

1.1. Motivation

Foam, leather have been in application in making the recoil pads for ameliorating the impact force felt after firing a firearm. In addition to minimizing the impact effect, these also facilitate additional comfort in using the weapon. Along with recoil pads, leather have also been used in the protective wear like helmets, kneepads, shin pads etc., Polyurethane foam play crucial role in this regard. Auxetic PU foams exhibit negative Poisson's ratio in contrast to the conventional PU foams and hence also exhibit some inherent properties like enhanced energy absorption capacity. The novelty of the research lies in establishing application of this Auxetic foam suitable in defense devices mentioned above due to its light weight and higher energy absorption capacity, thus rendering enhanced comfort.

Figure 1: Image showing currently available recoil pad at the butt end of the gun.

Figure 2: Currently available protective wear Helmets and Knee pads.

1.2. What are Auxetic materials?

Auxetic materials are special materials that have a negative Poisson's ratio. This type of material becomes thicker in the direction perpendicular to the applied force when stretched. Auxetic materials have generated considerable interest in recent years because of their unique mechanical properties and have been demonstrated to provide a number of advantages over the more conventional engineering materials, such as higher indentation resistance, higher fracture toughness and greater resistance to impact damage. These unique features of the Auxetic materials make them potential candidates for a variety of applications.

In order to take advantage of the unique features of Auxetic materials, Auxetic PU foam was fabricated from the conventional foam by thermo-mechanical process for the defence applications. After the fabrication of the Auxetic foam, it was tested to determine its different properties. This report analyses its microscopic structure, negative Poisson’s ratio, compression test, the effect of different volumetric compression ratios on the Poisson’s ratio obtained. These tests prove the suitability of using the Auxetic foam in the recoil pads over the normal PU foams.

Chapter2.Literature Review

2.1. Basic characteristics of Auxetic materials

Our everyday experience tells us that when we stretch a piece of material, for example an elastic band, the material not only becomes longer in the direction of stretch but also becomes thinner in cross-section. Similarly, a material under compression usually expands laterally. In both of these cases the behaviour of the material under deformation is governed by one of the fundamental mechanical properties of materials, named the Poisson's ratio. The Poisson's ratio of a material is defined as the ratio of the lateral compressive strain to the longitudinal tensile strain for a material undergoing tension in the longitudinal direction, i.e., it tells us how much a material becomes thinner when it is stretched. Consequently, by definition most materials have a positive Poisson's ratio.

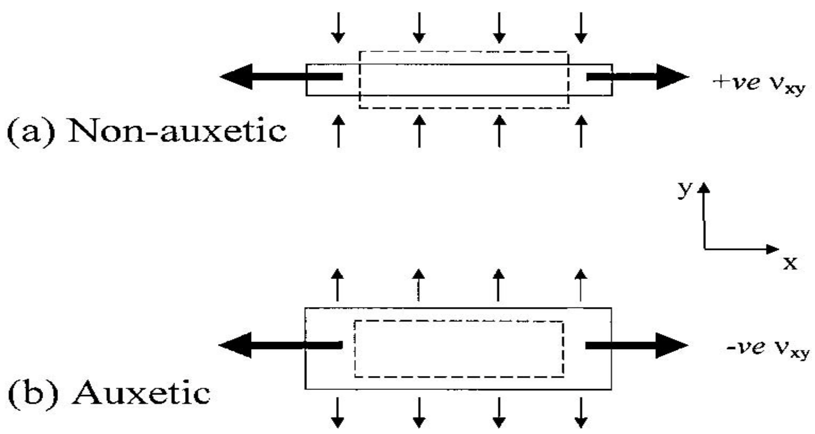


Figure 3: Schematic diagram showing deformation of conventional foam and Auxetic foam when they are stretched.

Poisson's ratio has historically been the least studied of the quartet of elastic constants for isotropic materials. The three other elastic constants are the Young's modulus (*E*), shear modulus (*G*), and bulk modulus (*K*), and they are important from an engineering point of view since they present the stiffness, rigidity, and compressibility of a material, respectively. In most of the undergraduate texts on the mechanics of materials, it was implied or even stated that all materials possess a positive Poisson's ratio. However, the possibility that v may be negative has been an accepted consequence of classical elasticity theory, implying that, in this case, the material undergoes lateral expansion when stretched longitudinally (see Fig. 3b), and becomes thinner when compressed. In fact when viewing the Poisson's ratio as a measure of a material's change in volume on being deformed, a negative v is simply an extension of the increase in volume exhibited by a material with a positive v of less than +1/2. Materials that exhibit this novel and counter-intuitive behaviour are known as Auxetic materials.

2.3. Unique properties of Auxetic materials

Because of negative Poisson's ratio effect, Auxetic materials exhibit a series of fascinating properties compared with the conventional materials[1], such as increased shear modulus, increased indentation resistance, increased fracture toughness and increased energy absorption. These properties will be discussed in the following paragraphs.

The Auxetic effect can be used to tailor the mechanical properties of a structure to reach enhanced performance. In elasticity theory, the material's elastic behaviour is expressed by four constants: the Young's modulus (*E*), the shear modulus (*G*), the bulk modulus (*K*) and the Poisson's ratio (v). For isotropic materials, the four constants are not independent. They are related by the following equations: $G = \frac{E}{(2(1+v))}$ and $K = \frac{E}{(3(1-2v))}$. Most structural materials are required to have a higher *K* than *G*. If we can change the microstructure of a material in a way that E remains constant but v changes, we can alter the values of *K* and *G*. For example, when decreasing v to -1, a very high shear modulus relative to the bulk modulus can be obtained. In other words, the material becomes difficult to shear but easy to deform volumetrically.

Hardness can be increased in an Auxetic material due to negative Poisson's ratio. When an object hits an Auxetic material and compresses it in one direction, the Auxetic material also contracts laterally, that is, material 'flows' into the vicinity of the impact as illustrated in Figure 4. This creates an area of denser material, which is resistant to indentation. This phenomenon can be explained theoretically. The indentation resistance or hardness of an isotropic material is proportional to $\frac{E}{1-v2}$ when an indenter with a uniform pressure distribution is assumed. The range of v for 3D isotropic materials is from -1 to 0.5. Thus, the $(1-v^2)$ term will approach to 0, when v approaches to -1. In this way, for an isotropic material with a given value of *E*, the indentation resistance increases towards infinity with increasingly negative Poisson's ratio.

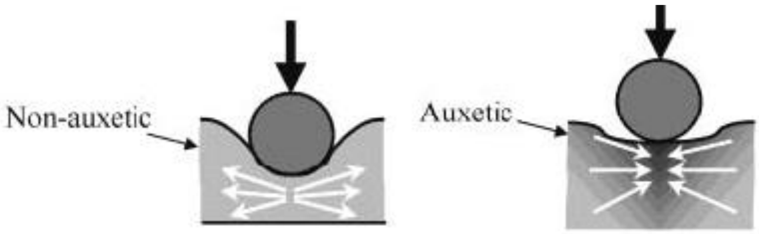


Figure 4: Image showing the flow of material in the vicinity of impact for Non-Auxetic and Auxetic material.

Compared with non-Auxetic materials, Auxetic materials have increased fracture toughness. The fracture toughness was explored experimentally as a function of permanent volumetric compression ratio, a processing variable. Compared to that of conventional polyurethane-polyester foam materials, the toughness of Auxetic foam is increased by factors of 1.7, 2.1, 2.3, 2.6 and 3.2 with increases of volumetric compression ratio of 2.0, 2.6, 3.2, 3.7 and 4.2 respectively. Auxetic materials also have high crack resistance. If the material has a crack, it expands and closes up the crack when being pulled apart. In other words, this type of material should possess more crack resistance to fracture.

Auxetic materials also show overall superiority on energy absorption compared to the conventional materials. Scarpa et al[2-3] investigated the stress-strain behaviours of conventional open-cell rigid grey polyurethane form and the corresponding transformed Auxetic material under dynamic crushing. The results indicated that the conventional rigid polyurethane foam did not demonstrate any noticeable resilience under impact, but the Auxetic foam showed significantly increased resilience under dynamic loading. The measured stress-strain curves indicated that the dynamic behaviour of the transformed Auxetic materials was like a high-density polyurethane cellular solid with low strain-rate sensitivity. For the same strain, the stress in the Auxetic material is in general two orders of magnitude higher than that of conventional foam. These results suggest the possibility of using the transformed open-cell forms in impact applications, such as industrial and sensor/equipment packaging.

Enhanced damping properties of the transformed Auxetic materials over the original conventional forms were also observed by Scarpa and co-workers[4-5]. The Auxetic foam samples were obtained from off-the-shelf open cell grey polyurethane form by following a manufacturing process based on mechanical deformation on a mould in a temperature-controlled oven. Viscoelastic material properties, including storage modulus and loss factor, were measured for small sinusoidal strain histories using a Viscoelastic analysis tensile machine. The same samples were also tested in an acoustic impedance tube to measure acoustic absorption and specific acoustic resistance. The hysteresis of the cycling loading curve was measured to determine the damping loss factors for the various foams. The measurements indicated that the Auxetic foams had loss factors 20% higher than those for the conventional foams.

Yet, the survey lacks in terms of stipulating precise information about the fabrication of Auxetic foam like exact temperature and duration required for a particular density of PU foam. So, the fabrication procedure involves PU foam exposed to a thermo-mechanical process for required time and at required temperature, both of which were discovered after several attempts of fabricating it with different combinations. This report has refined the exact procedures required to fabricate the same.

Chapter3.Fabrication of Auxetic foam and its analysis

3.1. Fabrication of Auxetic PU foam from conventional PU foam

Fabrication procedure of Auxetic foam has been briefly described in the following steps:

a) An Aluminium mould is prepared of 42*42*90 mm^3 which is obtained after dividing the given volume of the conventional PU foam by the Compression ratio.

b) Conventional PU foam of 48.1kg/m^3 was compressed tri-axially in the Aluminium mould fabricated in the last step and then it was kept in a muffle furnace at 200^0C, for 25 minutes.

c) After this, it was taken out of the furnace and then was allowed to cool down to room temperature by keeping it in the air. And the compressed foam was then carefully taken out of the mould.

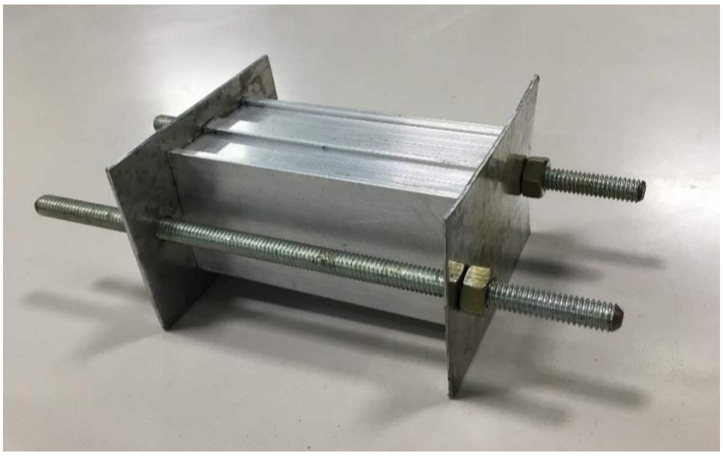


Figure 5: Aluminium mould fabricated in workshop for tri-axial compression.

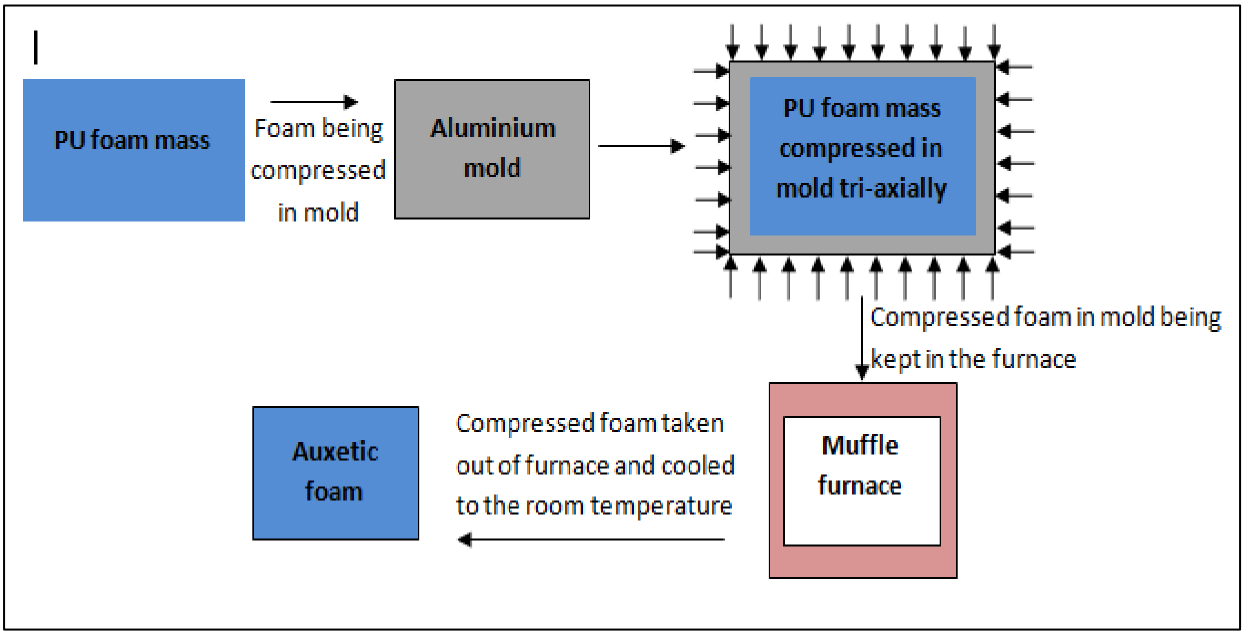
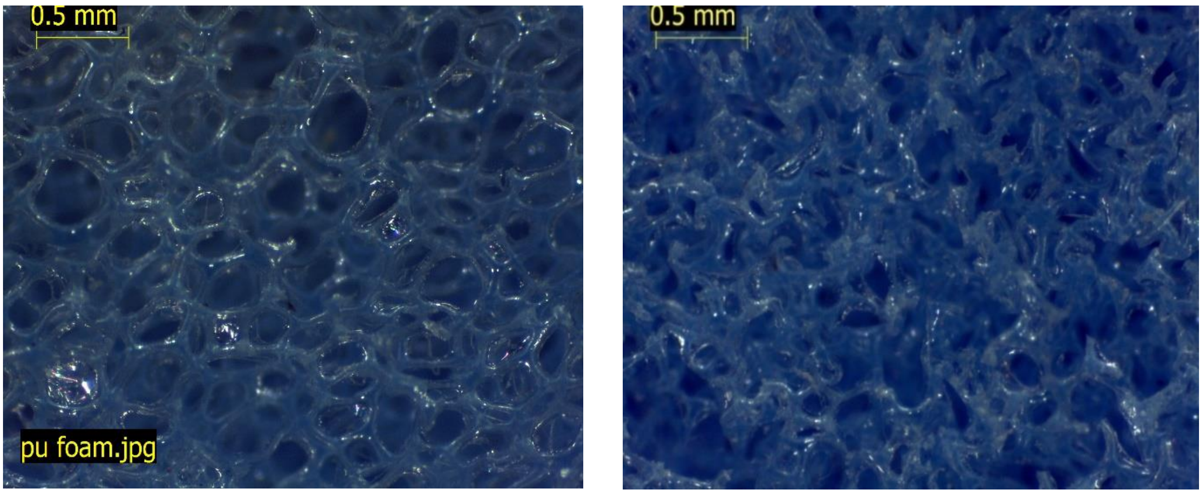


Figure 6: Auxetic foam fabrication process flowchart.

3.2. Microscopic Analysis



7.1 Conventional PU foam. 7.2 Auxetic PU foam.

Figure 7: Images of conventional polyurethane foam and Auxetic PU foam using optical microscope.

Figure 7.1 shows the normal honeycomb structure of the conventional polyurethane (PU) foam, when seen under optical microscope and figure 7.2 shows the re-entrant structure of the Auxetic foam, this change in the microstructure of PU foam has occurred during the tri-axial compression of PU foam. This re-entrant structure is the primary reason for its Auxetic behaviour. While referring to these figures, it can be observed that significant change in the microstructure of the foam has induced, making it denser and compact.

3.3. Calculation of Poisson's ratio

Poisson's ratio was measured based on images acquired from the backend camera of an iPhone 6s, 12 Megapixels, digital camera and processed by using the MATLAB software image processing tools "imshow and ginput". The images were continuously captured in burst mode during quasi-static tests performed with a universal testing machine. The quasi-static tests were performed using a Tinius Olsen universal testing machine. Before mounting the foam samples on the UTM machine three horizontal and three vertical equidistant lines were drawn on the surface of the foam which will give us 9 points and the relative displacement between these points was measured to calculate the Poisson's ratio. The foam was not directly mounted on the Universal testing machine, at first they were glued to an in-house manufactured T joint using epoxy adhesive and then the T-joint was clamped to the machine to prevent slipping of foam while performing the quasi-static test. The dimensions of the sample which were used to perform this test were 42mm x 42mm x 90mm and the tests were performed until breaking of the sample at 12mm/min. Then the images at certain regular intervals were taken to measure the deformation occurred in longitudinal and transverse strain during the testing. Since original dimensions of the foam sample are already known it is possible to calculate the lateral (ε_y) and longitudinal (ε_x) strain.

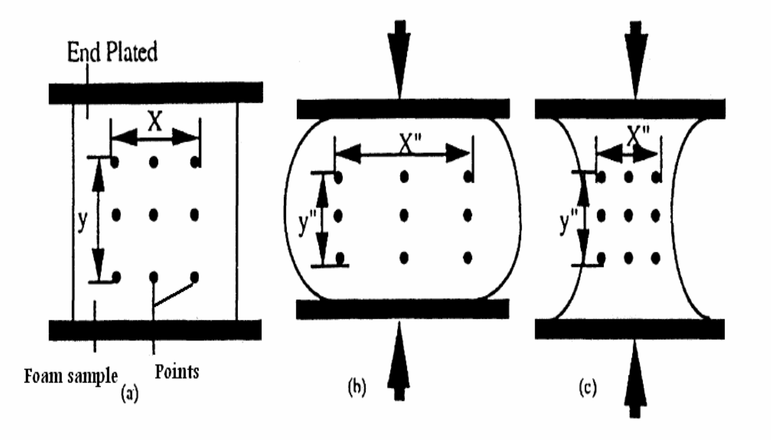


Figure 8: Poisson's ratio using array of points marked on the sample during tensile test.

3.4. Tensile test

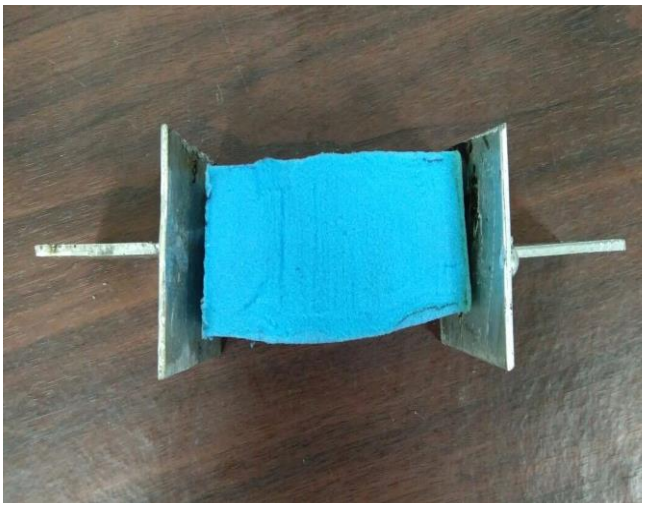


Figure 9: Auxetic PU foam sample pasted to the T joint.

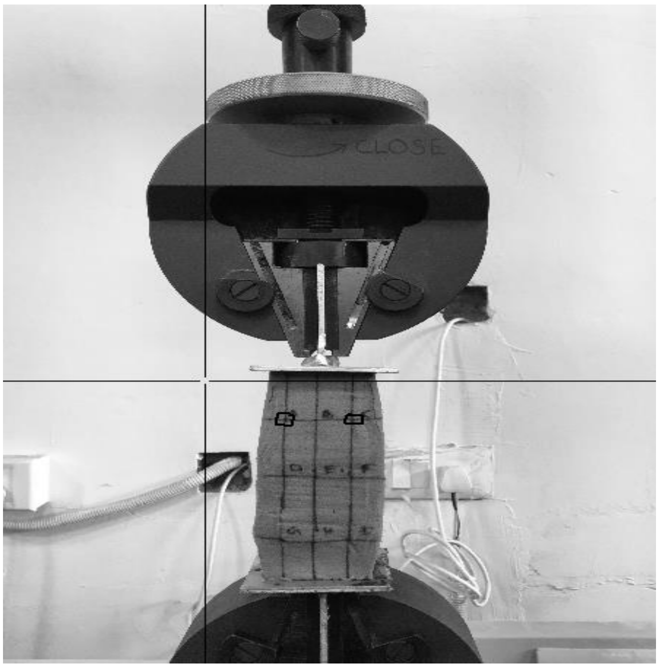


Figure 10: Auxetic PU foam sample mounted on the UTM for tensile test.

An Auxetic foam which was fabricated in 3.1 and was used for tensile testing. The test was performed using Tinius Olsen universal testing machine. In this test, tensile test was performed for both normal and the Auxetic samples of the same dimensions of 42*42*90 $mm^{3.}$ First, Auxetic foam sample was pasted on the T joint as shown in the Figure 9 with the help of epoxy resin and after the drying of resin, which took around 48 hours, the sample was mounted on the UTM as shown in the Figure 10. Foam was stretched at the elongation rate of 12 mm/min.

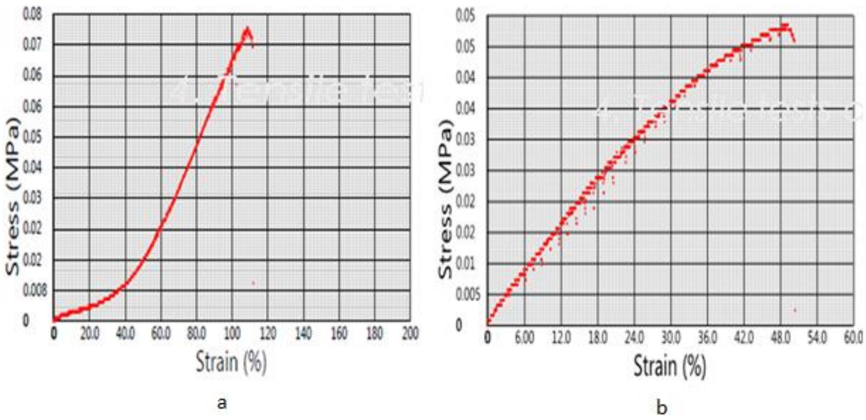


Figure 11: The stress vs. strain graphs obtained in the tensile test for Auxetic foam and conventional PU foam samples respectively.

By comparing the above stress vs. strain graphs of Auxetic and conventional PU foam, we can notice that ultimate stress of Auxetic foam sample is 0.75MPa, which is around 37% higher than the ultimate stress of conventional PU foam i.e., 0.55MPa.

3.5. DSC Analysis

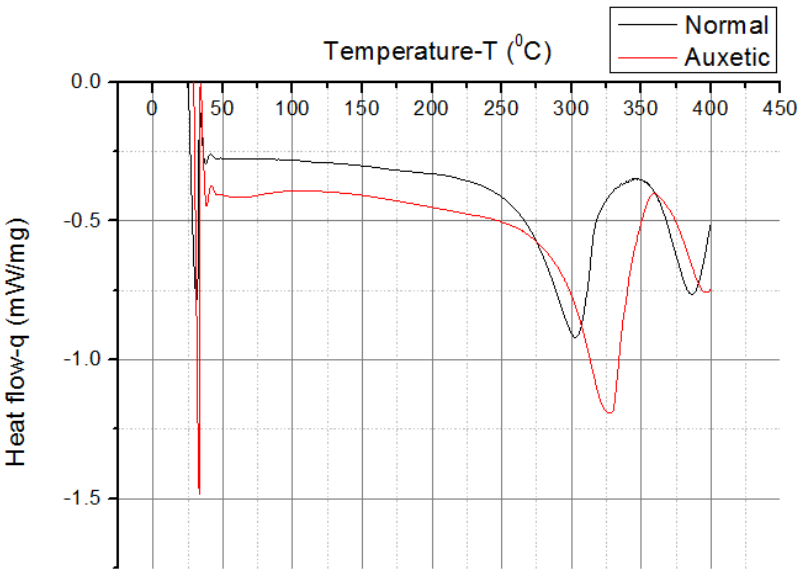


Figure 12: DSC analysis of normal and Auxetic foam.

Differential Scanning Calorimetry (DSC) has been carried out to study the differences in the thermal behavior of conventional PU foam and Auxetic PU foam. DSC analysis of the samples was performed on the DSC 214 *polyma* apparatus. Samples weighing 10mg were heated from room temperature to 400 °C at a heating rate of 10 °C/min. By comparing the DSC curves of these foams one can notice the shift of melting peak from 303.5°C to 325.5 °C, a shift of crystallization peak from 349.5 °C to 359 °C, and an increase in the magnitude of the endothermic peaks. These differences have occurred due to increase in the crystallinity of PU foam during the process of instilling the Auxetic behavior in it. Polyurethane foam is partially crystalline material[6]. In partially crystalline materials, melting peaks increases and shifts to higher temperatures with the increase of crystallinity because polymer chains shifts to lower energy configurations during the crystallization process[7].

3.6. Compression test analysis

The quasi-static compression tests were carried out at speed of 18mm/min. The quasi-static compression tests were applied on three different compression strain levels (25%, 50% and 75%) for all samples. The samples were cut in dimensions 35×35×70 mm. Before starting the experiment, the top flat clamp end is moved up until there is enough space for a sample to easily fit between them. By this way, the machine was adjusted to keep a constant distance of 70 mm between the two flat grips. At this moment the samples were placed between the two flat grips. There is no contact between the top clamp and the sample, so the force of machine is measuring will be set to zero. The grips were lubricated to minimize the friction between the contact surfaces. After that the top clamp was moved lower. The data were acquired in displacement and force on the computer monitor. With the knowledge of the initial sizes of the specimens it was then possible to plot a stress strain curve for every case.

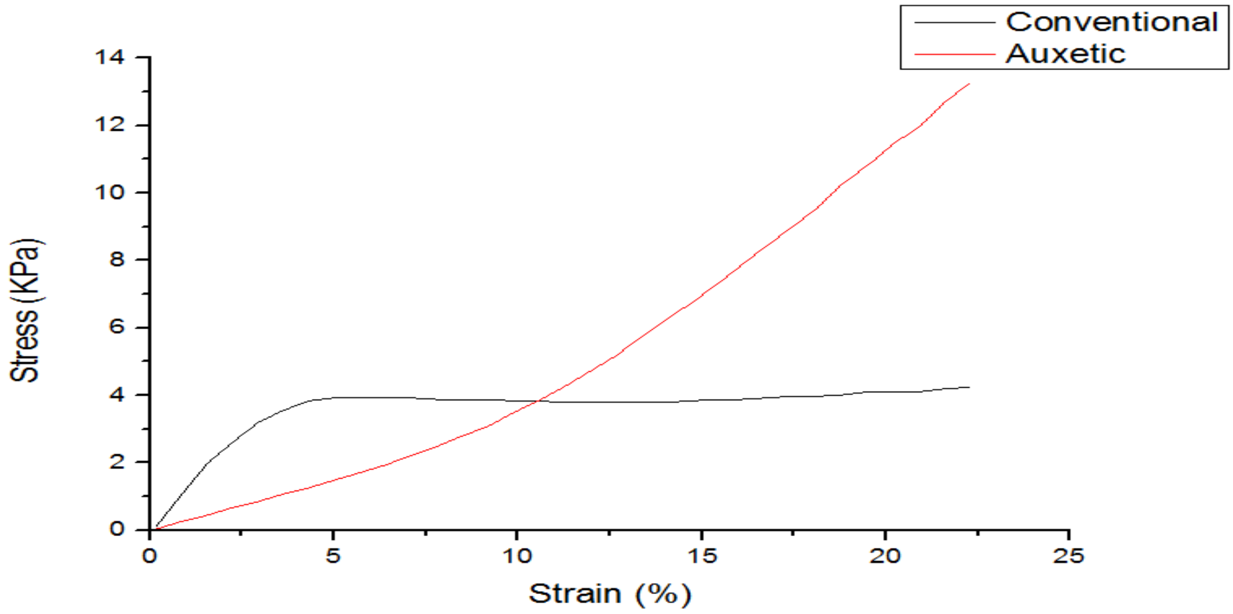


Figure 13: Compression stress- strain curve of Auxetic and conventional PU foam up to 25% strain limit.

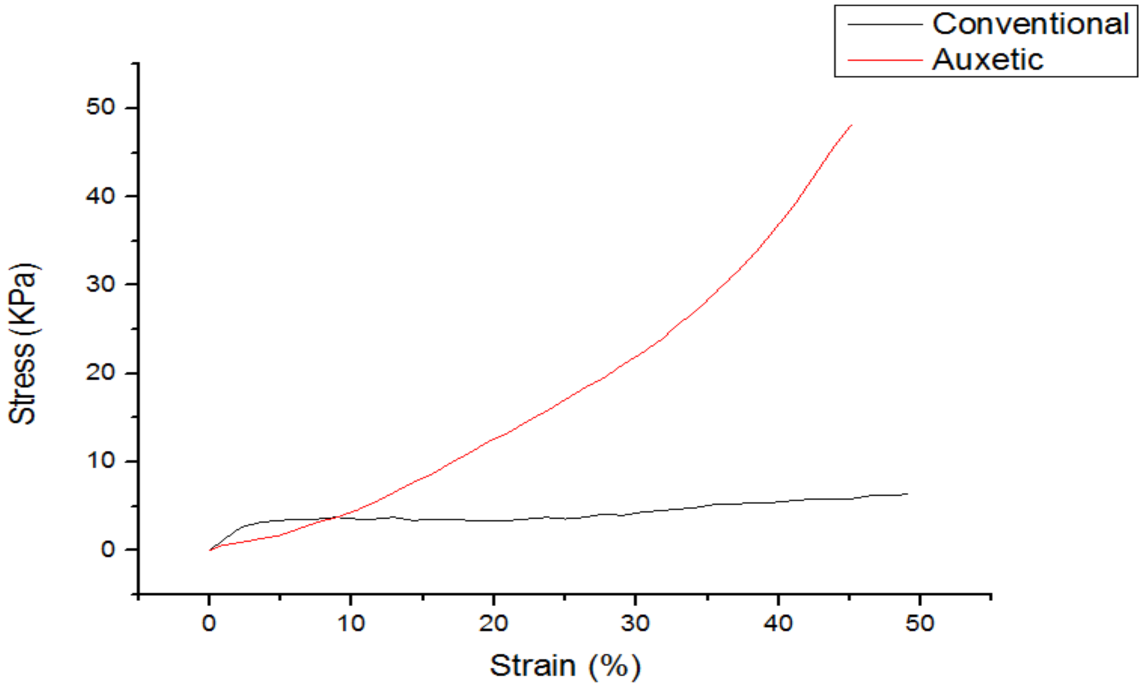


Figure 14: Compression stress- strain curve of Auxetic and conventional PU foam up to 50% strain limit.

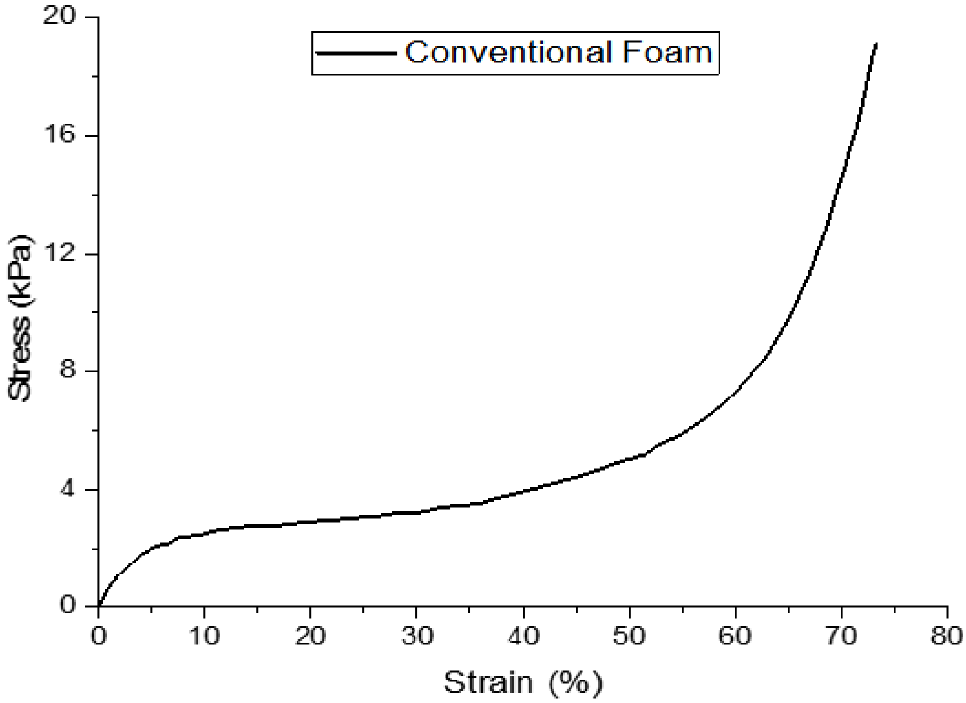


Figure 15: Compression stress- strain curve of conventional PU foam up to 75% strain limit.

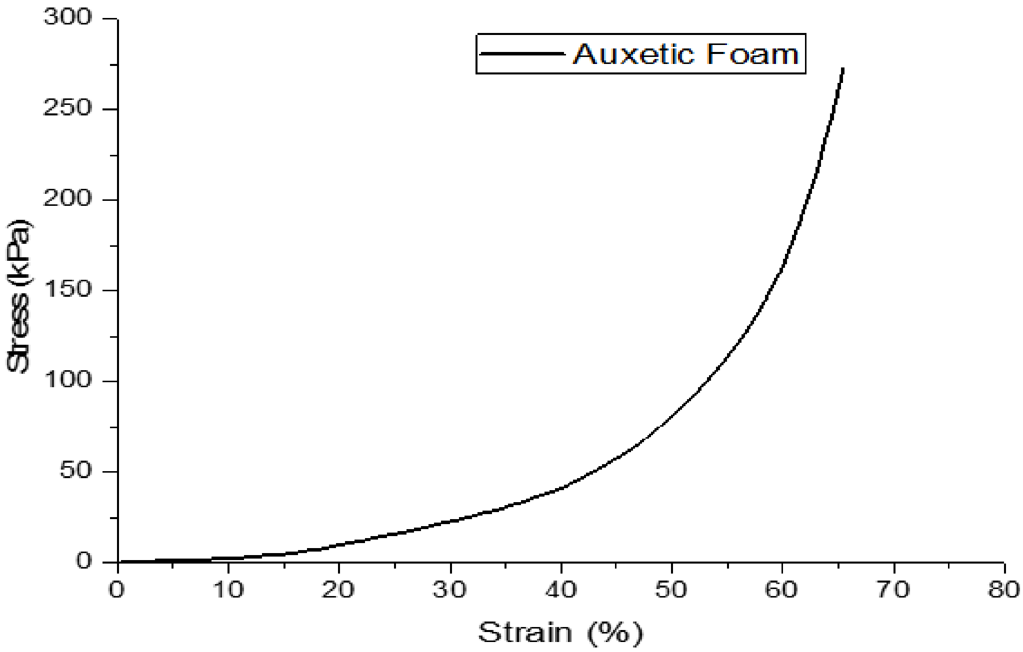


Figure 16: Compression stress- strain curve of Auxetic PU foam up to 75% strain limit.

The compression test is carried out on grey and yellow samples using three strain levels 25%, 50% and 75% for both conventional and processed Auxetic foam. The reason behind the use of these three strain levels is to observe how the processed foam will retain the Auxetic behavior. At the75% compression strain level the material has started to behave as a solid polymeric PU material. Thus, it has been noticed that the Auxetic samples do not reach the required strain level but, it decreases by 10-15 %, when compared to conventional foam.

Generally, for both grey and yellow samples, the conventional foam showed a typical stress strain curve with the well-known plateau with the three regions of the deformation mechanism explained by Gibson and Ashby[8] as follows:

a. Linear elastic region which follows the theory of elasticity.
b. The plateau, which is formed because of the elastic buckling of the unit cell walls.
c. Post-buckling of the unit cell wall or what so called densification of the foam in which the foam behaves like solid polymer.

For all processed Auxetic samples, the stress-strain curve showed different behavior which consists of mainly two regions:

a. Linear elastic region which follows the theory of elasticity, and
b. Post-buckling of the unit cell wall or what is so called as densification of the foam in which the foam behaves like solid polymer.

This behavior can be referred to that the elastic buckling of the wall cells does not occur due to the irregularity of the unit cell which takes the form of a re-entrant hexagon.

Chapter4.Results

1. The results drawn from the microscopic analysis reveal that the microstructure of the normal PU foam has changed from regular honeycomb structure to re-entrant structure. It has become denser and compact.

2. The Poisson's ratio calculations yield the value of Poisson's ratio as -0.72.

3. The tensile test performed proves that the ultimate tensile strength of the foam has increased from 0.55MPa to 0.75MPa for Auxetic foam.

4. From the DSC test analysis, it can be observed that there is a shift in crystallization temperatures and increase in intensity. These differences have occurred due to increase in the crystallinity of PU foam during the process of instilling the Auxetic behavior in it. Polyurethane foam is partially crystalline material. In partially crystalline materials, melting peaks increases and shifts to higher temperatures with the increase of crystallinity because polymer chains shifts to lower energy configurations during the crystallization process

5. The compression test revealed that there is an increase in the compressive strength of the Auxetic material.

Chapter5.Conclusions and future work

Based on present results, the following can be concluded:

1. The present work is focusing on the development of new class of polymeric flexible foam called Auxetic foam which has negative Poisson's ratio. The foam is successfully fabricated using commercial conventional Polyurethane PU foam.
2. The microstructure of the conventional foam and the processed foam has been examined first to compare both of the conventional and the processed foam and second to ensure that the Auxetic behavior will be obtained. The microstructure of the processed foam showed the Auxetic microstructure presented in the literature. Several mechanical tests have been carried out to determine the mechanical properties of the foam. The tests carried out on the conventional and the Auxetic poly PU foam are tensile and compression tests. The following remarks have been concluded:
   a. From the tensile test it can be noticed that the ultimate stress of Auxetic foam sample is 0.75MPa, which is around 37% higher than the ultimate stress of conventional PU foam i.e., 0.55MPa.
   b. In compression testing the conventional foam has showed a typical stress strain curve with the well-known plateau while for all processed Auxetic samples, the stress-strain curve showed different behavior which consists of mainly two regions, linear elastic region and post-buckling of the unit cell wall or what is so called as densification of the foam in which the foam behaves like solid polymer.
   c. Also, in compression stress-strain graph, it can be seen that for the same amount of strain in Auxetic and normal PU foams, higher value of stress is present in Auxetic foam as compared to the normal PU foam. So, from this, it can be concluded that the Auxetic foam is difficult to compress compared to the normal PU foam hence it will be denser at the point of impact and provides better protection again impact force.

The future scope of the research involves:

1. Study of the fatigue life of this foam.
2. And there is a scope to study the response of Auxetic foam Poisson's ratio to different compression ratios used.
3. Impact energy absorption is an important property of this foam, which will be evaluated with the impact energy absorption test set-up and high frequency data collection system.

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