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Study of Non-linear Stress-Strain Curves of Locally Available Low Density Polyurethane Foams

I. D. Ishan Pradeep Iddamalgoda and Ramal V. Coorey
Department of Physics, University of Colombo, Colombo 3

ABSTRACT

This paper describes the design and construction of two experimental setups to study the non-linear stress-strain behaviour of locally available polyurethane (PU) foams of low densities in the range of 12 $-$ 23 kgm^{-3}. The experimental stress-strain curves were parabolic and they showed an elastic region followed by a short plateau region about the maximum stress (collapse stress) followed by a reduction in stress at higher strains. However, they didn't exhibit a long plateau and densification (a rapid increase of stress after collapse stress), which is the usual stress-strain behavior of high density PU foams. Experimental stress-strain curves were used to obtain elastic properties such as Young's modulus, in the range of 7200 – 9900 Nm^{-2}, Bulk modulus in the range of 9000 – 11800 Nm^{-2}, collapse stress in the range 1150 – 2860 Nm^{-2}, and Poisson's ratios in the range of 0.3 – 0.4. All experiments were performed at constant temperature and humidity conditions. Furthermore, power-law relationships $A \propto \rho^n$ were obtained for each elastic property (A) as a function of foam density (ρ) where $-0.02 < n < 1.4$.

1 INTRODUCTION

Polyurethane (PU) foams refer to different types of foam consisting of polymers consisting of a chain of organic units connected by urethane links and are formed by the reaction of at least two isocyanate functional groups. PU foams are classified according their range of densities as solid elastomers, microcellular foams/elastomers, high and low density foams. Low density PU foams are classified as flexible, rigid and semi-rigid foams. PU foams are 'open-cell' foams where a very little energy is absorbed in the linear elastic region but it gives a long flat plateau that allows large energy absorption at constant load [1, 2]. This property of PU foams has been used in many industrial applications such as designing cushion material types, packing, foam-based systems for damping vibrations etc. [1, 3]. For example stiffness of cushion material is a measure of Young's modulus. The mechanism of Goods and co-workers have shown that the mechanical properties (A) of cellular solids are related to their density (ρ) and the relationship is expressed as a power law function, $A = k\rho^n$, where k is a constant and n is the density exponent [4]. Another objective in this research is to find the power law relationship of elastic properties such as Young's modulus, Bulk modulus, collapse stress, Poisson's ratio as a function of density of foam materials. Since, foam density is the parameter that can be measured once the foam is made and power law function is important in determining initial properties of foam materials.

2 EXPERIMENTAL

2.1 Polyurethane foam materials

Polyurethane foams with densities 12, 15, 21, and 23 kg m^{-3} were obtained from one of the reputed local manufacturers. The most appropriate sample size of the foam was determined initially by considering ten samples of foams of a given density having standard thicknesses and cross sectional areas. Each one was tested within the range scale of the balance. The initial thickness and the cross sectional area of the sample were found to be as 60.000 ± 0.005 mm and 25.000 ± 0.001 cm^2 respectively. Three samples of foams of this thickness and cross sectional area from each density were considered to take measurements.

2.2 Design and construction of the experimental setup to study the linear stress-stain behavior of foam materials

Young's modulus (E) of an isotropic elastic material is defined as the ratio of the uni-axial stress over the uni-axial strain in the elastic region in which Hooke's Law is valid

$$\text{Young's modulus}\left(E\right)=\frac{\text{stress}}{\text{strain}}=\frac{F/A}{\delta L/L}$$

In order to determine the variation of linear stress as a function of linear strain for a given foam of cross sectional area A and height L, the required variable parameters to be measured are the applied uni-axial force (F) and change in height of foam (δL).

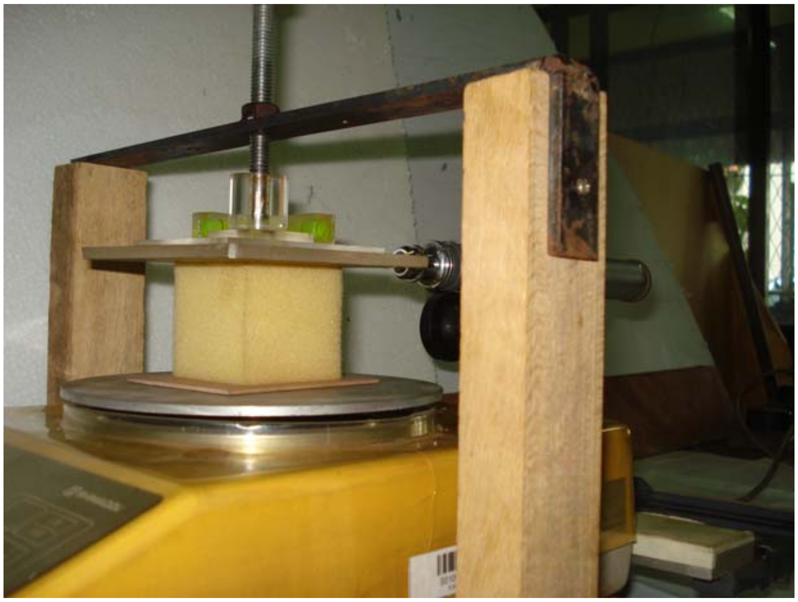

Fig. 1: The experimental setup used to measure linear stress-strain behaviour of foam materials

The experimental setup designed and constructed for this purpose is shown in Fig. 1. A Perspex plate was kept underneath a PU foam and the system was kept on a top pan balance (Shimadzu, Japan). In order to apply the uni-axial compressive force very slowly on the foam material a special mechanism was adopted. A clamped stand was used to bear the screw of piston which compresses the foam material such that the piston could be moved vertically without rotating its own axis and hence a uniaxial force could be applied on to the foam material. The top pan balance (Shimadzu, Japan) and the travelling microscope (Pika Seiko Ltd., Japan) were used to measure the applied uni-axial force and the change in height of the foam material. Two liquid levels were used to ensure that the piston was at a horizontal position throughout the measurements.

2.3 Design and construction of an experimental setup to study the volumetric stress-strain behavior of foam materials

The bulk modulus (*K*) of a substance measures the substance's resistance to uniform compression. The bulk modulus is defined as the pressure increase needed to cause a given relative decrease in volume or the ratio of volumetric stress to volumetric strain in the elastic region in which Hooke's Law is valid.

$$\text{Bulk modulus}\left(K\right)=\frac{\text{Volumetric stress}}{\text{Volumetric strain}}=\frac{\delta P}{\delta V/V}$$

In order to determine the variation of volumetric stress as a function of volumetric strain for given foam of volume *V*, the required variable parameters to be measured are the applied uni-axial force (*F*) and volume change of the foam material (δV).

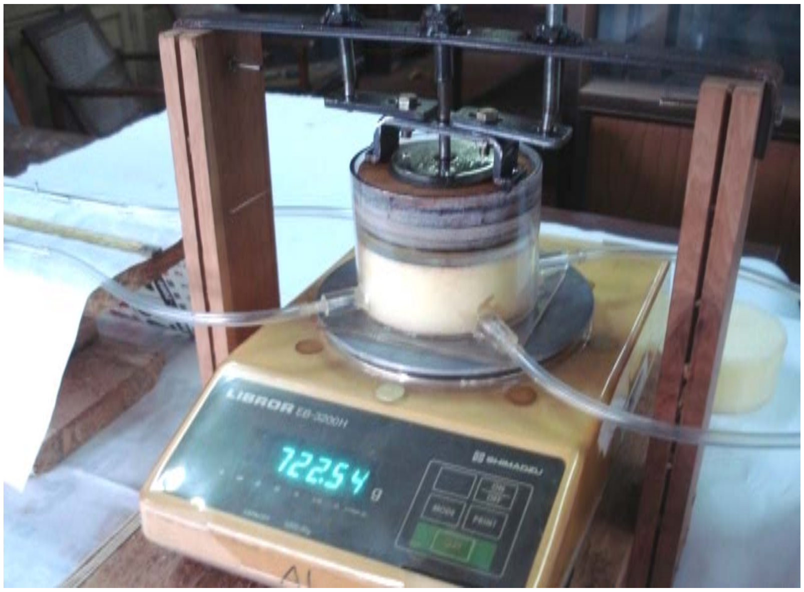

Fig. 2: The experimental setup used to measure volumetric stress-strain behaviour of foam materials

As shown in Fig. 2, the constructed experimental set up consists of a piston controlled by the center-screw which was used to apply a uni-axial force on to the foam material and the piston controlled by the corner screws was used to compress the volume of the foam material inside a cylindrical container. The clamped stand was used to bear the screws of the pistons by which the uni-axial force was applied on to the foam material and pressed the air inside the container. The change in volume was measured by the displaced length of a mercury bubble in four capillary tubes connected to the cylindrical container with flexible tubes.

The piston consists of three o-rings, an insulation layer, thread seal layer and an air seal which were used to prevent release of air in the cylindrical container to the outside environment except from capillary tubes and to keep the balance of the whole piston. The measured average radius of the cylindrical container was 47.510 ± 0.002 mm and the average radius of four capillary tubes was 2.15 ± 0.002 mm. A top pan balance was used to measure the applied uni-axial force applied to the foam material and to measure the volume change (movement of the mercury bubble in the capillary tubes) the meter scale was used.

3 RESULTS AND DISCUSSION

3.1 Linear stress- strain behaviour and collapse stress of foam materials

The stress-strain curves for foam materials with different densities are illustrated in Fig. 3.

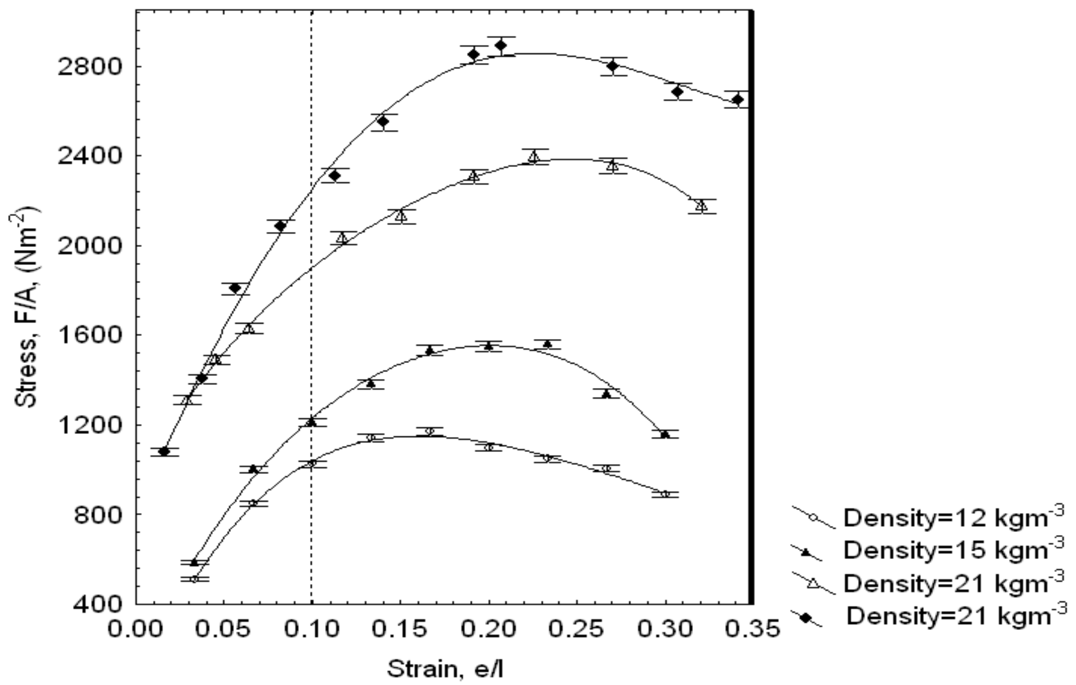

Fig. 3: Stress- strain curves of PU foams with different foam density

When foam material of different densities is compressed, the all the observed stress-strain curves were parabolic in shape and hence there exists a maximum value of stress (i.e. collapse stress) for a given strain. The experimental curves do show a region of linear elasticity but do not exhibit a long plateau and densification (a rapid increase of stress after collapse stress), which is the usual stress-strain behavior of high density PU foams (density > 100 kg m^{-3}) [1, 2, 4]. All foam materials used in this study are low density PU foams and they show a short plateau regime about the maximum stress followed by a reduction in stress at higher strains. This may be the characteristic stress-strain behaviour of low density PU foams.

Table 1 : The collapse stress at various foam densities

Foam density (kgm^{-3})	Collapse stress (Nm^{-2})
12	1158
15	1560
21	2387
23	2856

The Table 1 shows observed values of the collapse stress as a function of foam densities. The variation of the collapse stress with foam density can be expressed in power law relation

$$\text{Collapse stress} = 39.865\ \rho^{1.3541}$$

3.2 Linear stress-strain behaviour and Young's modulus of the foam materials

The Fig. 4 illustrates stress-strain curves of PU foam materials in elastic region for different densities. The strain values less than 0.1 is the criterion used to select the proper linear region for all stress-strain curves shown in Fig 3. The Table 2 shows the gradients' of stress-strain curves for different densities. It implies that the Young's modulus is increased with the density. The observed values of Young's Modulus are in the range 6.2 – 8.6 kPa which is approximately ten times lower than published results for Young's Modulus of Foamex, a flexible low density PU foam [5].

Table 2: Observed values for the Young's modulus

Density (kgm^{-3})	Young's modulus (Nm^{-2})
12	7232 ± 46
15	7943 ± 24
21	9183 ± 33
23	9863 ± 31

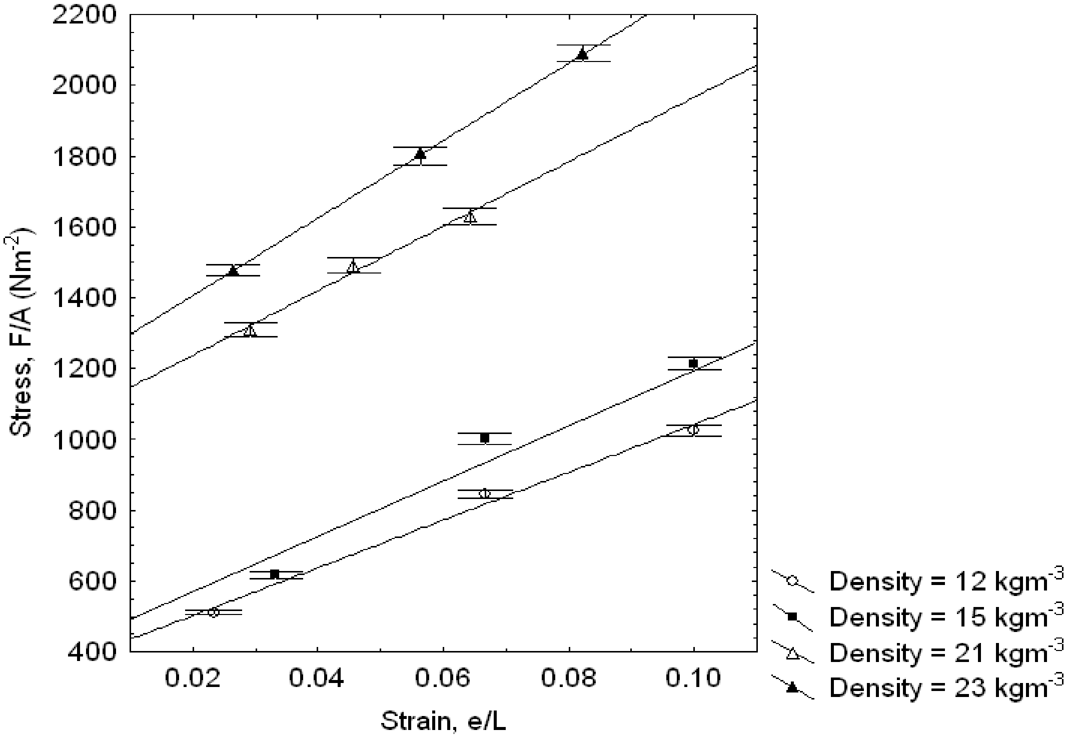

Fig. 4: Linear stress- strain behaviour with foam density in elastic region

The variation of the Young's modulus with foam density can be expressed in power law relation

$$\text{Young's modulus} = 2183.97\,\rho^{0.4791}$$

3.3 Volumetric stress-stain behaviour and Bulk modulus of foam materials

The distributions of volumetric stress-strain behavior for different foam materials at low strain values are illustrated in Table 3 and Fig. 5. All variations are in the elastic region and the observed values of bulk modulus are in the range 9.0 – 11.8 kPa.

Table 3: Observed values for the Bulk modulus

Density (kgm^{-3})	Bulk modulus (Nm^{-2})
12	9042 ± 24
15	9649 ± 18
21	11074 ± 34
23	11756 ± 29

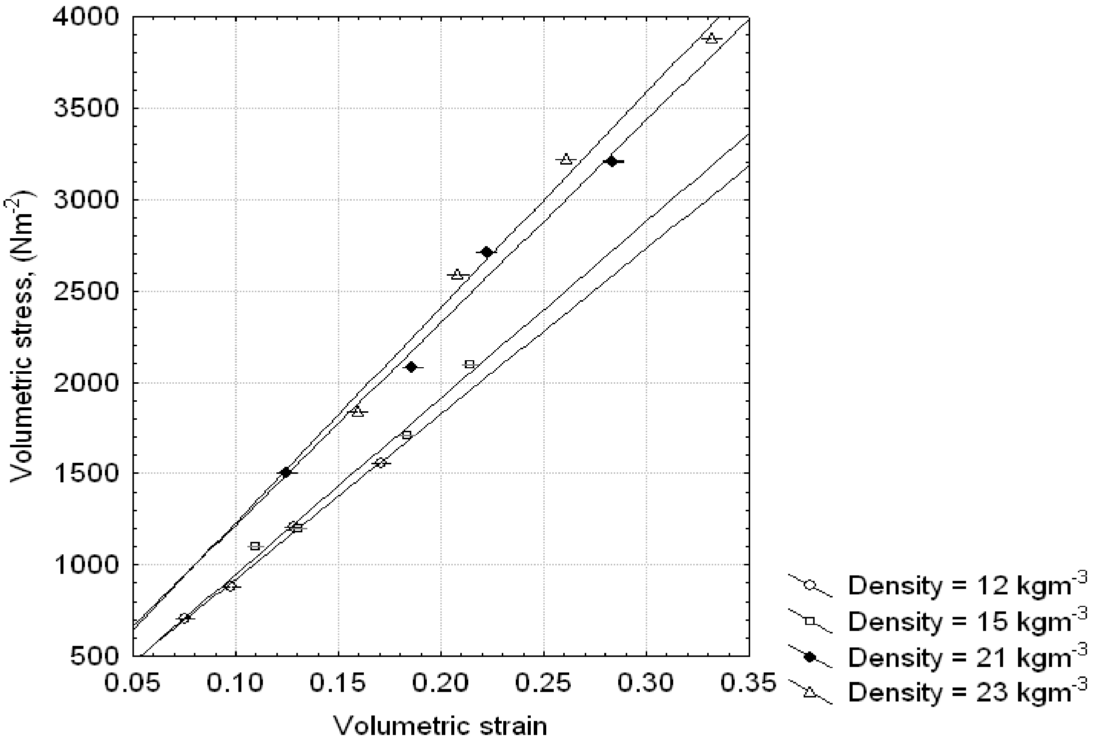

Fig. 5: Volumetric stress-strain behaviour with foam density at low strain values

The variation of the bulk modulus with foam density can be expressed in power law relation

$$\text{Bulk modulus} = 3320.59\,\rho^{0.3989}$$

3.4 Poisson's ratio of foam materials

The Poisson's ratio (μ) is given through the relation $E = 3K(1 - 2\mu)$, where E is the Young's modulus and K is the bulk modulus. Table 4 summarizes the observed values of μ for different densities of PU foams.

Table 4: Observed values for the Poisson's ratio

Density (kgm^{-3})	Poisson's ratio
12	0.367 ± 0.024
15	0.363 ± 0.036
21	0.362 ± 0.024
23	0.360 ± 0.033

The variation of the Poisson's ratio with foam density can be expressed in power law relation

$$\text{Poisson's ratio} = 0.3884\,\rho^{-0.0239}$$

Poisson's ratio is decreased with increasing foam density. Previously published results on cellular materials including polymeric foams Poisson's ratio are in the range 0.1 – 0.4 [6].

4 CONCLUSION

Two experimental setups were designed and constructed to study the non-linear stress-strain curves of locally available low density polyurethane foams. Useful elastic properties such as Young's modulus, bulk modulus, Poisson's ratio and collapsed stress were determined for polyurethane foams of different densities. Power-law relationships were obtained for each elastic property as a function of foam density.

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