An Experimental Study on Mechanical Behavior and Microstructures of Polyurethane Foams for Design Applications

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Received on 13/02/2010; Accepted on 30/07/2010

Abstract
A unified study on mechanical characterization and correlation with microstructures of three major varieties of polyurethane foam namely, viscoelastic (VE), high resilience (HR), and semi-rigid (SR), with engineering design applications in mind has been reported here. Cubical foam samples of VE, HR and SR varieties and different densities are tested under compressive loading. The recorded force-displacement data is used to clarify the distinct behaviors of short-term and long-term recovery of VE and HR foams, and crushability of SR foam. It is pointed out that foam of a given type can be suitable for a particular engineering design application based on its recoverability, strength and energy-absorption attributes. A possible relation between foam cellular structure and its mechanical behavior has been discussed.

Keywords: Polyurethane foam; Viscoelastic; High resilience; Semi-rigid; Compression test; Closed cell; Open Cell; Load-displacement; Energy-absorption.

1. INTRODUCTION

Foams are cellular materials that can be made of metals, polymers, ceramics, glasses and even composites. Their mechanical properties depend to a great extent on cell configuration (i.e. open or closed, size, shape, etc.), cell wall thickness and overall density [1]. High strength-to-weight ratio and specific energy absorption capability (i.e. energy absorbed per unit mass) under compressive loads are key attributes of foams. Polymeric foams such as polyurethane (PU) and polystyrene foams comprise the widest variety of foams in terms of applications. Considering mechanical behavior, such foams can again be broadly classified as: viscoelastic (i.e. recoverable) and rigid (i.e. crushable). The former category is suitable for repetitive use such as in seat cushions while the latter type of foam is preferred for applications requiring impact energy absorption with higher stroke as a main performance objective. Energy absorbing PU foams are frequently used as vehicle occupant protection countermeasures in doors and instrument panels, or even for improving vehicle crashworthiness in low velocity impact as packaging in front and rear bumpers. Expanded polystyrene foams with their relatively higher strength are often found as protective liners in motorbike crash helmets.

Foams in general, when subject to compressive loading, exhibit a typical stress-strain behavior shown in Fig. 1. The initial linear part is generally treated as representing elastic behavior followed by a zone of plastic yielding which may continue till 60–80% of foam deformation. The latter phase is also referred to as a plateau region as indicated in Fig. 1. The last stage is the densification phase in which compressive force in foam rises steeply while little energy absorption takes place as compared to the previous plateau zone. The plateau region may be considered as the most important phase of a given foam for energy absorbing applications.

Polymeric foams have been studied widely in literature in terms of their microstructures, phenomenological behavior, and engineering applications. A number of investigators have also focused

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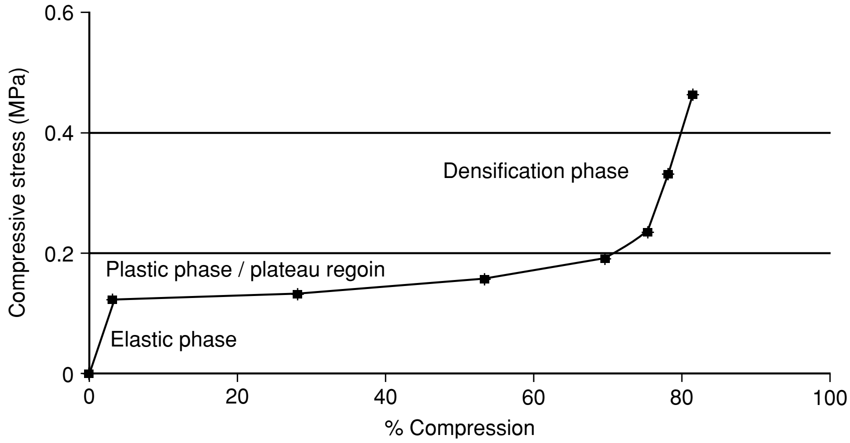

Figure 1. Typical stress-strain behavior of polymeric foam.

on the yielding of polymeric foam under uniaxial and multiaxial compressive loads, structural efficiency, energy absorption attributes, and effects of density and strain rates on engineering properties [2–6]. Shaw and Sata [2] found the yield criterion for a cellular material to be the maximum compressive stress when experiments were performed on foamed polystyrene under a variety of loading conditions. Maiti, Gibson and Ashby [3] studied the mechanical properties of three types of cellular solids (flexible, plastic and brittle) as a function of density. Saha et al. [4] considered polyvinyl chloride (PVC) and polyurethane (PU) foams under compressive loading at low (0.001–0.1s^{-1}) and high (130–1750 s^{-1}) strain rates. The authors studied the effects of foam density, foam microstructure and strain rate on peak stress and energy absorption. The densities of foam considered were relatively on a higher side (100–300 kg/m^3). Kurauchi et al. [5] tried to explain the energy-absorption mechanism of polymeric foams with progressive "layer by layer" crushing of cells beginning with the layer containing the weakest cell. Hinkey and Yang [6] investigated the behavior of polyurethane foams over a range of densities and strain rates, and derived empirical relations for modulus of elasticity and yield stress as functions of density. As revealed in these published studies, polymeric foams exhibit a high degree of dependence on dynamic strain rate compared to solid metallic materials. This dependence is due to the solid material properties and to the presence of a fluid, generally air, inside the foam [7].

A majority of investigations appear to have focused on the mechanical behavior of PU foams of different types, although some authors have also reported their microstructures [3, 8, 9] and their effects on selected foam properties or behavior. The cell structures and configurations of PU foams can typically be seen in SEM (scanning electron microscopy)-based micrographs. To the authors' best knowledge, a comparison of main types of PU foams which can be distinguished in terms of their mechanical behavior and design applications, and the possible correlation of these behaviors with their microstructures has not been reported in published literature. By conducting static compression tests (at a cross-head speed of 1 mm/min, i.e. an average strain rate of approximately 0.0017 s^{-1} for a foam specimen of 50 mm height) on three varieties of foam cubes obtained through variations in isocyanate and polyol reactants, and examining the recorded force-displacement relations, their interpretation as viscoelastic (VE), high resilient (HR) and semi-rigid (SR) foams has been explained. Additionally, with the help of SEM images, the possible correlation of cell configuration (i.e. predominantly open or closed) on mechanical attributes such as geometric recovery and specific energy absorption has been pointed out. Considering the dependence of mechanical properties of PU foam on strain rate as noted already, it needs to be mentioned that further studies are needed to confirm the connotations of VE, HR and SR foams under dynamic and impact loading conditions.

2. FOAM SAMPLES FOR COMPRESSION TESTS

Molds of size 50 × 50 × 50 mm^3 were initially made using perspex sheets. Foam samples were then fabricated by mixing polyol and isocyanate compounds of appropriate types in different proportions. Three types of foam namely, HR, SR and VE of different densities, were obtained and are shown in Fig. 2. The trade names of the reactants used for making HR, SR and VE foam specimens along with the relative proportions of these compounds as recommended by the supplier are given in Table 1. The

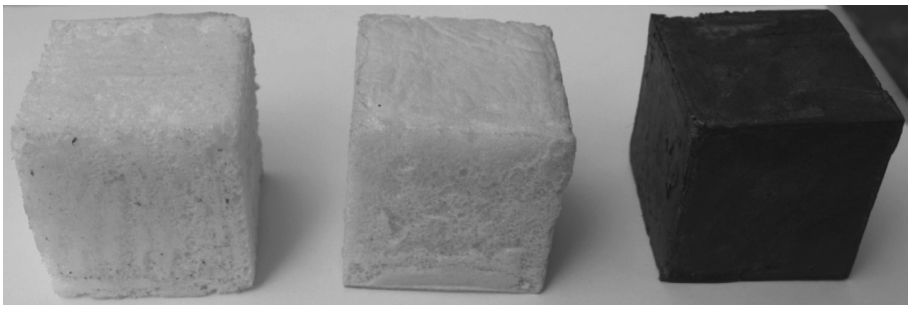

Figure 2. Typical SR, HR and VE (from left to right) foam samples.

Table 1. Trade names of reactants (i.e. polyol and isocyanate) used in the formulation of VE, HR and SR foams

Foam type	Polyol	Isocyanate	Recommended ratio by volume (Polyol:Isocyanate)
VE	Daltoflex JI 85320	Suprasec 6456	100:50
HR	Daltoflex JC 85220	Suprasec 6456	100:55
SR	Daltoflex JC 85220	Suprasec 5005	100:65

nominal proportions of polyol and isocyanate given in Table 1 had to be varied for formulating foam samples of different densities.

It may be noted that the VE foam is black in color while HR and SR foams are predominantly creamish. The gross density of each foam sample was obtained by dividing its measured mass by its total volume. The fabricated foam cubes were separately subjected to compression tests in a standard Universal Testing Machine (UTM). Each sample was crushed approximately to 70% of its original length of 50 mm in the crush direction. Design of applications using PU foam needs to be preferably done within this phase as beyond a deformation of 70% in the loading direction, densification can set in causing foam load response to rise sharply. A continuous digital record of compressive load and corresponding axial shortening (displacement) was made during a given test.

3. IDENTIFICATION OF FOAM TYPE USING COMPRESSION TEST RESULTS

For each variety of foam i.e. VE, HR or SR, two samples of different densities were subjected to quasi-static axial crush; thus a total of six tests were carried out. A summary of experimental data generated from the six compression tests mentioned is presented in Table 2. Load-displacement curves for the tested foam samples are given in Figs. 3 through 5 with two curves in each figure for the same type of foam. For a given test, the total energy absorbed by the relevant foam sample at 70% axial crush is given by the area under the force-displacement curve for that test. The specific energy absorption is then obtained by dividing the total absorbed energy by the measured mass of the foam sample.

Table 2. Details of foam samples and results obtained from compression tests

Foam sample identification	Mass (gm)	Density (gm/cc)	Total energy absorbed (J)	Specific energy absorption (J/gm)
VE-1	18.2	0.146	5.272	0.2896
VE-2	11.2	0.0896	2.734	0.2441
HR-1	9.4	0.0752	2.2452	0.2388
HR-2	8.8	0.0704	2.0954	0.2381
SR-1	9.0	0.072	4.0453	0.4494
SR-2	8.4	0.0672	3.1107	0.3703

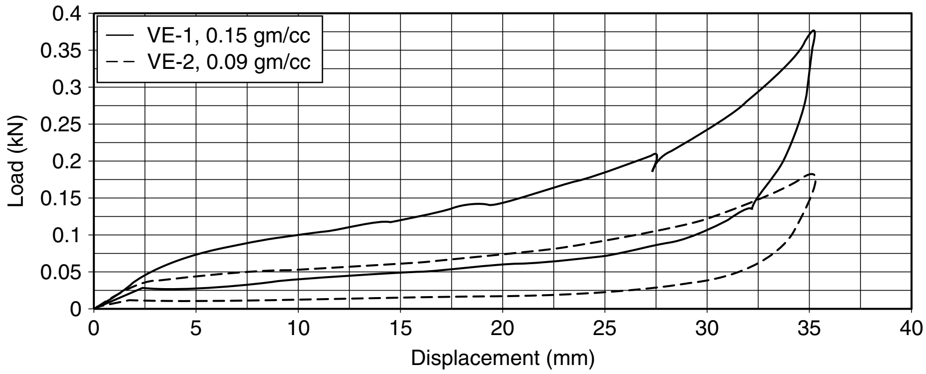

Figure 3. Compressive load versus axial displacement curves for foam specimens of assumed type VE.

Referring to Figs. 3 through 4, it can be immediately concluded that terming a given PU foam as VE, SR or HR depends on its mechanical behavior in the unloading phase. Each of the foam load-displacement curves in Fig. 3 indicates immediate recovery of foam deformation during the unloading phase. By dividing the load at any instant with the original foam sectional area, nominal stress can be obtained. Also, engineering compressive strain can be computed by dividing the change in volume with the undeformed volume of a given foam sample. The resulting stress-strain curve will have a similar shape as the corresponding load-displacement curve. The type of behavior exhibited in Fig. 3 by each relevant foam sample is regarded as viscoelastic as the final short-term residual strain is practically zero combined with the fact that plateau strength (defined in a previous section) is a function of strain rate. This latter aspect (i.e. quantification of strain rate dependence) has not been studied here.

Additionally, it is seen especially for the curve with solid line in Fig. 4 that there is initially a residual displacement of about 22.5 mm, however, there appears to be a gradual recovery towards the origin along the x-axis (i.e. the displacement axis). The dashed line in Fig. 4 points out to a small initial residual displacement. A physical inspection of the two tested samples for which the load-displacement curves are given in Fig. 4 revealed that, in the long run, the foam samples all but regained their original shape and size. The foam of this behavior has been termed as HR due to its resilience i.e. ability to rebound although in a different manner with respect to time compared to the VE foam.

The load-displacement behaviors displayed in Fig. 5 can be immediately distinguished with respect to those in Figs. 3 and 4. Permanent near-term displacement is seen at the end of loading phase for each case in Fig. 4. Substantial residual axial deformation was observed even long after tests were completed in each of the relevant foam specimens. A foam of this type can thus justifiably be called as SR i.e. semi-rigid. In an extreme case, such foams are also termed as ‘rigid’ due to their tendency to turn into a fragmented (i.e. amorphous) state on being crushed.

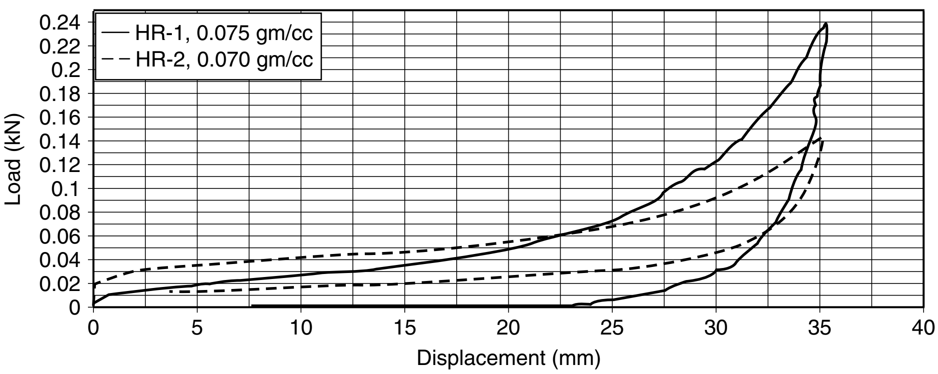

Figure 4. Compressive load versus axial displacement curves for foam specimens of assumed type HR.

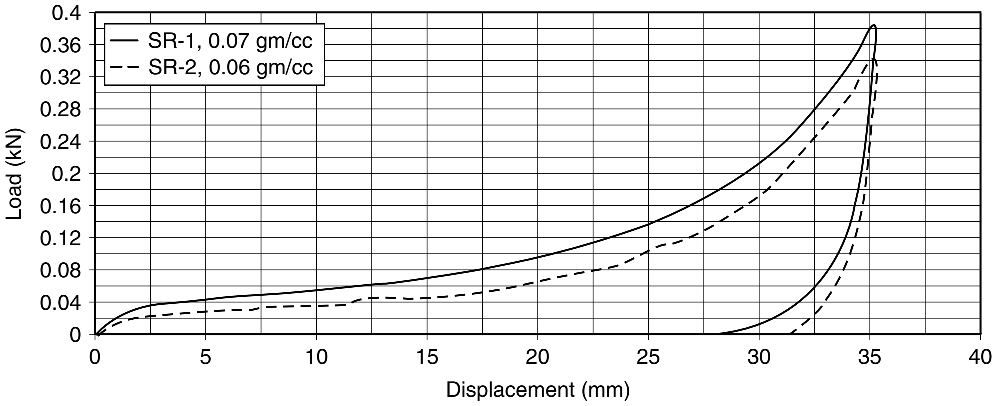

Figure 5. Compressive load versus axial displacement curves for foam specimens of assumed type SR.

A further observation, in terms of energy absorption, is due for the present categories of foam from Table 2. The total energy absorbed by each foam sample is given in the fourth column of Table 2; the energy absorbed per unit mass (i.e. specific energy absorption) is a normalized parameter and is given in the last column of the same table. This latter parameter can be used for comparing the efficiencies of the present varieties of foam in terms of energy absorption. It is seen that specific energy absorption is higher for SR foam when compared to VE and HR foams. Thus, SR foam can be typically more suitable for automotive impact safety countermeasures where energy absorption is a major target, while VE and HR foams can be useful in environments in which geometric form and functionality need to be retained under repeated application and withdrawal of load.

Confidence in the repeatability of the qualitative behaviors, especially under unloading, could be further increased by adding more samples to each of the foam type (i.e. VE, HR and SR). However, the distinct differences in unloading behaviors seen in Figs. 3–5 for every pair of samples corresponding to VE, HR and SR foam justifying the names of the latter is too unlikely to be caused by mere coincidence. Figs. 3–5 also show the effect of density on foam. As the difference in density is marginal between the SR foam samples tested, the load-displacement responses for these cases are also close to each other as apparent in Fig. 5. Foam strength in general increases with rising density which is also confirmed qualitatively in Figs. 3–5. For a given type of foam, samples of a number of different densities need to be tested in order to quantitatively lay down the effect of density on foam mechanical properties. However, the objective here has been mainly to study the qualitative differences in load-displacement responses of VE, HR and SR foams especially with respect to unloading.

4. A MICROSTRUCTURE-BASED STUDY OF VE, HR AND SR FOAMS

In terms of microstructure, PU foams can be classified into two major categories i.e. ‘open cell’ or ‘closed’. The formation of closed or open cells can be linked to the main reactions, i.e. blow and gelation, which take place during the production of PU foams. If the gelation reaction, or cross-linking, occurs too quickly a tight close-celled foam may result; on the other hand, if the blow, or gas-producing, reaction occurs too quickly it may lead to an open-cell foam [8]. The cells of closed-cell foams are tiny enclosures with walls of variable thickness and are predominantly closed units filled with trapped gases. The cell-walls in an open-cell foam are largely perforated resulting in a grid-like microstructure.

Images of the cellular structures of VE, HR and SR foams studied here have been captured using a scanning electron microscope. Initially, foams were identified as VE, HR or SR with the help of load-displacement curves as explained in the previous section. In order to probe the microstructure of a given variety of foam, an untested sample (as shown in Fig. 2) was sectioned along a plane perpendicular to one its three dimensions with a band saw and then coated with gold particles using an ion sputtering device. Photographs of the treated cross-section were next taken at different magnification (zoom) levels as shown in Figs. 6 through 8 for VE, HR and SR foam specimens respectively. The micrographs, especially the images of higher magnification, corresponding to VE

(a) (b)

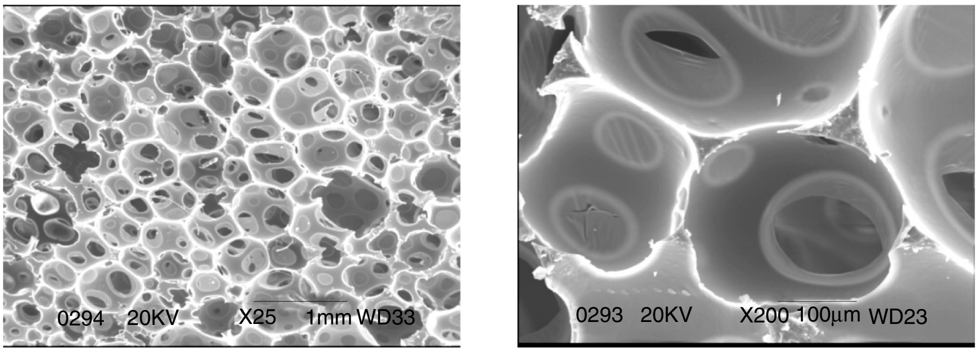

Figure 6. Microphotographs of VE foam at (a) lower and (b) higher magnifications.

(a) (b)

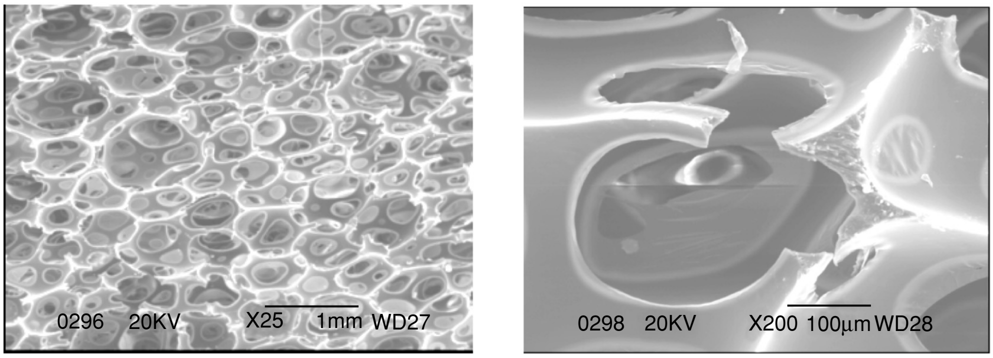

Figure 7. Microphotographs of HR foam at (a) lower and (b) higher magnifications.

and HR foams (in Figs. 6 and 7 respectively) indicate that cell faces are made of thin continuous membranes. The latter conclusion is also based on the observation that the magnified individual cells in the images given in Figs. 6(b) and 7(b) lack hollowness and possess grey shades due to reflection of light from the intact cell membrane walls. The cells in VE foam, however, appear to be more uniform in size and tightly packed as compared to the HR variety. The cells of SR foam are depicted in Fig. 8(a). These cells are less uniform geometrically as compared to the VE and HR foam cells. A closer scrutiny of SR foam cross-section with a high magnification level in Fig. 8(b) points out to see-through structures of cells; thus, SR foam can be considered to be principally of open-cell type.

In addition to examining the microstructures of undamaged PU foam samples, SEM images were obtained from cross-sections of foam specimens which were already tested quasi-statically under compressive loading conditions. Magnified images of VE and HR foam cells indicated that, despite the

(a) (b)

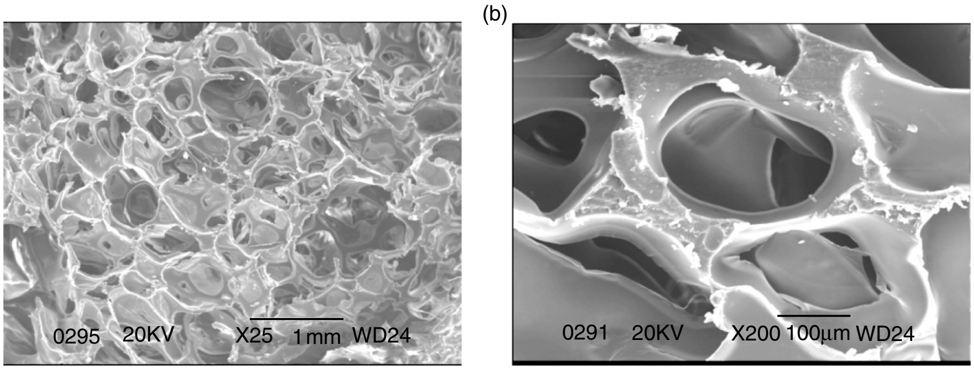

Figure 8. Microphotographs of SR foam at (a) lower and (b) higher magnifications.

deformations undergone, the cells did not loose their closed configurations. This may have contributed toward the VE and HR foam specimens regaining their original shape and size on withdrawal of load. On the other hand, extensive damages observed in the solid regions separating the voids in a tested SR foam specimen bear testimony to the high residual deformations witnessed in SR foam in axial compressive tests.

It needs to be pointed out that SEM micrographs were generated from more tested specimens; however, the general observations made above remained valid.

5. CONCLUSIONS

By mixing isocyanate and polyol compounds of different grades in varying proportions, three varieties of polyurethane (PU) foam, namely viscoelastic (VE), high resilient (HR) and semi-rigid (SR), of different densities were obtained. By carrying out compression tests on cubical foam specimens of size $50 \times 50 \times 50$ mm^3 and examining the load-displacement results obtained, the reasons for naming the foams as VE, HR and SR are outlined. This differentiation clearly drives home the suitability of these foam types for various design applications in which one or more parameters such as preserving geometry under repetitive loads, strength, and energy-absorption can be the design target(s). In particular, the SR foam is found to have higher mass-specific energy absorption when compared to VE and HR foams. SR foams, however, undergo permanent deformation on application of compressive load while VE and HR foams regain their original geometric configuration on removal of applied load. The recovery of VE foam is quicker than that of HR foam; also, the plateau strengths of VE and HR foams may not be the same for similar density. Foams such as VE and HR are sometimes called as 'recoverable' and the SR variety as 'crushable'. The reason for the distinct differences in the mechanical behavior of PU foam may lie in their microstructures. SEM images of the current foam varieties indicate that the recoverable VE and HR foams are predominantly made of closed cells while the crushable SR foam contains open cells. To the authors' best knowledge, a unified study on mechanical characterization and correlation with microstructures of three major varieties of PU foam with engineering design applications in mind has not been reported before.

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