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Characterization of commercial rigid polyurethane foams used as bone analogs for implant testing

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Abstract Mechanical properties and microstructure characterization of a series of graded commercial rigid polyurethane foams commonly used to mimic trabecular bone in testing orthopaedic devices is reported. Compressive testing conducted according to ASTM standard F1839-08, which requires large specimens (50.8 mm × 50.8 mm × 25.4 mm blocks) gave elastic modulus and compressive strength values ranging from 115 to 794 MPa and 4.7 to 24.7 MPa, respectively, for foams having densities of 0.240–0.641 g/cm^3. All these results were within the requirements of the specification for the corresponding grades. Compression testing using smaller specimens (7.5 mm diameter × 15 mm) typical of testing bone, gave results in good agreement with those obtained in the standard tests. Microstructural measurements showed the average pore size ranged from 125 to 234 μm for densities ranging from 0.641 to 0.159 g/cm^3, respectively. The relative modulus as a function of relative density of the foams fit well to the model of Gibson and Ashby. Cyclic testing revealed hysteresis in the lower density foams with a loading modulus statistically equivalent to that measured in monotonic testing. Shore DO durometry (hardness) measurements show good correlations to elastic modulus and compressive strength. The results suggest additional parameters to consider for the evaluation of polyurethane foams for bone analog applications.

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1 Introduction

Rigid polyurethane (PU) foams are popular testing substrates for the evaluation of orthopaedic devices and training of orthopaedic surgeons. Many previous device evaluation studies incorporate rigid closed-cell PU foams as testing substrates, as these foams are reported to mimic the mechanical properties of cancellous bone [1–5]. Hein et al. [6] originally developed the concept of using PU foams for mechanically modeling trabecular bone. An advantage of PU foams over other testing substrates, such as cadaver bone, is their consistency from lot to lot. As an analog for trabecular and cortical bone, however, the synthetic foams are typically more homogeneous and less anisotropic. Nevertheless, in monotonic compression, PU foams exhibit stress–strain behavior similar to trabecular bone. The stress–strain curve exhibits three regions: the initial linear elastic response in which the cell walls are elastically compressed and bend, transitioning to a near-zero slope region in which cell walls collapse and buckle under increased applied force, and finally to a steep increasing slope in which the cell walls meet, impinge or contact each other increasing resistance to further deformation [4, 5, 7, 8]. The similarity in mechanical response to bone has made PU foams attractive trabecular bone analogs.

2 Background

Early studies that evaluated PU foams for trabecular bone analogs used Daro foam developed from the mixing of two

liquids (resin and isocyanate catalyst) in varying volume ratios [4–6]. Szivek, Thomas and Benjamin reported the first study on mechanical properties of these foams with two different "bubble" diameters using different ratios of resin to isocyanate (10:7.9 and 10:9.0) [4]. Compression testing was conducted on 2.5 cm cubes cut from the foamed PU using a MTS servo-hydraulic testing frame at a crosshead speed of 0.5 mm/s and the samples were conditioned prior to evaluation by compressing once to 70% of the compressive strength and unloading. The same group later reported further work with three compositions (10.0:5.0, 10:7.9 and 10.0:10.0) of Daro foam and evaluated the same properties using identical testing parameters except that the testing speed in this study was 1.2 mm/s [5]. The foaming direction was considered in the second study and all testing was done parallel to the foaming direction. The mechanical properties and "bubble" diameter for these foams are listed in Table 1. Unfortunately, the apparent density of these foams was not reported in either study, making it difficult to compare the results with other work, but the modulus and strength values are in the range of values reported for rigid PU foams by others.

Later work by Thompson et al. [1], examined the shear and compressive properties of commercially available rigid PU foams (Sawbones Europe AB, Malamö, Sweden). Four different nominal densities (120, 160, 200 and 320 kg/m^3 corresponding to 7.5, 10.0, 12.5 and 20.0 lb/ft^3) were evaluated under uniaxial compression using a dumbbell shaped specimen glued to aluminum collars with epoxy at each end. The specimens had a gauge length of 40 mm and a gauge diameter of 20 mm. Preconditioning was preformed three times by displacement to 0.4 mm (1% strain) at 0.017 mm/s and testing was performed to 8% compression. Cell diameters were estimated based on optical microscopy but the microstructure was not shown. The results are shown in Table 1 for the properties measured.

Although monotonic mechanical properties are useful in the characterization of PU foams, for a material to be

Table 1 Density, compressive strength and elastic modulus values from previous PU foam studies, ASTM standard requirements for graded foams and reported General Plastics foam properties

Publication	Composition ratio, nominal density and/or grade	Apparent density (g/cm^3)	Elastic modulus (MPa)	Compressive strength (MPa)	Cell/bubble diameter (μm)
Szivek et al. [4]	10.0:7.9	N/A	69.5 ± 20.7	3.36 ± 1.9	279 ± 74
	10.0:9.0	N/A	103.8 ± 7.7	6.03 ± 0.18	203 ± 49
Szivek et al. [5]	10.0:5.0	N/A	110.1 ± 10.41	3.28 ± 0.39	489 ± 63
	10.0:7.9	N/A	114.9 ± 8.65	4.98 ± 0.36	477 ± 55
	10.0:10.0	N/A	134.0 ± 22.20	5.61 ± 0.63	432 ± 63
Thompson et al. [1]	0.120 g/cm^3	0.115 ± 0.002	22.0 ± 1.47	0.85 ± 0.03	~2000
	0.160 g/cm^3	0.158 ± 0.0037	38.7 ± 4.5	1.44 ± 0.08	~1000
	0.200 g/cm^3	0.209 ± 0.0029	79.3 ± 7.6	2.71 ± 0.21	~500
	0.320 g/cm^3	0.332 ± 0.0057	164 ± 27.8	5.14 ± 0.15	<250
ASTM F1839-08 required values [3]	Grade 10: 0.160 g/cm^3	0.144–0.176	45.75–71.70	1.745–2.820	No value specified
	Grade 12: 0.192 g/cm^3	0.173–0.212	64.50–100.5	2.485–3.970	
	Grade 15: 0.240 g/cm^3	0.216–0.264	98.00–151.0	3.820–6.050	
	Grade 20: 0.240 g/cm^3	0.288–0.352	167.5–257.5	6.630–10.45	
	Grade 25: 0.401 g/cm^3	0.360–0.440	253.5–390.0	10.15–16.00	
	Grade 40: 0.6407 g/cm^3	0.5765–0.7050	603.0–941.0	24.60–39.55	
GP reported values [22]	Grade 10	3710: 0.160	3710: 77.5	3715: 2.41	No values reported
		6710: 0.160	6710: 70.0	6710: 2.40	
	Grade 12	3712: 0.192	3712: 95.8	3712: 3.36	
		6712: 0.192	6712: 106.1	6712: 3.39	
	Grade 15	3715: 0.240	3715: 140.5	3715: 5.11	
		6715: 0.240	6715: 155.8	6715: 5.17	
	Grade 20	3720: 0.320	3720: 230.2	3720: 8.43	
		6720: 0.320	6720: 255.6	6720: 8.90	
	Grade 25	3725: 0.400	3725: 337.6	3725: 12.60	
		6725: 0.400	6725: 375.4	6725: 13.57	
	Grade 40	3740: 0.640	3740: 756.7	3740: 29.42	
		6740: N/A	6740: N/A	6740: N/A	

considered for bone analog applications, the cyclic response must be evaluated. The only known published reports on the cyclic testing of PU foams examined the response of open-cell foams in cyclic testing with applied stress above the yield strength [9, 10]; therefore, the results are not comparable to low cycle testing within the elastic region of the stress–strain curve. A study by Palissery, Taylor and Browne [2] examined the compressive fatigue below the yield strength of polyvinyl chloride (PVC) foams for orthopaedic device evaluation. The compressive elastic modulus was calculated as the secant between 0.1 and 0.4% strain. Prior to fatigue testing, preconditioning was conducted by applying ten cycles at approximately one-third of the compressive strength measured from the monotonic testing. This preconditioning allowed for the calculation of the secant modulus in the elastic range. The fatigue testing was carried out until failure of the foams, as defined by a 30% reduction in the secant modulus. The number of cycles to failure varied from 5 to $\sim 1 \times 10^5$ [2]. This work demonstrated that there was an accumulation of strain under cyclic loading, due to the material not returning to the original specimen height between each cycle. The work suggests that cyclic or fatigue testing must be completed to properly evaluate a bone analog material used for micromotion studies [2].

Due to factors such as testing orientation, specimen geometry, modulus calculation method and testing conditions, direct comparison of foam property measurements from different studies is difficult. Foams often display anisotropic behavior due to the rise of the gas bubbles in the foaming process; therefore the direction of mechanical testing in relation to the foaming direction is expected to have an influence on the mechanical properties. In addition, the testing rate influences the compressive properties of closed-cell foams.

As the use of PU foams for orthopaedic device evaluation increased, ASTM developed ASTM F1839-97 [11], "Rigid polyurethane foam for use as a standard material for testing orthopaedic devices and instruments." This standard provided a method of classifying foams as graded or ungraded based on the physical and mechanical behavior with a particular nominal density. The "graded" foams in F1839-97 are 10, 12, 15, 20 and 40, corresponding to nominal densities of 10, 12, 15, 20 and 40 lb/ft^3. As dictated by ASTM F1839, there are to be no cracks in the foams and voids must be smaller than 6.35 mm in diameter with additional restrictions on the size and number of smaller macroscopic voids [3, 11, 12]. However, no microstructural parameters (e.g. cell size) are specified in the standard. In addition, each foam must fall within specified ranges for apparent density, compressive strength, compressive modulus, shear strength, shear modulus and screw pullout resistance. For the compressive testing, ASTM D1621-04, "Standard Test Method for Compressive Properties of Rigid Cellular Plastics" [11], is incorporated in ASTM F1839, which specifies large block specimens (50.8 × 50.8 × 25.4 mm, minimum) tested in the foaming direction with a crosshead displacement rate of 2.5 ± 0.25 mm/min [13].

In ASTM F1839-97, General Plastics (GP), Tacoma, WA, is identified as a satisfactory supplier of graded rigid PU foams commercially supplied in solid form. For classification, GP identifies foams with four numbers: the first two numbers identify the foam series based on the additives and the last two numbers identify the foam grade (nominal density in lb/ft^3). The two types of GP rigid PU foams, 37XX and 67XX, sold under the trade name Last-A-Foam® are the focus of this study, and both types are currently used in orthopaedic device evaluation.

ASTM F1839 has been revised twice since the original introduction in 1997; however, the major difference is a widening of the allowable ranges of properties and an increase in the number of nominal density grades. The later editions of the standard acknowledge that GP cannot guarantee to meet the requirements in the standard [11, 12]. Table 1 displays the range of mechanical and physical properties that are given in ASTM F1839-08. Table 1 also displays the typical properties of these foams as reported by GP.

The aim of the present study is to evaluate the monotonic and cyclic compressive properties and hardness of graded PU foams following standard test methods, examine their mechanical properties in relation to microstructural features and to compare the results to previous work. This work was part of a larger study that investigated the compressive properties of human trabecular bone across the tibial plateau (to be published separately). Since the standard test specimen is much too large for this purpose, the same foams were also tested using a smaller sample (7 mm diameter × 15 mm) commonly used for testing bone. These tests enabled a direct comparison with the standard test for any specimen size effects, which to the authors' knowledge has not been reported.

3 Materials and methods

Seven different types (3712, 6712, 3715, 3720, 6720, 6725 and 3740) of bulk PU foam manufactured by GP were evaluated. Apparent densities were obtained by measuring the mass and dimensions of five machined specimens for each type of foam using calipers and an electric balance (0.001 g).

A scanning electron microscope (JEOL, 35CF) was used to view and analyze small rectangular sections of foams 3712, 6712, 3715, 3720, 6725 and 3740 after AuPd

sputtering. Stereology was performed on the resulting SEM images and the average cell (pore) size, number of pores per inch (ppi) and mean intercept length $(\overline{L_3})$ were measured for each foam type. The average cell size was calculated by averaging all cell diameters within a particular image plane. The common way of specifying cell density is through the ppi parameter, which is the number of pores intercepted per inch of test line. A related but more fundamental measure of cell size is the mean intercept length. The mean intercept length was calculated based on the following [14]:

$$\overline{L_3} = \frac{L_L}{N_L} \quad (1)$$

where L_L is the total length of cells intercepted by the test line divided by the total length of the test line ($=V_V$, the pore volume fraction) and N_L is number of cells (pores) intercepted per length of test line. The pore volume fraction was used together with the apparent density measurements to estimate the true density (i.e., pore free) of the PU.

Five specimens of each type of foam for mechanical testing were cut to 50.8 × 50.8 × 25.4 mm blocks as per ASTM F1839-08 [3] using a table saw (Delta Shopmaster, Model TC200LS) and vertical mill (Delta Shopmaster, Model DP350). In addition, five cylindrical specimens of each type of foam were prepared by cutting the bulk material into 15 mm thick sheets using a vertical mill. A drill press with a trephine (inner diameter of 7.55 mm) cutting tool operated at 3,900 rpm was used to core specimens from the 15 mm thick sheets. The cylindrical foam specimens were 15 mm high by 7.5 mm in diameter. Mechanical testing was conducted on the two specimen geometries using two different testing machines.

A screw-driven Instron (Model 4505 with a load cell of 100 kN) testing machine was used for the monotonic testing of the foam blocks and cylinders, while a servo-hydraulic EnduraTEC (Model SmartTest with a load cell of 12.5 kN) testing machine was used for the monotonic and cyclic testing of the smaller foam cylinders. The Instron setup included an extensometer to measure platen displacement (readability 0.025 mm). For the EnduraTEC, titanium platens were modified to house a 6-mm differential variable reluctance transducer (DVRT) (Microstrain, Inc., Model MG DVRT-6) for a more precise measurement of platen displacement (readability of 0.001 mm) compared to the crosshead displacement (readability of 0.01 mm). All testing was performed parallel to the foaming direction, which is the normal orientation for bone analog applications.

PU foam blocks were tested according to ASTM F1839 and the referenced standard D1621-04a, such that five blocks of each specimen type were subjected to compression at a crosshead rate of 2.5 ± 0.25 mm/min [3, 13]. The ASTM standard calls for straining to 13% or until yielding; however, the specimens were strained to 20% in order to evaluate post-yielding behavior. As dictated in ASTM D1621-04a, "compressive strength" was calculated as the stress at 10% strain [13]. The elastic modulus was calculated as the slope of the linear portion of the stress–strain curve.

As previously described, the mechanical evaluation of the PU foams should mirror common testing parameters for trabecular bone cylinders. For monotonic compression testing of bone, previous work has suggested an optimal strain rate of 0.005/s [15–17]. Therefore, PU foam cylinders were strained at a crosshead rate of 0.075 mm/s corresponding to an initial (and approximately constant) strain rate of 0.005/s to 20% total strain.

Cyclic testing was conducted on the cylindrical specimens using the EnduraTEC. Testing was carried out by ten cycles of the following: load to a displacement corresponding to 50% of the compressive strength, unload at the same rate as loading and dwell for 4 s at zero load, corresponding to the original starting position. The elastic modulus was calculated for each loop as described for the monotonic testing. Since the monotonic testing showed that the mechanical properties of the foam specimen were highly uniform, only three specimens of each type were tested under cyclic loading.

Durometry (hardness) measurements on the foams were initially conducted using the Shore D test but the sharp tip (0.1 mm radius) of the conical indentor penetrated through the cell wall of the foams and gave low readings. Therefore, hardness was evaluated using a Shore DO durometer (PTC Instruments, Model 202DO), which uses a 3/32-in (2.4-mm) diameter ball indentor, according to ASTM D2240-05 [18]. Five specimens per foam type were tested to ensure consistency, as specified in the standard.

4 Results and discussion

4.1 Microstructure

The SEM images in Fig. 1 show the closed-cell microstructure of the PU foams. Table 2 displays the density and cell size measurements for each type of foam shown in Fig. 1. The pore size distributions were highly uniform across the surfaces examined in the SEM.

The cells are gas bubbles formed during the foaming process [19]; therefore, a longer foaming time or more foaming agent results in larger pores. In general, there was an inverse relationship between measured density and average cell size. As expected, the mean intercept length follows the average pore size, with a larger value associated with a lower density. The highest density foam, 3740,

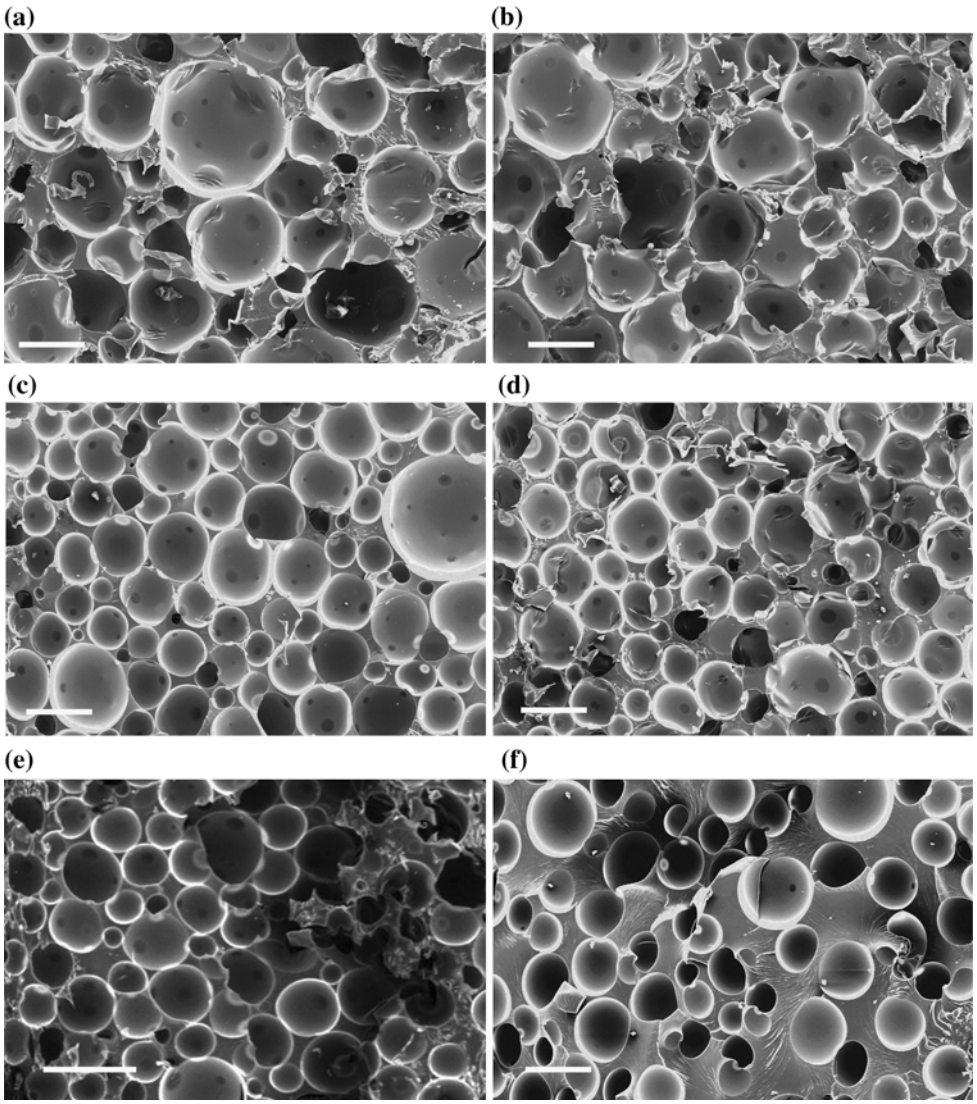

Fig. 1 SEM images of General Plastics PU foams: **a** 3712, **b** 6712, showing similar cell volume fraction and size distribution **c** 3715, **d** 3720, **e** 6725 and **f** 3740. Scale bar is 200 μm

Table 2 Measured density, pore size, relative density and linear pore density of foams shown in Fig. 1

Foam type	Apparent density (g/cm^3)	Relative density[a] ρ_{rel}	Pore size range (μm)	Avg pore size (μm)	Linear pore density (ppi)	$\overline{L}_3(\mu m)$
3712	0.192	0.160	61–349	213	116	158
6712	0.191	0.159	87–419	234	111	193
3715	0.240	0.200	35–402	136	169	115
3720	0.320	0.267	33–163	115	187	104
6725	0.398	0.332	40–188	109	178	102
3740	0.641	0.534	52–253	125	90	124

[a] Relative density based on $\rho_{true} = 1.23$ g/cm^3

deviates slightly from this trend, as the cells are isolated. The linear pore density (ppi) increases with increasing foam density, as the cells are smaller in the higher density foams. Again, the highest density foam shows a ppi below the trend, which is due to more solid PU material between cells. Figure 1a shows the 37XX series compared to the 67XX series in Fig. 1b. The similarities between foams with the same grade are expected. The addition of microstructural analysis to the standard may help further characterize performance of the foams.

Using the volume fraction measured by stereology ($V_V = L_L$) from the images in Fig. 1, together with the apparent density measurements, the true density was calculated and compared to the reported true density of PU

[20], 1.23 g/cm^3. For all except the grade 40 foam, this method gave considerably lower values due to overlapping of the cells and associated distortion of the image plane. However, the calculation of true density from the SEM photomicrograph for the grade 40 foam gave 1.23 g/cm^3, which is identical to the reported true density of PU. As shown in Fig. 1f, at the lower volume fraction, the cells are mostly isolated and distinct, enabling an accurate estimate of their volume fraction by stereology.

Based on the true density value of 1.23 g/cm^3, the relative apparent densities of the foams (volume fraction solid) ranged from 0.16 (Grade 12) to 0.53 (Grade 40), as given in Table 2.

4.2 Mechanical properties

Table 3 shows the monotonic mechanical properties measured on the two specimen geometries. Comparison to Table 1 shows the block specimens tested according to ASTM F1839-08 are all within properties specification for each grade tested. The smaller cylinder specimens were also tested in the Instron setup, and although the strength values were in good agreement with those measured on the block specimens, the elastic modulus values deviated by up to 38%, most likely due to low sensitivity of the load cell at the much lower loads of the tests using the small specimens. For example, using the Instron with a 100 kN load cell, the applied load at 50% of the compressive strength for the lowest density foam in the cylindrical geometry is only $\sim$100 N or 0.1% of the full range.

Figure 2 shows the typical compressive stress–strain behavior for the smaller cylindrical specimens tested in the EnduraTEC; curves for the standard block specimens tested in the Instron were nearly identical. As shown in Table 3, the compressive strength values were nearly identical for the same grade of foam tested in the two different machine/specimen configurations. The elastic modulus values measured in the two tests were slightly different, most likely due to the differences in load and displacement resolution. Although specimen geometry (aspect ratio) [13] and strain rate differences could also be factors, the small differences are probably within the uncertainty of the graphical determination of slope from the stress–strain curves. Clearly, caution should be exercised when testing the smaller specimens on a load frame of the higher capacity necessary for standard testing using the large block specimens.

Table 3 also shows that there was no significant difference between mechanical properties measured for the 3720 and 6720 specimens. These results suggest that there is no significant difference in the intrinsic mechanical properties of the polyurethane in the 37XX and 67XX series foams.

As expected, both elastic modulus and strength increases with density, which is due to the increasing cell wall thickness. An increase in the material surrounding the pores results in an increase of the load carrying capacity. Patel and Finnie [8] as well as Gibson and Ashby [7] pioneered work on the structural behavior of rigid cellular foams. Gibson and Ashby [7] developed the following equation for estimating the relative modulus for closed-cell foams, which includes a factor for membrane stresses and gas pressure in the cells:

$$\frac{E^*}{E_s} \approx \phi^2 \left(\frac{\rho^*}{\rho_s}\right)^2 + (1-\phi)\frac{\rho^*}{\rho_s} + \frac{p_o(1-2\nu^*)}{E_s\left(1-\frac{\rho^*}{\rho_s}\right)} \quad (2)$$

where E* is the Young's modulus of the foam, E_s is the Young's modulus of the solid cell wall material, ϕ is a parameter used to describe the cell wall geometry (estimated at 0.8 for PU rigid foams [7]), ρ^* is the apparent density of the foam, ρ_s is the true density the material, p_o is gas pressure in the cells and ν^* is Poisson's ratio. For typical values of the cell gas pressure (0.1 MPa [7]), Poisson's ratio (0.33 [7]) and PU elastic modulus the third term is several orders of magnitude smaller than the other two terms and thus can be neglected. Equation 2 is plotted in Fig. 3 together with the experimental measurements of this study, assuming a true density of 1.23 g/cm^3 [20] and

Table 3 Mechanical properties from monotonic compression testing in the Instron (large block geometry) and EnduraTEC (small cylindrical geometry) as well as loading elastic modulus from cyclic testing

Machine	Instron		EnduraTEC		
Geometry	Block		Cylinder-monotonic		Cylinder-cyclic
Foam type	Elastic modulus (MPa)	Compressive strength (MPa)	Elastic modulus (MPa)	Compressive strength (MPa)	Loading elastic modulus (MPa)
3715	115 ± 17	4.7 ± 0.1	134 ± 9	4.8 ± 0.1	134 ± 4
3720	195 ± 32	8.4 ± 0.1	216 ± 17	8.5 ± 0.3	224 ± 5
6720	195 ± 53	8.4 ± 0.1	206 ± 12	8.2 ± 0.4	229 ± 12
6725	332 ± 64	12.6 ± 0.1	356 ± 25	13.5 ± 0.2	335 ± 6
3740	794 ± 36	24.7 ± 0.3	752 ± 43	24.6 ± 0.3	669 ± 20

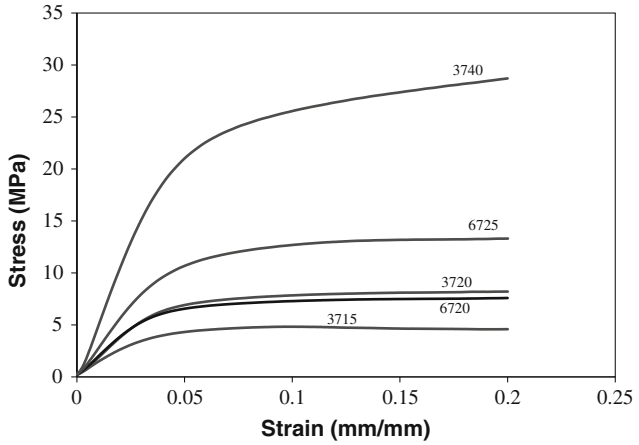

Fig. 2 Typical stress–strain curves for General Plastics PU foams tested using the smaller 7.5 mm diameter × 15 mm specimens

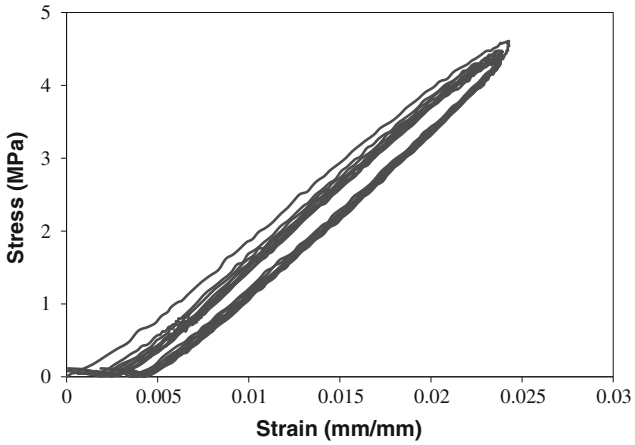

Fig. 4 Typical stress–strain hysteresis exhibited in low cyclic testing of foam grade 20. Data displayed is for ten load–unload compressive cycles

the upper and lower bounds of reported values for the elastic modulus of fully dense PU, $E_s = 1.6$–2.7 GPa [1, 20, 21]. Using the higher bound of the reported range of E_s to normalize the modulus, the experimental results show very good agreement with the model over the entire range of foam densities. When using the lower bound of E_s, the agreement is also good for the lowest density foam but deviates increasingly with increasing density.

Figure 4 shows the typical stress–strain hysteresis behavior for foam Grade 20 for ten compression-unload cycles. Slight stabilization of the foam occurred in the first cycle, the extent of which decreased with increasing density (grade), after which the loops nearly overlap. The average elastic modulus values measured on the loading portion of the cycle (Table 3) are not significantly different from those measured under monotonic loading. The open area of the hysteresis loop represents the amount of anelastic (viscoelastic) deformation occurring in the foam. In the lowest density foam, higher local stresses are applied to the thin cell walls; therefore, as expected the lowest density foam was observed to have the largest hysteresis and the highest density was associated with the smallest hysteresis. As in the compressive monotonic properties, the higher density foams are associated with higher modulus and strength values, as shown in Table 3. Based on the results of the cyclic testing, no strengthening occurred between cycles; however, only ten cycles were run, which is low in comparison to dynamic fatigue testing.

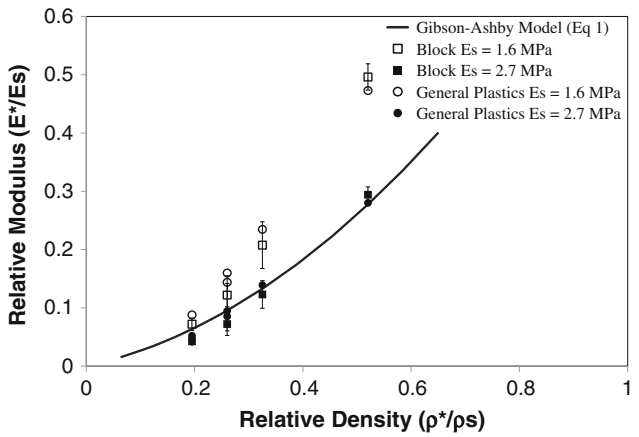

Fig. 3 Relative elastic modulus versus relative density comparing experimental values (standard block specimens measured in this study and manufacturer reported values; density normalized using $\rho_s = 1.23$ g/cm^3) normalized using upper bound ($E_s = 2.7$ MPa) and lower bound ($E_s = 1.6$ GPa) values reported for the modulus of PU. *Solid line* represents rigid closed-cell foams model from Eq. 2 of Gibson–Ashby [7]. General Plastics is the reported PU manufacturer data [22]

The Shore DO hardness values measured on the PU foams are shown in Table 4. A search of the literature suggests this is the first report of Shore DO hardness values for rigid PU foams. The hardness increases with increasing density as a direct result of more bulk PU material in the cell walls. Furthermore, the hardness values show a reasonably linear correlation with foam density ($R^2 = 0.79$) and similar correlations with elastic modulus and compressive strength. These plots are not shown, however, as

Table 4 Shore DO hardness and apparent density measurements of rigid PU foams

Foam type	Apparent density (g/cm^3)	Hardness (Shore DO)
3715	0.240	70 ± 1.2
3720	0.320	81 ± 0.4
6720	0.320	82 ± 0.8
6725	0.398	87 ± 0.5
3740	0.641	93 ± 0.5

the theoretical bases for such correlations are not known. Nevertheless, with further work it may be possible to develop the empirical relationships that would allow rapid estimates of compressive properties by hardness testing of these foams.

5 Conclusions

A series of commercial graded rigid PU foams spanning the range of densities typically employed in bone analog applications has been systematically characterized. Mechanical properties measurements correlated with quantitative microstructure analyses. A general conclusion is that the synthetic foams are more consistent and homogeneous in their mechanical properties than trabecular bone. Specific conclusions from the study are as follows:

(1) Microstructural analysis showed that the commercial graded PU foams have uniform cell size and volume fraction distributions, and average cell sizes of $\sim$100–200 μm with a slight trend of increasing cell size with decreasing density.
(2) Stereological analysis on the high density (Grade 40) foam allowed a measurement of the PU true density of 1.23 g/cm^3, in good agreement with previous measurements. Using this value, bulk density measurements yielded relative densities of 0.16 to 0.53 for the range of Grade 12 to Grade 40.
(3) Mechanical testing using large block specimens (50.8 mm × 50.8 mm × 25.4 mm high) according to ASTM F1839 showed all the foams were within specification by grade for compressive elastic modulus and strength.
(4) Using smaller cylinder specimens (7.5 mm diameter × 15 mm high), more typical of testing actual bone, the elastic modulus values were only slightly different from those measured using the larger standard block specimens, most likely due to differences in load and displacement resolution. No statistically significant differences in compressive strength were measured using the two different test specimens.
(5) Using the upper bound of the reported range of elastic modulus for fully dense PU, the normalized elastic modulus versus density fit very well to the Gibson and Ashby model over the entire range of density.
(6) Low cycle compression–compression fatigue testing to a peak stress of half the compressive strength showed hysteresis but the elastic modulus on loading did not change significantly out to ten cycles.
(7) Hardness measurements are not included in the ASTM standard, but allow for a quick evaluation of PU foams. The Shore DO hardness was shown to be linearly related to the apparent density of PU foams.

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