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Polyurethane foams: Effects of specimen size when determining cushioning stiffness

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Abstract—Polyurethane (PU) foams are used as inexpensive materials for reducing interface pressure in a number of rehabilitative applications, particularly seating and prosthetic limb interfaces. Specimens of three different PU foams were cut to four different sizes and compressed according to ASTM protocols to determine their stiffness capabilities. It was found that the test results varied according to the relationship between the size of the test specimen and the test indenter. It is recommended that investigators create a testing situation that reflects their application when determining the cushioning capabilities of these materials.

Key words: *biomechanics, decubitus ulcer, elastic modulus, mechanical stress, polyurethanes, pressure, wheelchairs.*

INTRODUCTION

Polyurethane (PU) foams are used extensively as inexpensive cushioning materials for wheelchair seating (1–5), mattress overlays (6,7), shoe insoles, and prosthetic limb interfaces (8,9). When these products are designed, a major focus is to minimize decubitus ulcer formation by reducing pressure. Knowledge of material properties related to the stiffness and cushioning capability of these flexible cellular materials will assist in attaining this design goal (3,5,6,9–18).

In a mechanical sense, the stiffness of a material controls the relationship between the force applied to a surface and the resulting deformation (19). In the simplest case, when a force is applied perpendicular to the end of a ductile bar, the deflection is proportional to the force by a material property known as the elastic modulus. As the direction of loading changes, and the specimen geometry becomes more complex, stiffness is characterized by a matrix of parameters known as stiffness coefficients. In more complex materials, such as cellular foams, the relationship between force and deflection is not necessarily linear.

To measure these material properties, a number of investigators have relied on the ASTM standard, ASTM D-3574-95, *Standard Methods of Testing Flexible Cellular Materials—Slab, Bonded and Molded Urethane Foams,* and its predecessors (6,20). The data from several of the tests from this standard are of particular use in determining these properties. For this study, ''Indentation Force Deflection Test—Specified Deflection'' was used as a large deformation test where the foam is compressed by 65 percent of its original thickness. ''Indentation Force Deflection Test—Specified Force'' was used as a small deformation test where the foam is compressed by a force up to 220 N. Note that for these types of cellular foams, a 220 N force can deform the specimen by as much as 25 percent of its original thickness. For both of these tests, the ASTM standard calls for a specimen that in no case shall have dimensions less than 380×380×20 mm and a 203 mm diameter indenter.

Several investigators with an interest in rehabilitation applications have reduced the specimen sizes while

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using the ASTM standard. Details of their investigations are shown in **Table 1.** Ferguson-Pell et al. indented smaller specimens of urethane foams and viscoelastic Temperfoams with a standard indenter to determine their material properties for the design of modular wheelchair cushions (13). They also indented full-size samples with a 70 mm diameter indenter that modeled the geometry of the ischial tuberosity. Chung used specimens identical to the size of the indenter to determine their material properties in his investigation of tissue-cushion interface pressure. He also tested several specimens of the same materials with a smaller indenter (15). Smith et al. used slightly smaller specimens with a standard-sized indenter to investigate the effect of coatings on several PU foams (17). Kang et al. used very small specimens of a PU foam to determine the relationship between the supporting properties and the loss of surface area due to holes drilled in the foams (16).

The purpose of this study was to examine the way in which the size of the specimen tested would affect its material properties. Typically, material properties are presented in the form of engineering stress data and strain data that are not affected by the dimensions of the test specimen. However, traditional engineering materials do not exhibit the large elastic region (25–65 percent strain or more) of these cellular foams. Due to this large elastic region and the specification of a minimum specimen size and an indenter size in the ASTM standard, it was believed that specimen size may affect the stress-strain relationship for large deflections. Thus, it was hypothesized that larger specimens of a material would appear more stiff than smaller ones. This change in stiffness would be related to the development of shear force between the specimen and the test indenter wall. More specifically, it appears that specimens with cross sections smaller than the indenter may be less stiff than those with cross sections larger than the indenter.

METHODS

As specified by the ASTM standard (20), the foam specimen was supported by a 330×330 mm aluminum plate with 6.4 mm diameter holes on 12.7 mm centers, and a 203 mm diameter aluminum circular plate was used as the indenter. For the smallest specimens tested, the weight of the standard indenter caused a large initial deformation, so a lighter 50×50×10 mm aluminum indenter was used for those specimens. This size indenter maintained the relationship of the indenter having a larger cross-sectional area than the sample.

For the large deformation test, each specimen was preflexed by compressing it twice to 80 percent of its original thickness at a cross-head speed of 0.42 mm/s. The foam material was then allowed to rest 6±1 min prior to beginning the formal test. The foam was compressed by 25 percent of its original thickness at a speed of 0.85 mm/s, then allowed to rest 60±3 s while the force drifted. The foam was then compressed by 65

Table 1.
Summary of tests performed by other investigators.

Investigators	Materials	Specimen Size	Indenter Size
Ferguson-Pell et al. (13)	a) Urethane Foams b) Viscoelastic Temperfoams	50 mm X 50 mm X 25 mm	203 mm dia
Ferguson-Pell et al. (13)	a) Urethane Foams b) Viscoelastic Temperfoams	405 mm X 405 mm X 20 mm	70 mm dia
Chung (15)	a) Polyurethane Foams b) Lamina Foams c) Viscoelastic Foams	203 mm dia X 76 mm	203 mm dia
Chung (15)	a) Polyurethane Foams b) Lamina Foams c) Viscoelastic Foams	203 mm dia X 76 mm	70 mm dia
Smith et al. (17)	Polyurethane Foams	305 mm X 305 mm X 100 mm	203 mm dia
Kang et al. (16)	Polyurethane Foam	40 mm X 40 mm X 50 mm	203 mm dia

percent of its original thickness, then allowed to rest 60±3 s. The indenter was then raised at a speed of 0.85 mm/s until it was no longer in contact with the cushion.

For the small deformation test, each specimen was preflexed by compressing it twice to a force of 330 N at a speed of 0.42 mm/s. The foam material was then allowed to rest 6±1 min prior to beginning the formal test. The foam was compressed to a 110 N force at a speed of 0.85 mm/s, then allowed to rest 60±3 s while the force drifted. The foam was then compressed by a 220 N force, then allowed to rest 60±3 s. Then the load was removed from the specimen at a constant rate of 0.85 mm/s.

In the present study, three types of PU cushioning foams currently used in medical applications were investigated: Fire Resistant PU (FRPU), #6 PU, and PU Beige. They were all urethane slab-cored materials.

The test proceeded with four different sizes of specimens. Two specimens had larger cross sections than the indenter: 380×380×100 mm (large block) and 305×305×100 mm (medium block). After these samples were tested, 100 mm thick disks with a 203 mm diameter were cut from the medium blocks. Then small blocks (40×40×50 mm) were cut from the disks. All testing was completed with Instron Universal Testing Machines (Instron Corporation, Canton, MA). A large machine was used for large blocks; the other specimens were able to fit into a tabletop machine. An illustration of the test setup is shown in **Figure 1.**

Four different specimens of FRPU and three different specimens of each of the other materials were tested. Each of the two tests was repeated six times for each specimen. Over the period of testing, temperature and relative humidity varied in the test facility from 17–24 °C and 43–86 percent humidity. The average of the six data sets was used to plot force versus deflection, stress versus strain, and modulus of elasticity versus strain curves for each specimen.

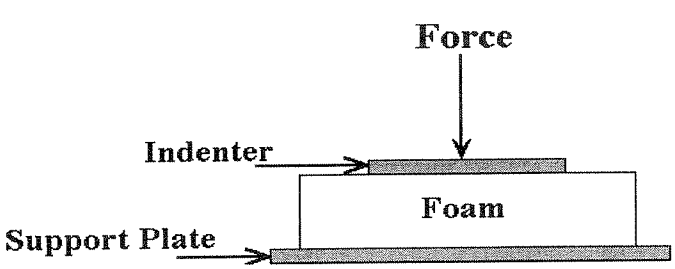

Figure 1.
Experimental setup.

An electronic data acquisition system was used to collect data from the large blocks. This system consisted of an SCXI1000 data acquisition card running Labwindows/CVI v. 3.1 on a 486-33 PC. A strip-chart recorder collected data from the tabletop INSTRON for the other specimens.

RESULTS

Results are shown for an FRPU sample with the force-deflection, stress-strain, and modulus of elasticity-strain curves shown in **Figures 2–4,** respectively. The data for the large deformation and small deformation tests are combined to clarify the results. The size descriptions in the legends refer to the foam specimen shape and size corresponding to the data.

Due to the variety of specimen sizes used, it is difficult to interpret the raw force-deflection data in **Figure 2.** The small blocks did not have as much material to deform as the larger blocks, and their information was lost until the deformation was nondimensionalized in the stress-strain curve in **Figure 3.** Stress-strain curves for #6 PU and PU Beige are shown in **Figures 5** and **6,** respectively. The modulus of elasticity-strain curve in **Figure 4** is difficult to interpret and is undergoing further analysis. However, it is clear from that Figure that these foam materials do not possess a constant elastic modulus.

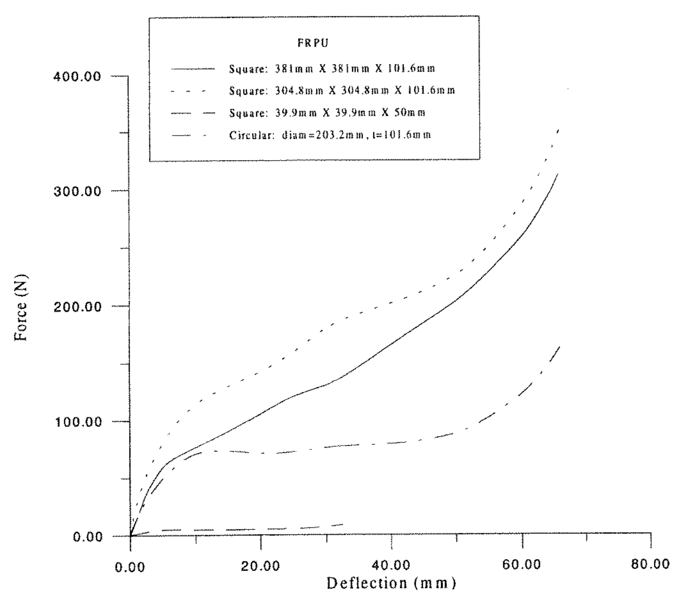

Figure 2.
Force-deflection curve for FRPU.

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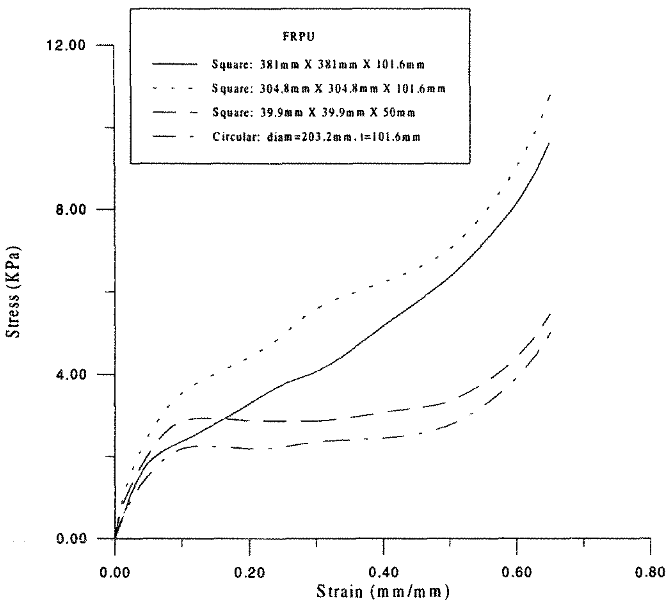

Figure 3.
Stress-strain curve for FRPU.

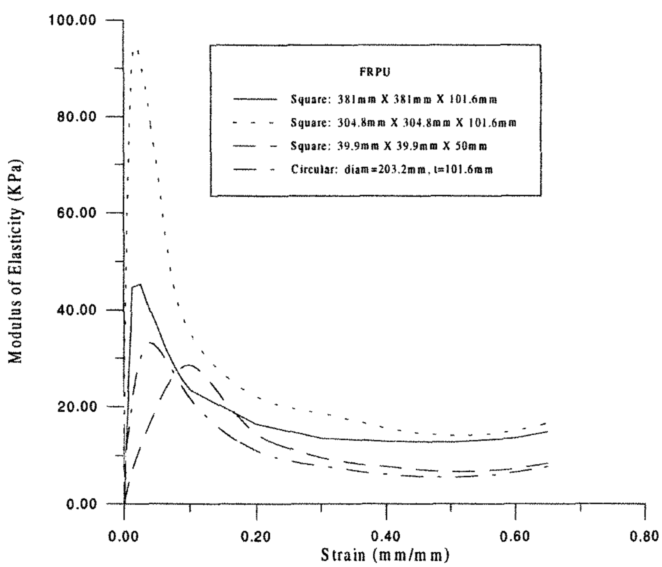

Figure 4.
Elastic modulus-strain curve for FRPU.

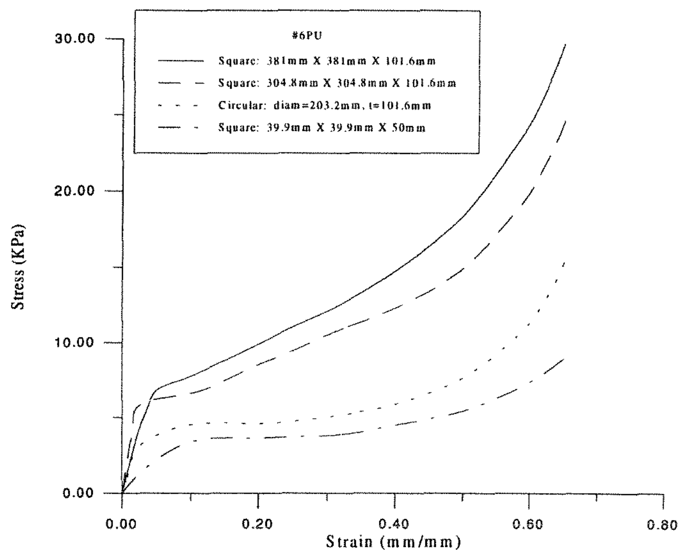

Figure 5.
Stress-strain curve for #6 PU.

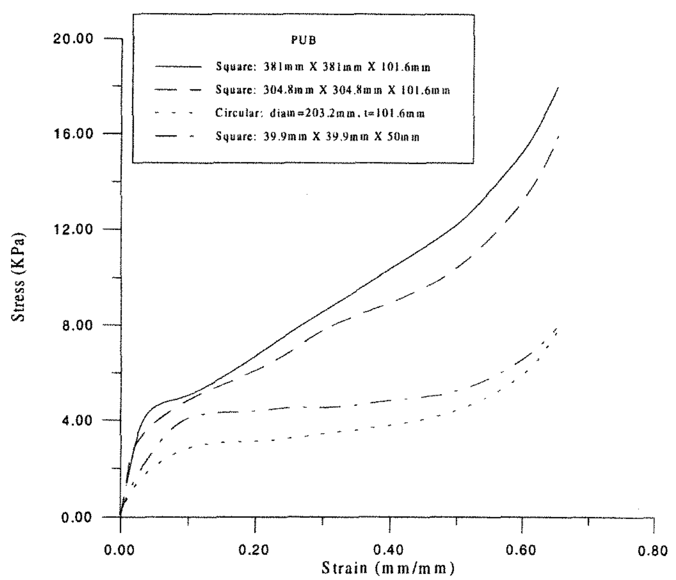

Figure 6.
Stress-strain curve for PU Beige.

When looking at the different size specimens, there are two distinct trends for each of the materials. At large strains, the larger and medium blocks carried a much larger stress than the disk and smaller block. For example, at 50 percent strain, the stress is 2 to 2.5 times as great for the larger specimens. This tendency was consistent for all of the samples tested.

In general, the stress-strain curves for FRPU, #6 PU, and PU Beige all behaved similarly to the foam materials investigated by Ferguson-Pell, et al. (13). There is a three-phase load-deformation characteristic due to the bending, buckling, and collapse of the cellular structure of the foam. This load-deformation relationship begins with an initial period of linearity followed by a change in slope at about 2 percent strain.

Then a second linear region begins, in which the materials exhibit a reduced stiffness. At slightly over 50 percent strain, the stress-strain relationship begins to exhibit nonlinearity with a stiffening of the material. None of the materials exhibit any plasticity.

DISCUSSION

Chung suggested that when a foam specimen has a larger cross-sectional area than the indenter that a shear force is created between the material and the sides of the indenter as the specimen is deformed (15). This is shown schematically in **Figure 7.** The results described previously follow this tendency. For small deflections, the shear force for the cushions larger than the indenter is approximately zero, and their stress-strain curves are similar to the specimens equal to or smaller than the indenter. As the deflections increase, the effect of the shear stress is included in the total stress, and the specimens larger than the indenter behave differently from the specimens smaller than the indenter.

This result can also be explained by the theory of elastic foundations. While this theory is primarily used to analyze the effect of the foundation on a structure (in this case, the effect of the specimen on the indenter), a general understanding of the displacement of the indenter will also lead to an understanding of how the specimen is deformed (19). In this theory, it is assumed that essentially continuous reactions are proportional to the deflection of the structure at each point along the structure-foundation interface (21). Through the derivation of equilibrium equations, it can be shown that deflection is a function of rotation, reaction moment, and reaction force at the ends of the beam. The case of an indenter sitting on a foam specimen would be modeled as a plate instead of a beam, but the same phenomenon would be seen, although it would be expanded into two dimensions (19).

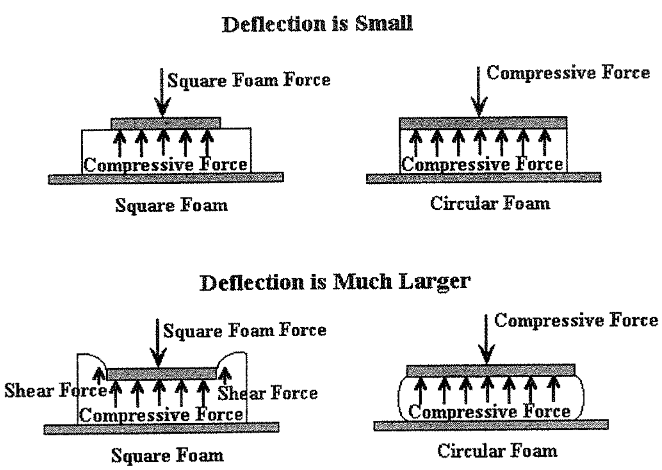

Figure 7.
Existing forces when different size specimens are compressed.

CONCLUSION

Through compression testing of different sizes of specimens of open cell foams using ASTM standard D-3574-95, it has been shown that stiffness varies as the material specimen cross-section changes in size relative to the indenter. Thus, when determining the mechanical properties related to stiffness and cushioning capabilities of these types of materials, it is recommended that investigators test for a situation similar to their application.

For instance, in the design of a wheelchair cushion to relieve pressure, for some types of disability the designer may wish to develop a cushion that will envelop the buttocks (2,11,14). In this case, material properties should be used for material specimens that are larger than the test indenter, because a shear stress will also exist when someone sits on a cushion. Additionally, it may be useful to explore the effect of using an indenter with curved sides to simulate the buttocks. In other applications, it may be more useful to use results from the case of specimens that are smaller than the test indenter.

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