Negative Poisson's Ratio Foam
as Seat Cushion Material

A. Lowe¶, and R. S. Lakes§
§Department of Engineering Physics
§Engineering Mechanics Program; §Biomedical Engineering Program
§Materials Science Program and §Rheology Research Center
University of Wisconsin-Madison
147 Engineering Research Building
1500 Engineering Drive, Madison, WI 53706-1687

¶Clive Industries
Salt Lake City, Utah

§Corresponding author

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SUMMARY

Negative Poisson's ratio foam was used in the development of seat cushions which exert reduced peak pressure upon the skin of seated persons. Foam processing techniques were scaled up. A longer processing time was required for cushion size samples in comparison with small samples. Pressure distributions on a seated subject were measured using a pressure-sensitive array. Seated pressure distribution became more favorable with decreasing sample density for both conventional and re-entrant foam blocks. Foam thickness played a small role in the seated pressure performance of foam cushions. Re-entrant foam at densities of between 2 and 4 lb/ft^3 (0.032 to 0.064 g/cm^3) performed better (lower maximum seating pressure) than conventional foam samples of comparable density.

INTRODUCTION

Seat Cushions

Polymer foams are used in seat cushions since they are compliant. This compliance has the effect of distributing the pressure over the buttocks of the seated subject, and reducing the peak pressure. If the cushion is too stiff, it will give rise to high peak pressure. If it is too soft, it will bottom out and also cause high peak pressure (1). Bottoming occurs when cell ribs in the foam come into contact: densification. During foam densification, the incremental stiffness is much higher than the initial stiffness near zero strain, a form of nonlinear response. Localized peak pressure is uncomfortable, and will soon cause a healthy person to change seating position. Peak pressure is more problematical in a person suffering paralysis, since that pressure may be prolonged, giving rise to pressure sores. Prolonged pressure can inhibit blood flow. The critical pressure for this to occur is considered to be the capillary pressure of 32 mmHg (4.3 kPa) (2,3). Severe pressure sores can lead to suffering and lengthy and expensive hospitalization (4,5). Therefore even a modest investment in improved seating would be both cost effective and humane. Several cushion materials have been tried to minimize the incidence and severity of pressure sores (6,7). Viscoelastic foam allows the cushion to progressively conform to the body shape. However, foam densification due to long term creep results in an excessively stiff cushion, therefore current foam cushions must be replaced after six months' use. Improvement in cushion materials is also of interest to those who design office furniture since improved ergonomics leads to improved productivity.

Foams

The compliance of polymer foams is governed by the foam composition and the foam density (8). Once the density is chosen, the characteristics of the linear elastic (or viscoelastic), plateau (deformation at near constant stress), and densification (abrupt increase of stress with an increment of strain), are determined. A further design variable may be introduced by modifying the shape of the foam cells. This was done by Lakes (9) and co-workers (10-14) who introduced and studied negative Poisson's ratio foams with re-entrant (inward bulging) cell structure. Poisson's ratio, represented by ν, is defined as the negative lateral strain of a stretched object divided by its longitudinal strain. Poisson's ratio is dimensionless, and for most solids its value ranges between 0.25 and 0.33. For most foams, Poisson's ratio is approximately 0.3. Poisson's ratio can be as low as -0.7 for re-entrant polymer foams (9) and -0.8 for re-entrant metal foams (8). The transformation process for polymer foams (which soften with heat) is initiated by triaxially squeezing a foam specimen into a mold. The mold is then heated above the softening point of the foam and cooled to room temperature (9). Other negative Poisson's ratio materials have since been presented. These include microporous foams (15), hierarchical laminates (16), α-cristobalite (17), chiral lattices (18), and closed cell polymer foams (19).

Applications of negative Poisson's ratio foams have been envisaged based on their physical properties (8,11,13,20); they may be used for sound absorption, fasteners, wrestling mats, and seat cushions. Use as a seat cushion is motivated by the following. Foams with a typical structure of tetrakaidecahedral (14-sided) cells exhibit a reasonably linear compressive stress-strain curve up to about 5% strain (8). At higher strains, the cell ribs buckle and the foam collapses at constant stress. Negative Poisson's ratio foams exhibited a reasonably linear relationship between stress and strain up to more than 40% strain, with no abrupt collapse (9). Such behavior may be expected to favor a more even pressure distribution upon a seated subject. Application of re-entrant foam technology to seat cushions necessitates scale-up. By modification of the molding process Loureiro and Lakes (21) produced specimens of sufficient size.

The purposes of this research are (i) to determine the pressure distribution upon subjects seated on foam cushions of conventional and re-entrant microstructure, and (ii) to characterize properties of the large size foam specimens.

MATERIALS AND METHODS

Foam materials and transformation

Seat cushion foams of various densities were obtained from Carpenter Foam Products, Elkhart, Indiana. According to the manufacturer, all of these foam samples were polyurethanes which had been manufactured the same way. The amount of water used in the manufacturing was varied to obtain different densities. The cell size was considered relatively uniform. Foam blocks were cut with a hot-wire cutter.

To arrive at an approximate heating time for larger samples, the time constant for thermal diffusivity was determined as follows. A temperature sensitive diode sensor (Model LM335. National Semiconductor, Inc.) was inserted in the middle of a slab of 2-inch (5 cm) thick foam. This sensor was directly calibrated in degrees Kelvin and had an operating range of -40 to 100 °C, with a linear output of 10 mV/°C. A step input of 48 °C was achieved by inserting the foam slab into a preheated oven. The temperature signal was captured digitally as a function of time.

Since cushion-size slabs of foam cannot be readily stuffed into a mold, the method of Loureiro and Lakes (21) was used. Based on this method, two aluminum molds were designed and made. Each mold is a metal aluminum shell which can be disassembled and reassembled around the foam block. After some preliminary trials a mold 15 x 15 x 2 inches (38 x 38 x 5 cm) was used as a standard, and foams were processed at 170 °C for one hour. Processing variables included time and temperature of transformation, and the permanent volumetric compression ratio (initial volume divided by final volume, CR in the figures) achieved during the transformation.

Foam characterization

Quasistatic measurements of the Young's and shear modulus were conducted using a method originally intended for property measurements of viscoelastic materials (22). Torque (sinusoidal for dynamic studies and step function for creep studies) was produced electromagnetically by a Helmholtz coil acting upon a high intensity neodymium iron boron magnet at the specimen free end. Angular displacement was measured via laser light reflected from a small mirror upon the magnet to a position-sensitive silicon light detector. To measure Young's and shear modulus, the coil and detector were oriented appropriately. Ten angular displacement readings were taken for ten input current values for each sample to obtain statistically robust data. Linear regression of the linear plot provides E and G as the slope of the load deformation curve for bending and torsion respectively. Rectangular section specimens were used. Some Poisson's ratio measurements were conducted by applying a specified axial deformation via a lag screw and measuring deformations with a micrometer.

Seat pressure measurement

Seat pressure measurement was conducted using the piezoresistive pressure sensing equipment manufactured by Xsensor, Model XS96, Xsensor Technology Corp. The sensor consists of a flexible mat containing an array of 1,296 pressure sensors. The mat was placed between the cushion (if used) and the seated person. The mat electrical output was connected to a desk-top computer for data reduction. The system incorporates software for mapping of pressure distributions and export of data. Pressure distributions were obtained for a 80 kg male volunteer. Data capture was repeated with the cushion in four orientations 90 degrees apart. Some time dependent tests were done, and one test was done with the subject seated upon wood. All other tests were conducted with the subject seated on a foam cushion upon a flat, non-contoured wooden chair. The test subject's thighs were parallel to the ground when seated with his back straight, and pressure data were captured 30 seconds after the subject sat down.

The data were first processed by using software which counted the number of sensors with a given pressure. The output from this calculation was a series of non-zero pressures from 1 to 210 mmHg (gauge) corresponding to the number of sensors on the pressure pad with that pressure. The composite score was obtained by summing the number of sensors with a pressure below 50 mmHg and dividing by the total number of non-zero reading sensors. Although the capillary pressure is 32 mmHg, 50 mmHg was used as the cutoff because such a threshold served to better discriminate between different cushions.

RESULTS AND DISCUSSION

The thermal diffusivity inferred from thermal transient measurements of the ~ 1.4 lb/ft^3 density foam was about $5.5*10^{-7}$ m^2/sec. The time constant obtained from an exponential curve fit was 6.65 minutes (399 sec).

Representative pressure distribution output is shown in Fig. 1. Pressure is concentrated in the region under the bony prominences of the pelvis. Effects of short term creep on the pressure distribution are shown in Fig. 2. Creep had the effect of increasing the regions of higher pressure, presumably due to a gradual densification of the foam. In order to eliminate any confounding effect of creep, subsequent pressure measurements were made at the same time (30 seconds) after the subject sat down. Fig. 3 shows pressure score vs. density data for conventional cushions of various density and thickness. Observe in Fig. 3 that in conventional samples, density plays a far greater role in the pressure score than the thickness. Indeed, the differences in the pressure scores between the 5 cm thick vs. the 10 cm thick conventional samples are not significant. Similarly, pressure score vs. density results for re-entrant foam of 2 inch (5 cm) and 4 inch (10 cm) thick samples disclose for re-entrant samples, lower compression ratios (CR) improve performance while increased thickness does not. Fig. 4 gives pressure score vs. density data for 5 cm thick re-entrant and conventional samples for comparison. In Fig. 4, observe that for a 5 cm thickness, the re-entrant samples at a compression ratio of 2.20 performed better than the conventional samples of similar densities. Results for re-entrant, 2-inch, CR = 1.57 samples were taken from 6 cushions of the same type. However, the superiority of re-entrant samples prevailed mainly at this compression ratio (2.20) which suggests an optimum given the available foam densities and the processing time chosen. In Fig. 5 is presented pressure score vs. density data for both re-entrant and conventional cushions of different thickness.

The general trend in nearly all of the pressure scores is towards improved performance with lower density. Thickness is less important in the range 2-4 inches (5-10 cm). Moreover, compression ratio plays a significant role in the performance of the re-entrant foam slabs. Performance of re-entrant samples is improved more by a lower compression ratio than by an increased thickness. At the intermediate to high range of densities (between 2 and 6 lb/ft^3, or 0.032 to 0.096 g/cm^3) achieved in the transformation of conventional foam samples, the re-entrant samples of low compression ratios (~2.20) exhibited superior performance in comparison with similarly dense conventional samples. The results suggest that re-entrant foams would perform even better, if starting material of lower initial density were available.

Stiffness measurements disclosed an increase in stiffness in the re-entrant samples (Fig. 6) in comparison with conventional foams from which they were derived. The increase in stiffness with transformation is in contrast to the effects seen in Scott Industrial Foam, a reticulated polyurethane foam. In Scott foam, re-entrant transformation of the degree considered here resulted in a reduction in Young's modulus (12).

Poisson's ratio of the present foams was measured directly rather than inferred from stiffnesses since values of Young's and shear moduli were inconsistent with isotropy. A foam of original density 1.13 lb/ft^3 (0.018 g/cm^3) given a compression ratio of 2.20, had a Poisson's ratio -0.13. A foam of original density 1.55 lb/ft^3 (0.025 g/cm^3) given a compression ratio of 3.38, had a Poisson's ratio -0.26. This is in contrast with Poisson's ratio as small as -0.7 observed in Scott foam(12).

In this study, the optimum permanent volumetric compression ratio was rather low, 2.2, for the best seated pressure distribution. Such processing gives a Poisson's ratio which is negative but close to zero. Higher compression ratios during processing are needed to attain more substantial negative Poisson's ratios for both the present seat cushion foam and for Scott Industrial foam studied earlier. In view of the difference in stiffness following transformation, it is likely that a re-entrant Scott foam would perform better than standard seat cushion foam, whether conventional or following re-entrant transformation. Further improvements in the pressure distribution performance of seat cushions are possible in view of the range of input foams and processing options available.

CONCLUSIONS

1. Increased foam thickness played a small role in the seated pressure performance of foam cushions, regardless of whether they are re-entrant or not.
2. Seated pressure distribution became more favorable with decreasing sample density for both conventional and re-entrant foam cushions.
3. Re-entrant foam at densities of between 2 and 4 lb/ft^3 (0.032 to 0.064 g/cm^3) performed better (lower maximum seating pressure) than conventional foam samples at comparable density. The best permanent compression ratio for pressure reduction was about 2.2 for this foam.
4. Further studies should be directed toward foams which do not become stiffer following transformation.

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FIGURE CAPTIONS

Fig. 1. Sample pressure distribution from Xsensor pressure mapping system. This reading is taken with the subject seated on a plywood board. The field to the left is the readout of the pressure sensors, while the field on the right gives the pressure legend (color in the original).

Fig. 2. Variation of seating pressure with time for subject on a polyurethane foam cushion.

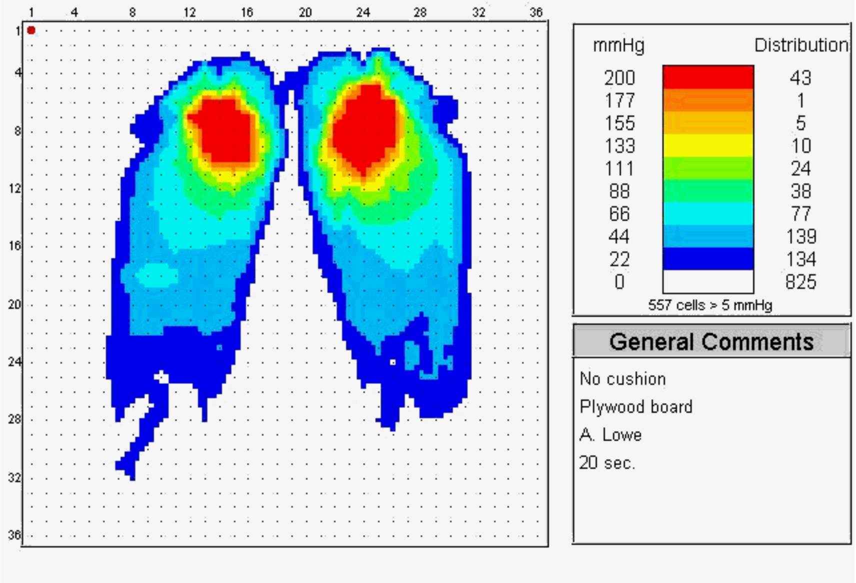
Fig. 3 Pressure fraction under 50 mmHg vs. foam density for a seated 80 kg man on a foam cushion. For conventional samples, density has more effect than thickness. 1 $lb/ft^3 = 0.016\ g/cm^3$.

Fig. 4. Pressure fraction under 50 mmHg vs. final density for a seated 80 kg man on a foam cushion. All cushions 2 inches (5 cm) thick. Re-entrant specimens with low compression ratios (CR) perform better than conventional samples at comparable densities. 1 $lb/ft^3 = 0.016\ g/cm^3$.

Fig. 5. Pressure fraction under 50 mmHg vs. final density for a seated 80 kg man on a foam cushion. For comparable densities, 2 stacked 2-inch (5 cm) thick re-entrant samples show improved performance over conventional 4-inch (10 cm) specimens. 1 $lb/ft^3 = 0.016\ g/cm^3$.

Fig. 6. Foam Young's and shear modulus vs. final density. Transformation increases the stiffness of foam samples. This contrasts with earlier Scott industrial foam studies in which re-entrant foam had a lower shear modulus. 1 $lb/ft^3 = 0.016\ g/cm^3$.

FIGURES



mmHg	Distribution
200	43
177	1
155	5
133	10
111	24
88	38
66	77
44	139
22	134
0	825

557 cells > 5 mmHg

General Comments

No cushion
Plywood board
A. Lowe
20 sec.

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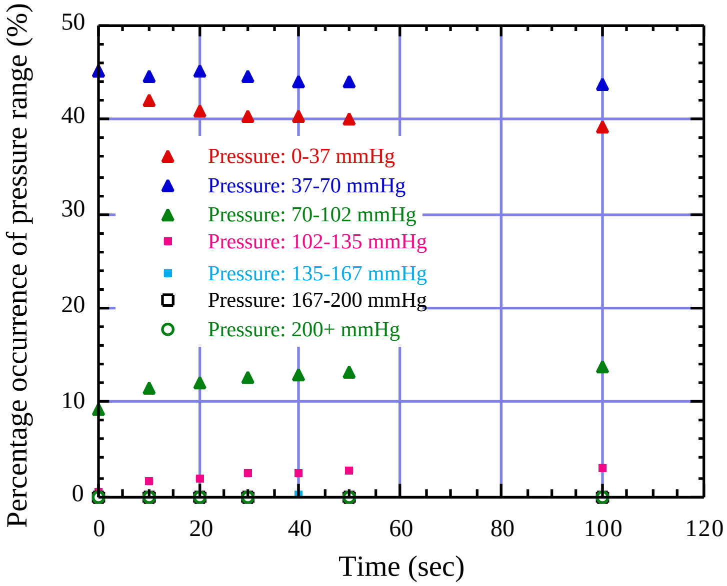

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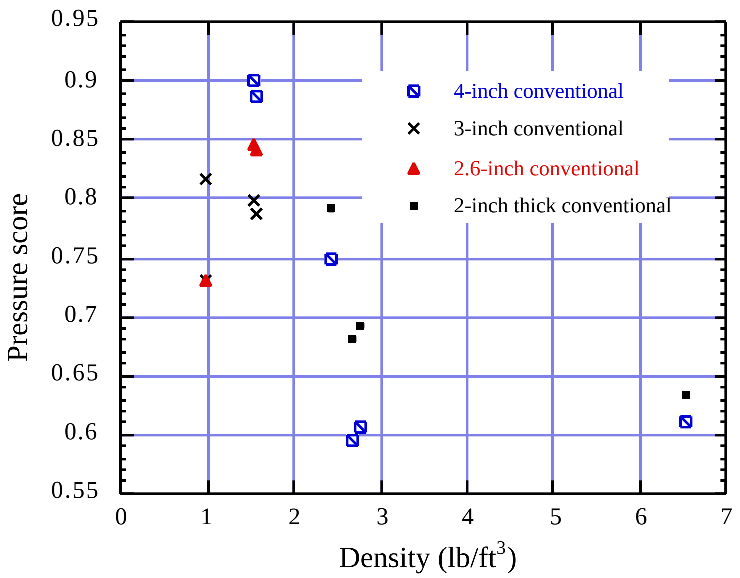

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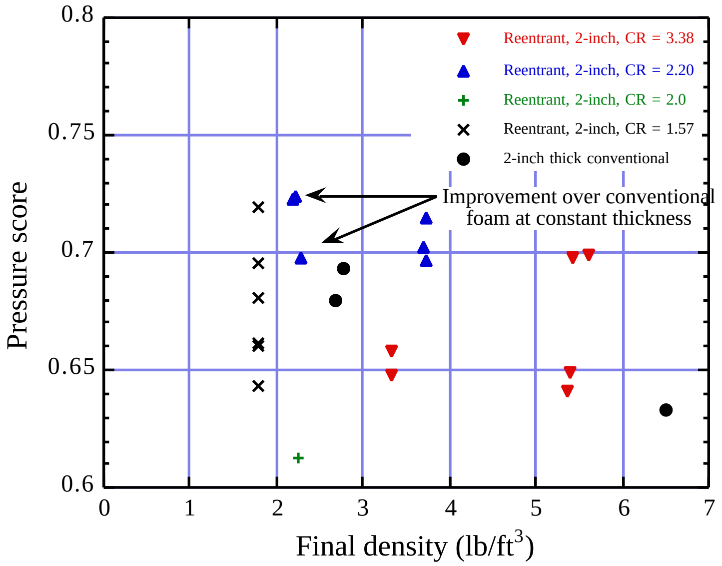

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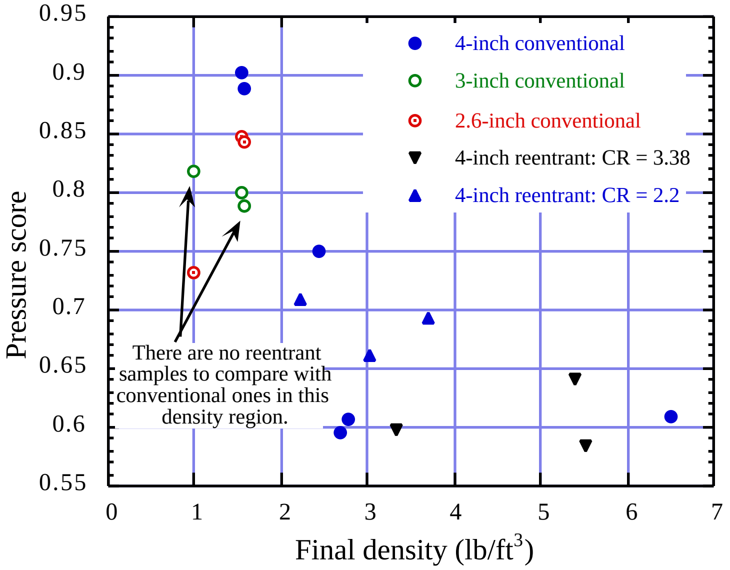

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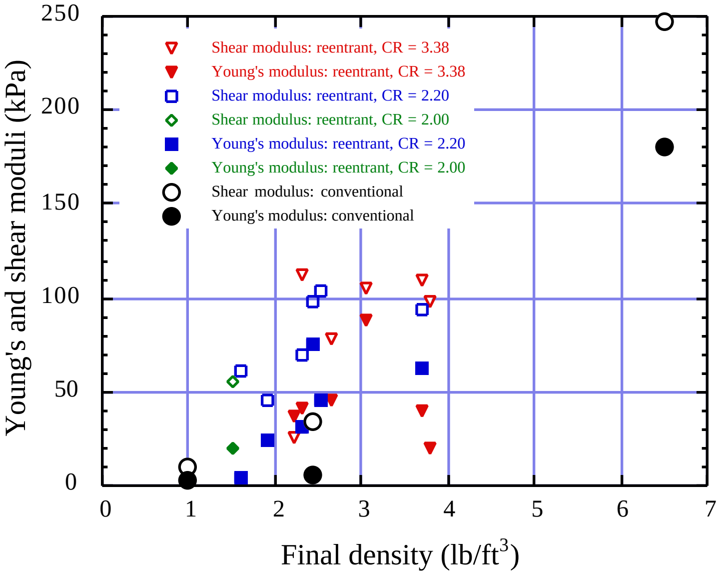

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