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MECHANICAL AND VISCOELASTIC BEHAVIOR OF FLEXIBLE FOAM UNDER COMBINED SHEAR AND COMPRESSION

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Abstract

The room temperature mechanical behavior (shear and normal stresses) of Dow Corning Silastic 5370 RTV foam, a flexible, open-cell, polysiloxane foam, was investigated under combined shear and compressive strains as functions of strain and time. Compressive stiffness of the foam showed a large dependence on compressive strain, while the shear stiffness was much less dependent on compression and shear. Interestingly, the normal (compressive) stress under shear showed a component that was quadratic in shear strain, decreasing with shear strain at compressions less than 20% (or even going into tension) and increasing with shear strains at compressions greater than 20%. Hysteresis in shear stress and normal stress was observed at high compressions. The foam showed slight viscoelasticity with the stress relaxing as t^{-n}, as is typical for filled elastomers. The relaxation time exponent, n, showed little dependence on shear strain but became larger with increasing compressive strain, indicating faster relaxation of stresses under high compressions. This is consistent with the increased hysteresis seen at larger compressions.

Experimental

Dow Corning Silastic 5370 RTV foam consists of a foamed, silicone elastomer filled with approximately 15% by weight diatomaceous earth. Flat slabs of foam were molded to a nominal thickness of 1 mm and a density of 0.40 g/cm^3, or a relative density of 0.37 (assuming a filled polymer density of 1.08 g/cm^3). Cylindrical specimens were cut from these slabs and subjected to compression in a Rheometrics Solid Analyzer (RSA-II) and combined compression and torsion in a Rheometrics ARES rotational rheometer (Rheometric Scientific, Piscataway, NJ). Samples subjected to torsion were bonded to the plates with epoxy (Hardman 5-minute epoxy, Elements Performance Polymers, Belleville, NJ) to prevent slipping at the surface.

Results

Compressive (or normal) stress, σ, was calculated as the normal force per unit area normal to the compression direction. Compressive strain, ε, is reported here as engineering strain: $\varepsilon=(h_o-h)/h_o$ where h is the thickness of sample at time t, and h_0 is the original sample thickness. A typical compressive stress vs. compressive strain curve (with no superimposed shear) is shown in Figure 1.

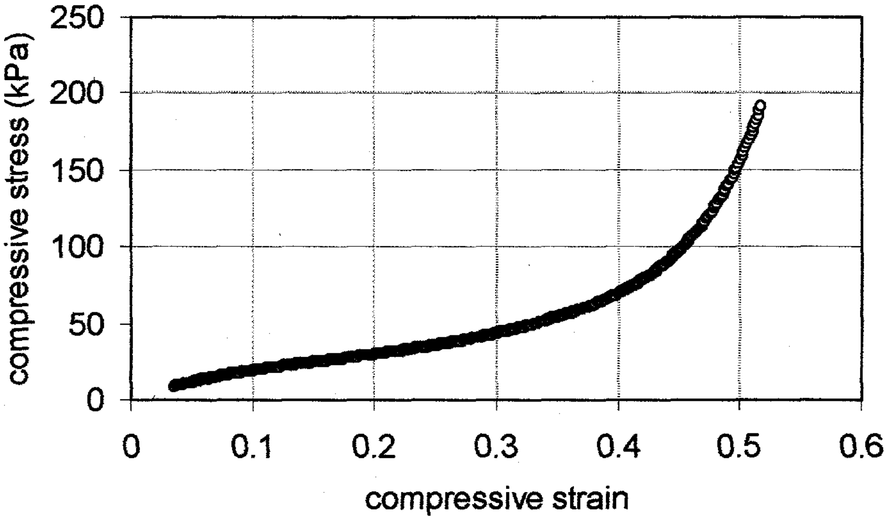

Figure 1. Compressive stress vs. compressive strain (no shear) measured on S5370 foam.

In samples measured in torsional shear, the sample was assumed to be homogeneous, hence the shear strain was assumed to be linear in radial position within the sample. Shear strains are reported here as apparent shear, or shear strain at the outer edge of the sample, γ_R, which was calculated as $\gamma_R = R\Theta/h$, where R is the radius of the sample, and Θ is the angle through which the sample is twisted (angular deflection of the rheometer motor). The torque, T, was found to be approximately linear in shear strain (see below), and the shear stress, τ_R, at the edge of cylindrical samples was calculated from the torque as $\tau_R = 2T/\pi R^3$.

The shear stress and normal stress measured on one sample as functions of shear strain at 0%, 10%, 20% and 40% (percent of original thickness) compression are shown in Figure 2. a-d, respectively. In each case, the compressive strain was held constant while the sample was steadily sheared at 0.01 s^{-1} in one direction then in the opposite direction several times. At compressions less than 40%, the shear stress was nearly linear in shear strain, but dependent on compression. Similar behavior was observed for higher shear rates. Significant hysteresis in shear strain was observed at a compression of 40%.

Under no compression, the foam goes into tension with shear strain (Poynting effect, see Chapman, 1976, p 156), and the tensile stress increases nearly quadradically in shear strain. At 10% compression, the compressive stress decreases with shear strain, At 20% compression (Fig. 2. (c)), the normal force shows a more complicated dependence on shear strain, with slight hysteresis. At 40% compression, the compressive stress increases with shear strain and shows significant hysteresis.

The normal stress observed in torsion under compression can be related to the compressive stress/strain behavior seen in Fig. 1. For compressions less than 20%, the compressive stress plotted against either shear strain or compressive is strain concave down, that is, the compressive stiffness decreases with increasing strain (either shear or compression). At compressions higher than 20%, the compressive stress as a function of strain is concave up, that is, compressive stiffness increases with strain. As seen in Fig.1, an inflection point occurs at a compressive strain of 20%. Interestingly, at a compression of 20% the normal stress as a function of shear strain is concave up at small shear strains (less than 5%) and concave down at higher shear strains (Fig. 2. (c)). The hysteresis in the compressive stress seen at 20% and 40% compression is presumably due to structural rearrangements of cell walls and perhaps friction between walls of collapsed cells in addition to the slight viscoelastic relaxation of compressive stress.

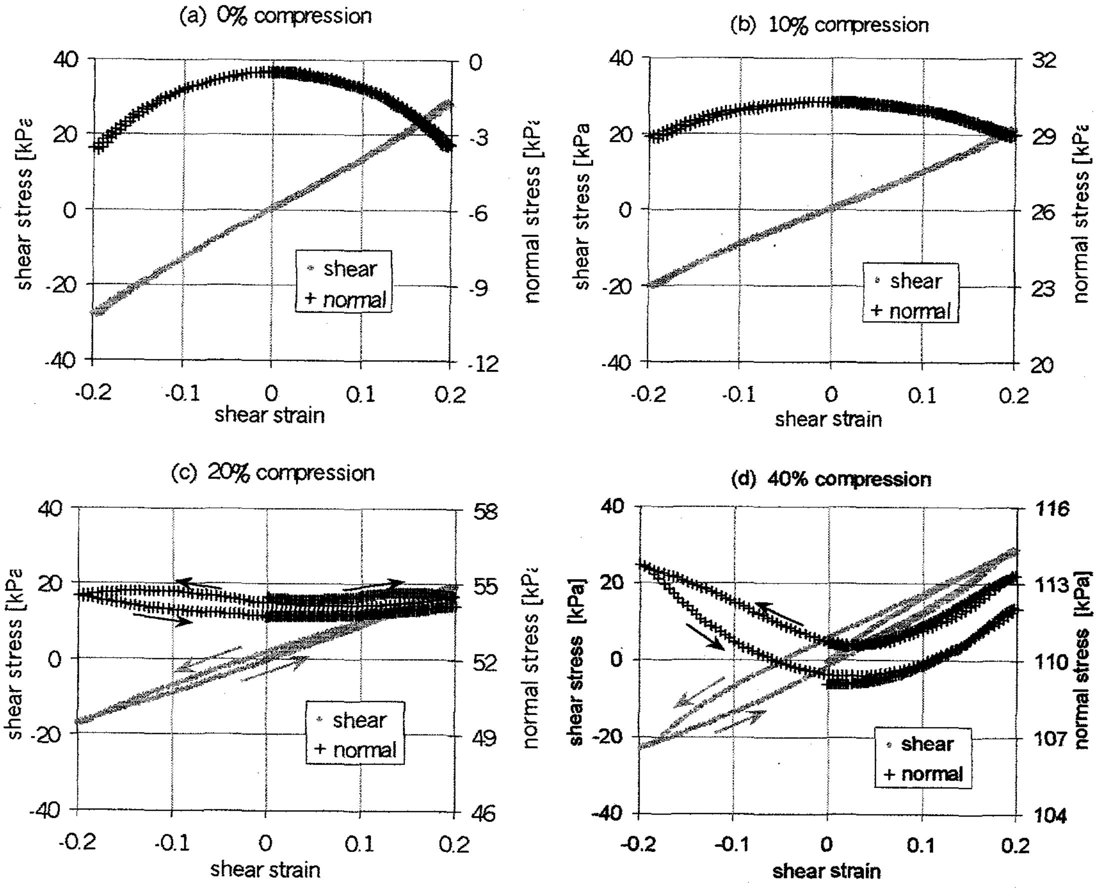

Figure 2.Shear stress and normal stress as functions of shear strain and compressive strain. The compressive strain was held constant at the compressions indicated while the sample was sheared several times at a rate of 0.01 s^{-1} in one direction then in the opposite direction. Compressive stress is positive, tension negative.

The viscoelasticity of the foam was investigated in compression and shear. The compressive stress relaxation modulus is shown in Figure 3 for compressive strains of 0.046 through 0.465. These measurements were made at 22°C on the same sample (but a different sample from that used in the combined shear/compression measurements shown in Fig. 2). The relaxation modulus in compression, $E(t)$, was observed to decay as $E(t)=E_o t^{-n}$, where E_0 is a constant, dependent on strain. The compressive stress relaxation modulus, measured at compressions of 0.045 to 0.465 is shown in Figure 3. The compressive modulus is tabulated in Table 1, and the dependence on compression is consistent with the stiffness change seen in Fig. 1, softening at low compressions (less than 20%) and stiffening at higher compressions. A slight strain dependence of the relaxation exponent, n, is observed with increasing compression, ranging from n=0.006 to 0.010 at compressive strains up to 0.47.

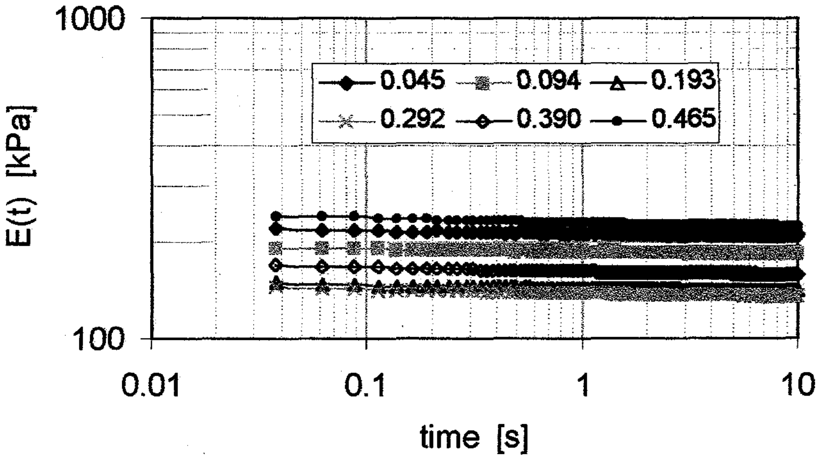

Figure 3. Compressive stress relaxation modulus measured at the compressive strains indicated.

The stress relaxation modulus in shear, *G(t)*, was measured at various compressions and showed little shear strain dependence (see Table 2), but similar dependence on time, that is, $G(t) = G_o t^{-n}$. The shear modulus decreases with compression at compressions less than 20%, then increases with higher compression, which is qualitatively similarly to the strain dependence of the compressive modulus (cf. Table 1). This foam is slightly viscoelastic, slightly nonlinear in shear, and highly nonlinear in compression.

Table 1: Comparison of shear stress relaxation modulus parameters as functions of shear strain and compressive strain.

Compressive Strain	E_o	n
0.045	213.7	0.0071
0.094	187.5	0.0074
0.193	143.8	0.0084
0.292	139.1	0.0093
0.390	162.9	0.0100
0.465	231.6	0.0111

Table 2: Comparison of Shear Stress Relaxation Modulus Parameters as Functions of Shear Strain and Compressive Strain.

	Compressive Strain	G_o	n
Shear Strain = 1%	0.0	143.5	0.0113
	0.10	109.7	0.0149
	0.20	113.8	0.0240
	0.40	217.5	0.0765
Shear Strain = 10%	0.0	137.1	0.0109
	0.10	103.2	0.0129
	0.20	100.0	0.0211
	0.40	166.3	0.0398

The relaxation time exponent, n, is larger in shear and is more sensitive to compressive strain than shear strain. At high compression, *n* does appear to be more sensitive to shear strain. In both pure compression and combined shear/compression, *n* increases with compression, indicating a faster stress relaxation. This may explain part of the increase in hysteresis seen at large compressions in the combined shear/compression measurements (Fig. 2. c and d), that is, more relaxation of shear and compressive stresses occurred at large compressions.

Discussion

The compressive stiffness of the foam showed a large dependence on compression. As is typical for open-cell elastomeric foams (Gibson and Ashby, 1997), the compressive stiffness decreased with increasing compression at low compressive strains, presumably due to buckling of cell walls. At compressions above 20% the compressive stiffness increased with increasing compression as the foam densified. Under combined shear and compression, the shear stiffness was nearly constant with shear, but exhibited a compression dependence similar to that of the compression stiffness. Interestingly, the normal (compressive) stress under shear showed a component that was quadratic is shear strain, decreasing with shear strain at compressions less than 20% (or even going into tension) and increasing with shear strains at compressions greater than 20%. Hysteresis in shear stress and normal stress increased at high compressions. The foam showed slight viscoelasticity with the stress relaxing as t^{-n}, as is typical for filled elastomers. The relaxation time exponent, *n*, showed little dependence on shear strain but became larger with increasing compressive strain, indicating faster relaxation of stresses under high compressions. This is consistent with the increased hysteresis seen at larger compressions.

Acknowledgments

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