Compressive Creep of Flexible Polyurethane Foam

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Synopsis

The compressive creep rate of polyurethane foams was found to be a complex function of deflection and time. The complexity has been shown to be related to the buckling of the cell struts as the foam is compressed. Of the parameters normally varied in the foam formulation, both the polyol molecular weight and the water content of the foam formulation seemed to have a measureable effect on the creep rate.

INTRODUCTION

Over the past ten years the role of flexible foam has continued to change from a cosmetic function into a structural load-bearing component of bedding, furniture, and automotive seats. The first uses for foam as a load-bearing material were in bedding and soft furniture. Then foam was used in deep foam seats by the automobile industry in the early 1960s up to present, Figure 1. In this application the flexible foam was used both as a load-distributing and vibration-dampening member of the seat assembly with zigzag springs used as the ultimate load-bearing component of the seat. There is currently a trend to make automotive seats exclusively out of flexible seat foam, Figure 2. This shell seat has a metal shell that confines the foam which is used for both load bearing and vi-

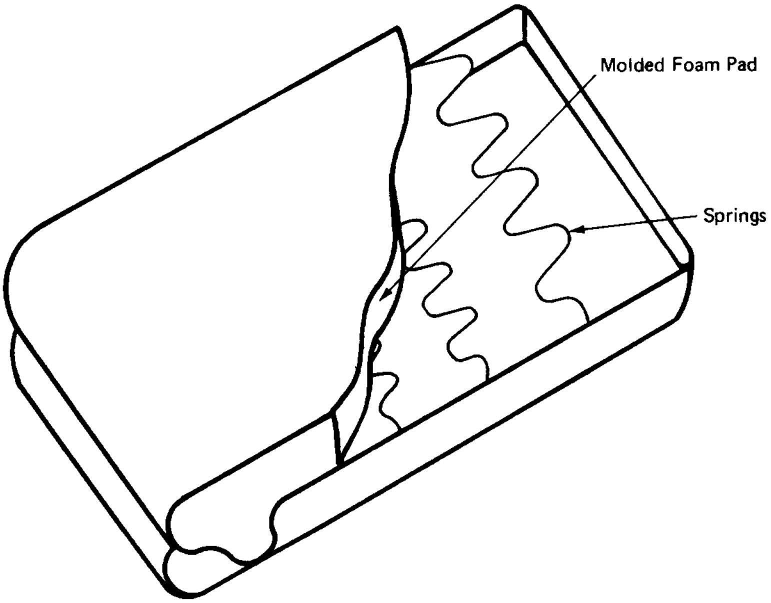

Fig. 1. Deep foam seat construction.

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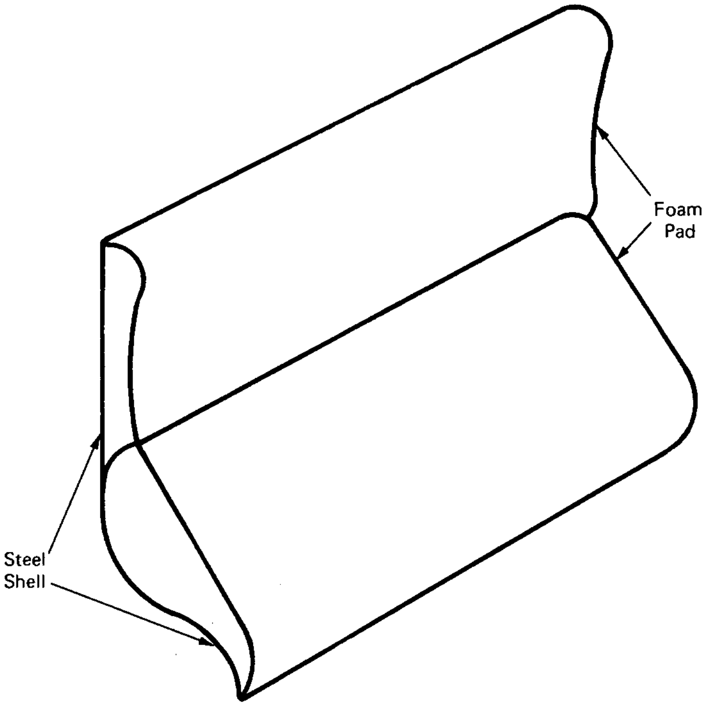


Fig. 2. Shell seat construction.

brational dampening. Thus, the springs which were previously used to carry the load are eliminated, and for the first time in automotive seating the foam must do all the work.

It has been well established that polymeric materials change their apparent modulus, that is, they creep under constant load.[1,2] The dynamic properties of polymeric foams are also discussed in detail by Meinecke and Clark.[3] Most of the work described in the area of creep is concentrated on the tensile and torsional modes at relatively low strains. Under these conditions several elaborate models have been developed which relate compliance to the retardation spectrum of the polymers.

Several investigations have been reported which addressed the problem of interpolation of the complex modulus–strain relationship of polymeric foam when tested in compression. Gent and Thomas[4] proposed the cubic model with strut buckling to explain the plateau in the compression stress–strain curve of natural rubber foam. Whittaker[5] extended this analysis to microporous polyurethane foams. Gent and Rush[6] and Payne and Whittaker[7] have investigated some of the viscoelastic properties of polyurethane foam concentrating on periodic forcing functions, and Terry[8] has suggested that the humid age compression properties of polyurethane foams are related to creep of the polymer. However, a thorough investigation of the factors that influence the compressive creep characteristics of flexible polyurethane foams at ambient conditions has not been reported. It is the goal of this work to address the question of the creep properties of flexible polyurethane foams under static compression loading at room temperature and 50% relative humidity.

EXPERIMENTAL

There are no conventional test procedures or test fixtures available in the literature which could be used to effectively test flexible foam in the compressive creep mode. An apparatus was developed which is shown in Figure 3. The whole assembly is made of 316 stainless steel. The platen rides on unlubricated stainless steel ball bearings which are located such that minimum side force is exerted on the platen. The guide bearings are adjusted so that if the platen is lowered onto a spring with a spring rate of 1000 g/cm, it would rebound to the initial height to within ±0.00254 cm. This ensures that the frictional resistance in the fixture does not interfere with the viscoelastic response of the tested sample. A linear variable differential transducer (LVDT) with a linear response of ±5 cm was threaded into the top of the platen such that the core moved in conjunction with the platen. The apparatus was then hooked up as shown in Figure 4. Because of the humidity sensitivity of foam systems, all testing is done at 21 ± 1°C and 50 ± 2% relative humidity. The samples are preconditioned for at least 16 hr in the humidity chamber which has internal circulation provided by small fans.

A typical experimental run begins by turning on the recorder and allowing the

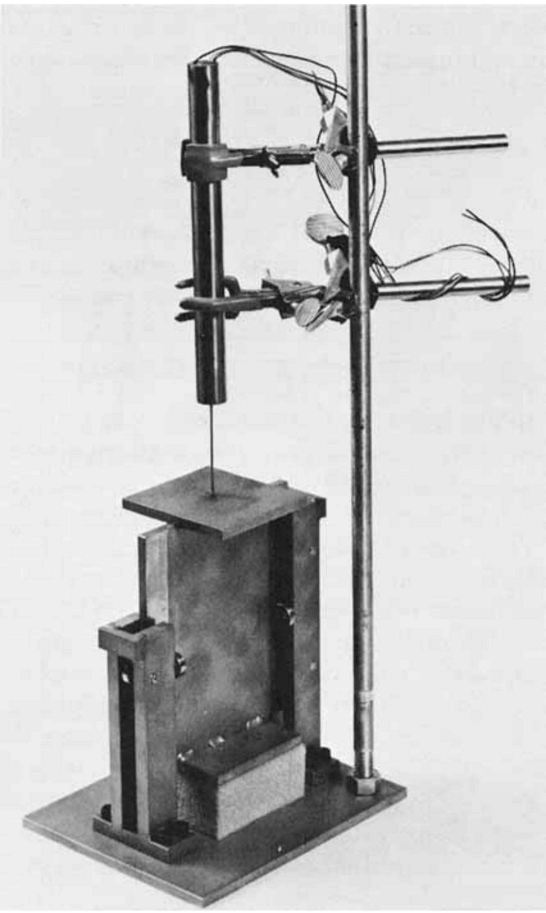


Fig. 3. Picture of creep apparatus.

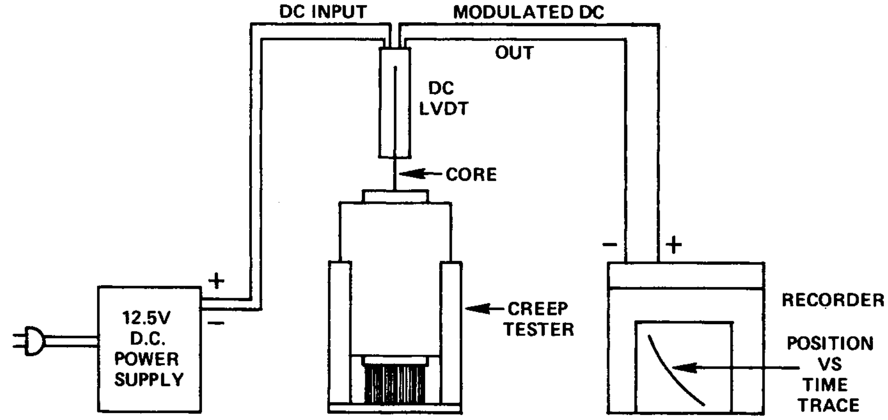


Fig. 4. Creep test setup.

recorder speed to stabilize. The platen, which is 56.25 cm^2 in size, is then raised to a height of greater than 5 cm to accommodate the 5 × 7.5 × 7.5 cm sample. The platen is then lowered slowly until it is in contact with the upper surface of the foam test sample. The platen is then released and allowed to free fall into the foam. Data are taken continuously for the first 60 sec and then at intervals at least every half-decade of time throughout the remainder of the test. A normal test runs for 2 hr, and the data are reduced using regression analysis by the following relationship:

$$y = -m \ln \theta + B$$

$$y = (L/L_0) \times 100$$

where y is displacement (in percent of original thickness), L_0 is original thickness, L is thickness at time θ, θ is time, ln stands for natural log, B is initial deflection, and m is rate of creep $\Delta(L/L_0)100/\Delta \ln \theta$.

RESULTS AND DISCUSSION

The reproducibility of the system was checked, and typical results are shown for a sample of hot foam. This hot foam was then compared with high-resilience (HR) foam, Figure 5. It is seen that the two hot foam samples 5-1 and 5-2 have the same deflection-versus-log time curve, indicating very good reproducibility in the system. Visual inspection of the two lines drawn through the points indicate that the HR foam appears to have a much higher slope than the hot foam, which agreed with the car test results, i.e., drivers tend to sink more quickly into HR foams than hot foam. It also indicates that the creep tester would differentiate between different foam systems. Foams now in use undergo a strain of 40%–45%; hence, it was felt that the creep test should be conducted at this strain to best simulate the end use. Thus, the effect of stress on the penetration of a 5.0 × 7.5 × 7.5 cm sample was determined when the sample was tested in the 5-cm direction. The results of the initial penetration as a function of stress are graphed in Figure 6. The results indicate that a stress of 5.68 kPa would be an adequate stress and that the movable platen (2.74 kPa) produced a strain of 10% in a typical seat foam.

Two foams, one hot and the other HR, were formulated such that they had

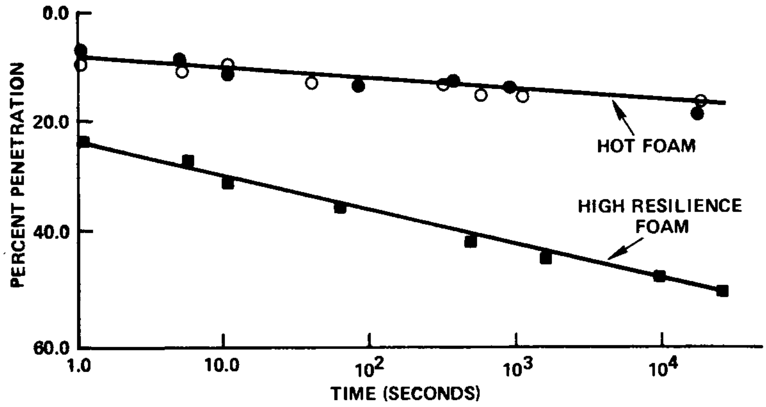


Fig. 5. Initial equipment tests (foam creep response): stress 4.25 kPa; (●) sample 5-1; (○) sample 5-2; (■) sample 7-1.

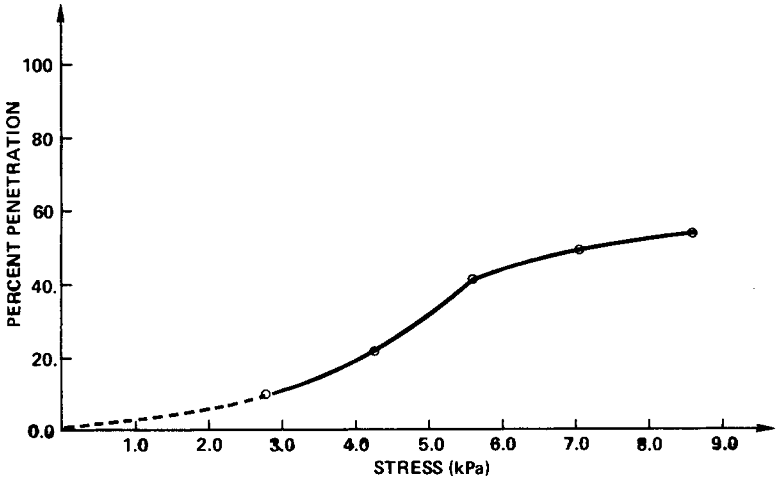


Fig. 6. Effect of stress on penetration for typical high-resilience seat foam.

the same 25–65 compression load deflection. They were then tested using 2.74 kPa and 5.68 kPa stress, and the results are shown in Figure 7. The calculation of the slopes from these experiments indicated that the creep rates at 40% deflection were about 30% greater than the creep rate at 10% deflection for both

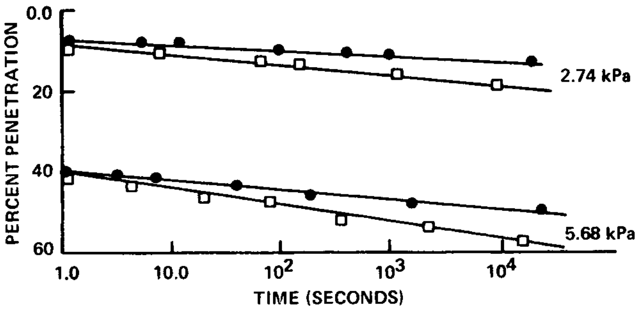


Fig. 7. Creep of hot and cold foam: (●) hot foam; (□) cold foam (HR).

the hot and HR foams. These results led to a more extensive investigation of the creep penetration relationship to be discussed later.

To further develop the creep rate penetration relationship, duplicate HR foam samples were loaded with four stresses and tested for an extended period of time, as indicated by the results in Figure 8. For this sample the initial creep rate, as indicated by the slope of the lines in Figure 8, appears to go through a maximum at 20% initial penetration. Examination of the data at longer times shows a marked increase in rate for the sample loaded with a stress of 2.74 kPa. This increase in rate seems to be a step function occurring at about 15%–17% deflection. Thus, the possibility was considered that the creep rate is a function of compressive strain. Short time data for the 4.25 kPa, i.e., data from 0.5 to 1 sec, showed a similar response. However, because these data are less accurate, they are not presented in this figure. The discovery of the very nonlinear function of creep rate with deflection as the independent variable warranted more investigation. This investigation was carried out using a series of duplicate H.R. foam samples and an added set of weights which provided the experimental capability of increasing the stress by 0.75-kPa increments. The relationship for the creep rate, $d[(L/L_0) \times 100]/d(\ln \theta)$, of HR deep seat foam from 6% penetration to 80% penetration is presented in Figure 9. From about 6% to 15% deflection the creep rate is constant. Then at 15% the rate has an apparent step function increase from about 0.8 to 3.2, by a factor of 4. The rate then decreases nonlinearly back to the initial value at about 70% penetration. These results indicate that any attempt to determine the effect of process and chemical changes in the creep rate must be done either at constant strain or over a spectrum of strains extending beyond both extremes of the anticipated use penetration.

Having determined that the creep rate-versus-deflection relationship contained a step function, the next step in the investigation was to determine what caused the four-fold increase in creep rate at the 15%–20% penetration levels.

Analysis of the foam physical construction suggested that one possible cause of the increased creep rate might be the phenomenon called long column buckling.[9] A qualitative description of the buckling mode of failure is presented in Figure 10. An end loaded column will store a certain amount of strain energy, Figure 10(a). As the column is loaded further, enough strain energy is accumulated to cause it to fail in the buckling mode if it is moved off the long axis,

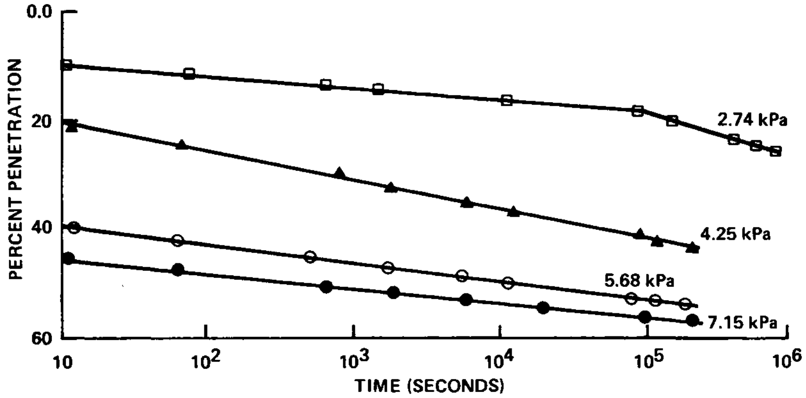


Fig. 8. Effect of stress-induced strain on creep.

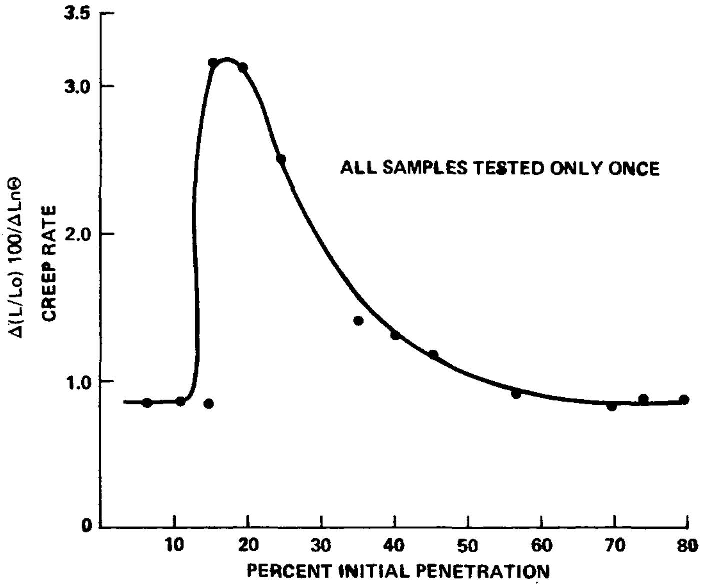
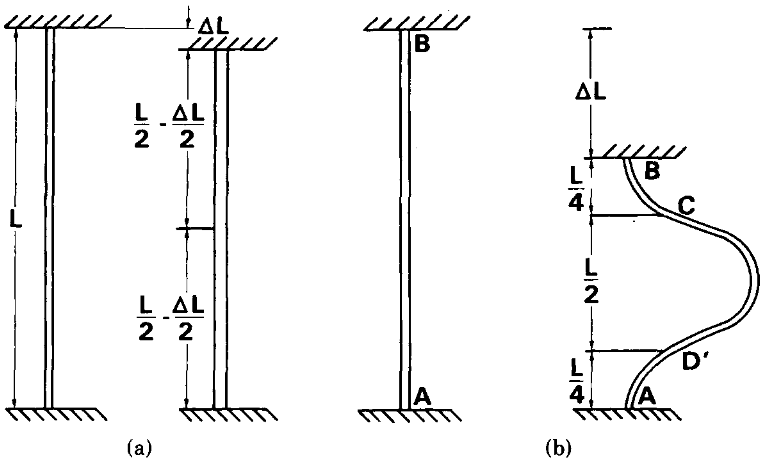


Fig. 9. Creep rate as function of penetration.

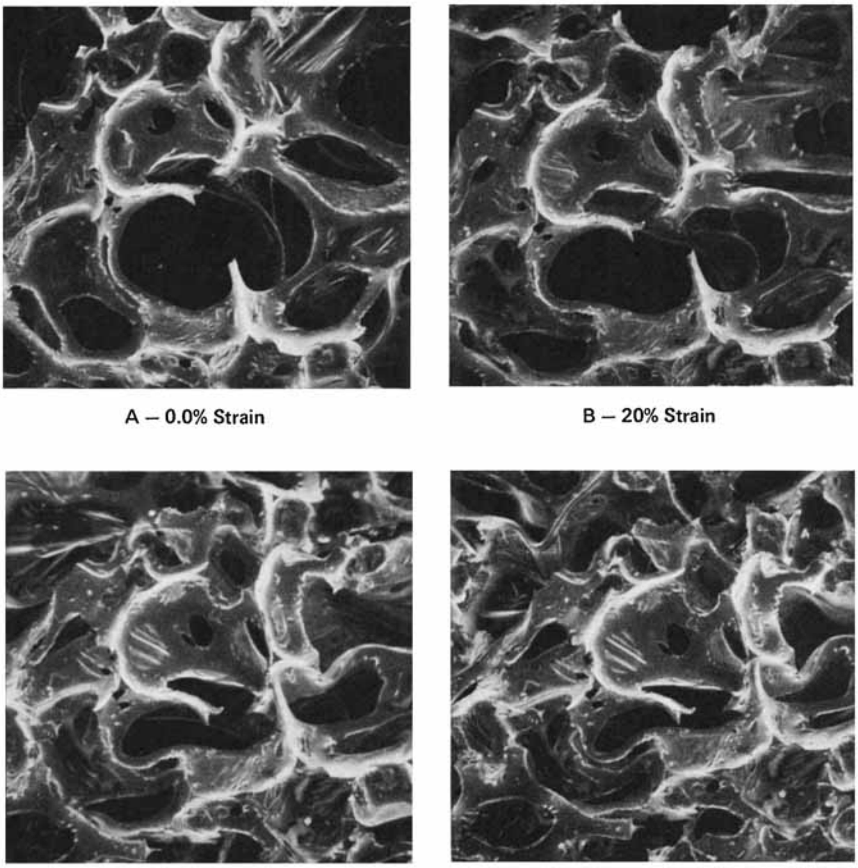


(a) (b)

Fig. 10(a). Long column buckling; (b) long column buckling.

Figure 10(b). The shape of the failure will be a cosine function.[9] It is obvious that in the buckled structure the localized strains will be much greater than just before the column buckles. It is likely that the rapid increase in strain in the buckled struts causes the almost step-function increase in the creep rate. This would suggest that creep is a function of microscopic strain.

The photographs in Figure 11 confirm that buckling does in fact occur. The series of photographs (a) through (c) show the continued deformation of the foam with the resulting buckling occurring. Another interesting observation was made using this set of pictures, namely, that the cell which had almost complete membranes did not exhibit the buckling phenomenon. Apparently, this cell was more stable because the membrane was kept under tension by the movement



A – 0.0% Strain

B – 20% Strain

C – 45% Strain

D – 70% Strain

Fig. 11. Electron micrographs of crushed foam: (A) % strain; (B) 20% strain; (C) 45% strain; (D) 70% strain.

in the neighboring cells. This is suggested by the increase in size of the membrane during the compression process while the struts in the adjoining cell have become distorted.

During this phase of the investigation the question arose, "Is the buckling only a surface phenomenon?" To test this possibility a light microscope was used and focused several cells below the foam surface. The results of this experiment are shown in Figure 12, with the percent penetration shown below each frame. These data confirm the former results and further show that during the first 12% compression the struts did not buckle but only compressed. At 20% penetration there had been a failure and the struts were buckled. Scanning the entire surface indicated that this phenomenon occurred at about the same proportion throughout the entire foam sample. Further compression caused the struts that have buckled to continue to deform. However, there did not appear to be many more struts buckling as the compression was applied. Depending on the length of the buckled strut and the size of the cell, the buckling continued until the strut came in contact with another solid member or until it closed on itself. The gross movement appeared to stop between 60% and 75% compression.

At this point it was felt that the creep phenomenon had been defined well

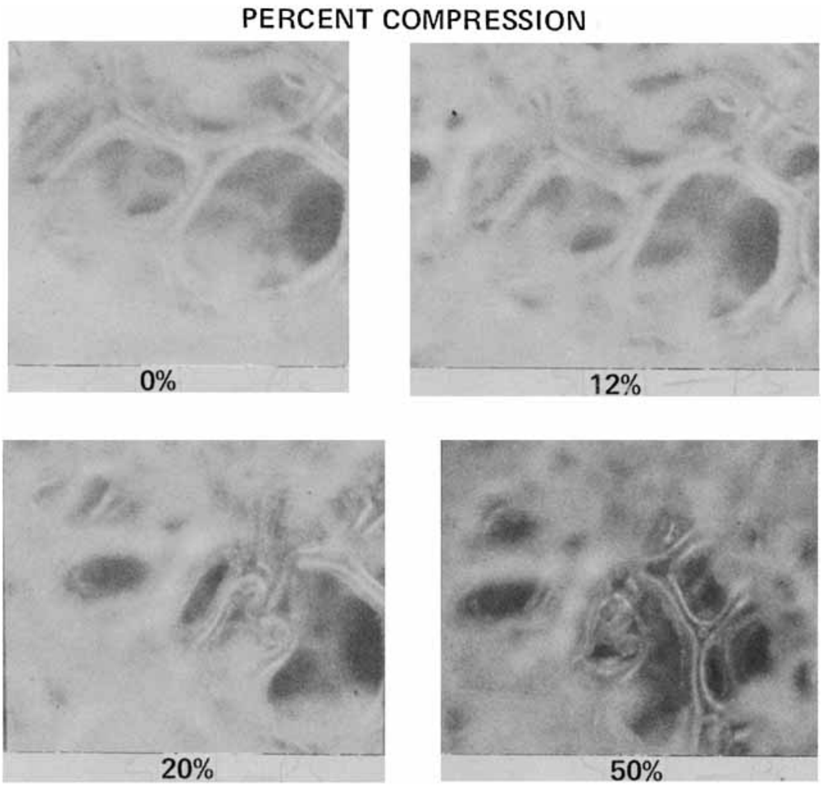


Fig. 12. Light micrographs of buckling in flexible high-resilience foam.

enough to proceed toward a better understanding of the effect of the formulation and process variables on the creep rate of flexible polyurethane foams. There are three ways to change the density of molded foam—packing, water content, and fluorocarbon content. As the core foam density was increased from 0.0384 to 0.0473 g/cm^3 by packing the mold, there was no effect on the creep rate of these foam systems, Figure 13. The effect of water as a blowing agent was determined in a separate experiment. When the water content was raised from 2.2 to 2.60 parts, the average creep rates for three samples at 60% penetration were found to be 0.70 and 0.85, respectively. Fluorocarbon was found not to affect the creep rate, as shown in Figure 14. Within the normal limits used in molded seat foam, i.e., less than 10% fluorocarbon, the addition of the fluorocarbon does not affect the creep rate at constant deflection. Thus, two methods for varying density appear to have little effect on the creep function within the constraints encountered in molded seat foams. The exception is water content in the formulation, which causes a marked change in the creep rate.

The next variable to be investigated was the effect of cure conditions, as related to water content, on the creep rate. A molded sample was cut into two pieces and half was crushed, followed by a 20-min postcure at 120°C. This was similar to conventional postcure cycles. The other half was cured for 2 hr in a vacuum oven at 120°C and then crushed. The results, which are graphically expressed in Figure 15, indicate that at high penetration the vacuum-cured sample has a lower creep rate than the standard cured sample. However, as the penetration

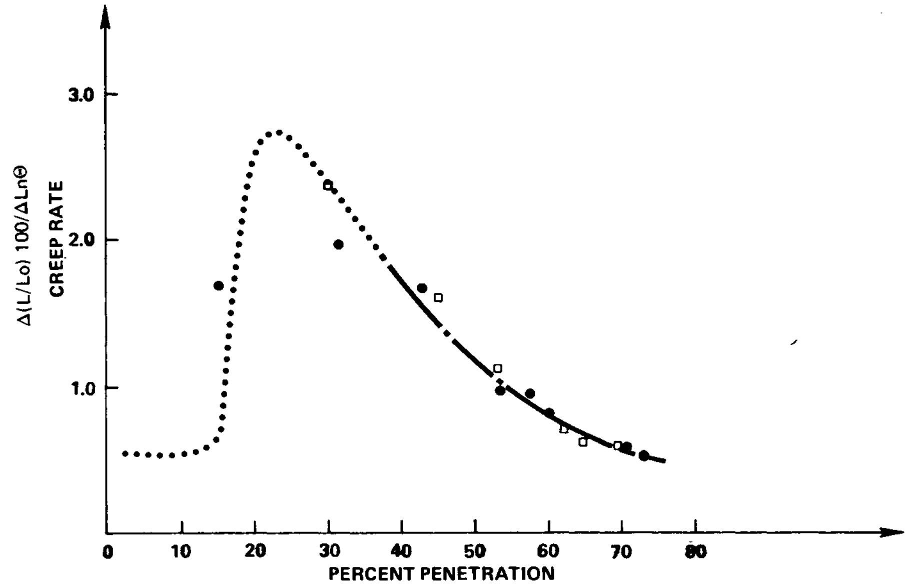


Fig. 13. Effect of mold packing on the creep function: density (■) 107-1,0.0384 g/cm^3; (□) 107-2,0.0423 g/cm^3; (●) 107-3,0.0473 g/cm^3.

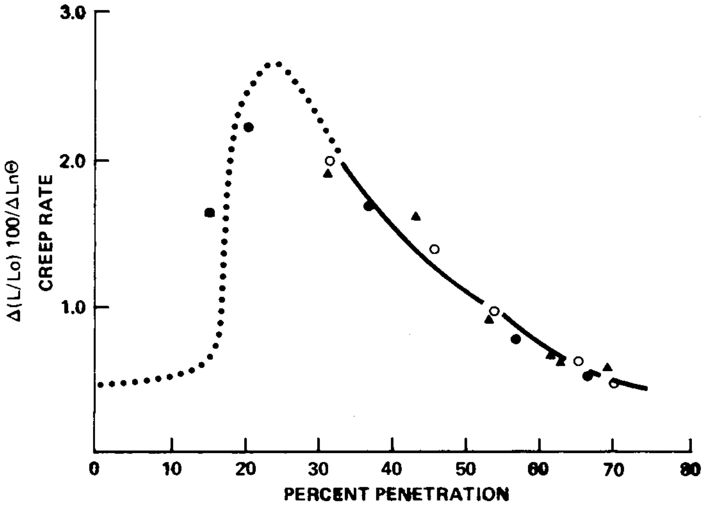


Fig. 14. Effect of fluorocarbon blowing on creep function: (▲) 107-3 (O) F-11; (●) 107-4 (4) F-11; (O) 107-5 (8) F-11; figure in parentheses is part of F-11.

decreases, they appear to approach the same creep rate. This may be due to the rupture of more membranes in the more highly cured sample. At the high penetration the vacuum curing lowered the creep rate from 0.5 to 0.4, a 20% reduction.

Several hot foam samples were tested with variable results. In all cases the creep rate was less than that found for conventional HR foam. The creep rates for the hot foams were found to be from 5% to 25% lower than in current H.R. foam systems at very high penetrations. The hot foam in Figure 16 has a creep rate 25% less than the HR foam, with the absolute difference maintained, throughout the 40% to 70% penetration range.

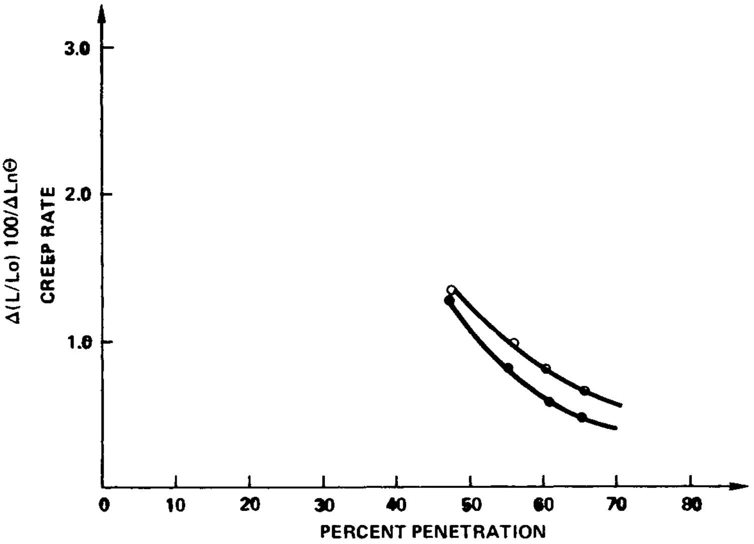


Fig. 15. Effect of cure on creep rate: (O) standard cure (20 min, 120°C); (●) 120 min, 120°C vacuum.

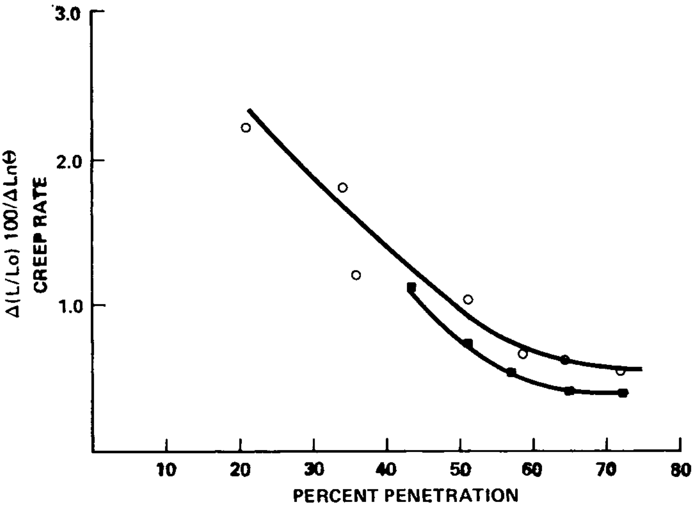


Fig. 16. A comparison of hot and high-resilience foam creep rates: (O) 109-1B7 (HR foam); (■) hot foam.

Another ingredient often used in foam formulation is an inorganic filler such as barium sulfate to vary the hardness of the foam. A sample with 20 wt-% barium sulfate, which calculates to about 6% by volume, was tested in conjunction with a sample which was chemically identical. It is seen in Figure 17 that the filled sample has higher creep rates at all penetrations and the foam creep rates are greatest at low penetrations. This may be due to the filler providing flaws which promote buckling of the cell struts at the lower penetration where strut buckling has been demonstrated to be the controlling mechanism for foam creep.

The effect of isocyanate type was next examined. Two isocyanate families

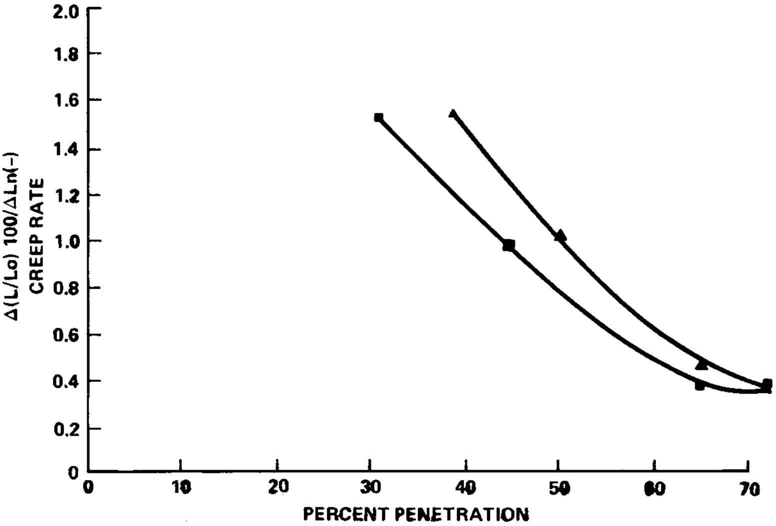


Fig. 17. Effect of inorganic filler on creep rate: (▲) 20 wt. % $BaSO_4$ filled; (■) unfilled.

were used in this experiment. The first was a 20% mixture of crude MDI (methylenedianiline diisocyanate) in 80%, 2-4, 2-6 TDI (toluene diisocyanate). The second system was a mixture of 2-4, 2-6 TDI and the dibiuret of MOCA, which was labeled the adduct. Using these materials, two samples with approximately 2.1 molar functionality for the isocyanate were tested, with the results shown in Figure 18. As seen from the two curves (●) and (■), there is no strong effect of isocyanate on the creep rate. At high penetration the adduct foam seems to reach its minimum earlier, but it has a higher creep rate at low penetrations. These differences could be due to cell geometry because both systems approach the same creep rate in the limit.

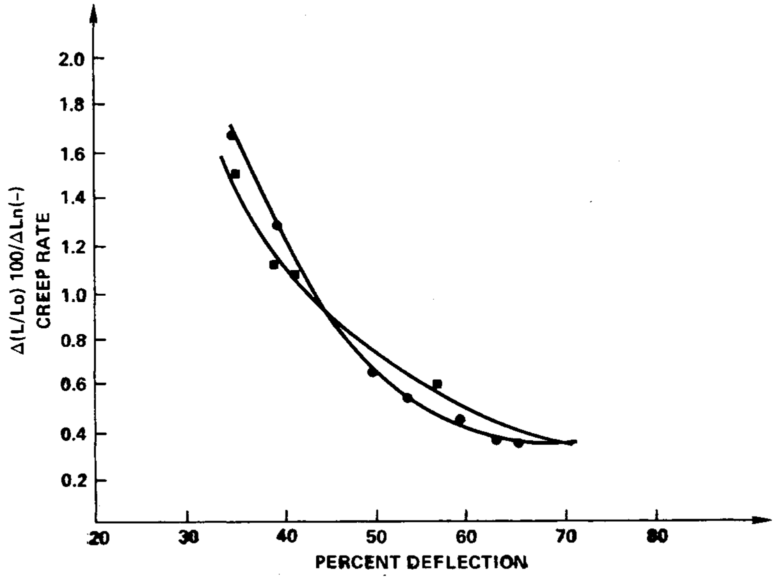


Fig. 18. Effect of isocyanate type on creep rate: (●) MDI-TDI (f = 2.1); (■) adduct-TDI (*f* = 2.1).

Since the foam is increasing in importance as a load-bearing support structure, two foams were tested to determine what effect the use environment would have on the creep rate. One sample was tested as made. The other underwent 400 hr of dynamic compressive loading at a minimum of 60% compression. The results of this experiment showed a marked increase in creep rate for the sample that had undergone the dynamic loading, Figure 19. These results led to a more thorough examination of the effect of test time and type on the creep of flexible foam.

A test was developed in which the sample was loaded for 2 hr, unloaded for 4 hr, loaded for 2 hr, and unloaded for 16 hr. These sequences constituted a cycle. The results of this test carried out through seven cycles is shown in Figure 20. After five cycles the initial penetration has increased by 4% and remains constant for the last three cycles. It also can be calculated from the data that the slope (creep rate) of the last three cycles is lower than the slope of the first cycle, 0.91 versus 1.18. Thus, cyclic constant stress with no dynamic forcing function has the effect of lowering the creep rate, which is an effect opposite that found for samples tested with 400 hr of dynamic forcing shown in the previous figure. This would suggest that a physical change, such as tearing of the cellular membranes, has caused the increase in creep rate of the formerly discussed sample.

Recalling the photomicrograph discussed in the previous section on buckling, the cell with the unbroken membrane is shown before and after compression at

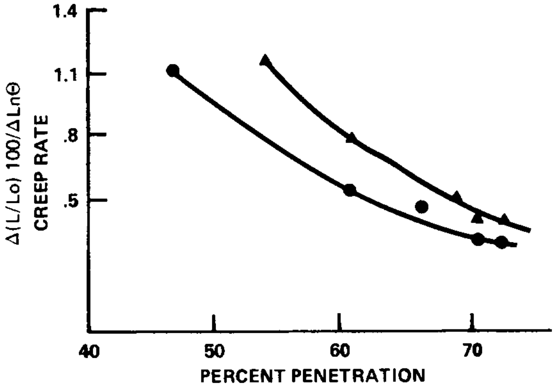


Fig. 19. Effect of dynamic loading on creep rate: (●) unworked; (▲) 400-hr dynamic testing.

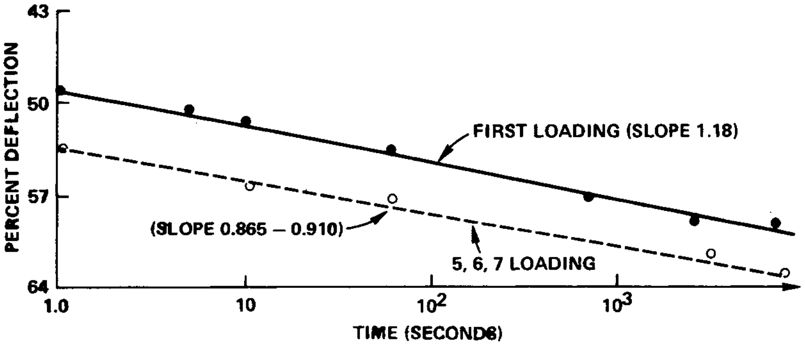


Fig. 20. Effect of cyclic loading on deformation of flexible foam: 2-hr load; 4-hr rest; 2 hr load; 16 hr rest; cycled fatigue, constant stress (5.68 kPa).

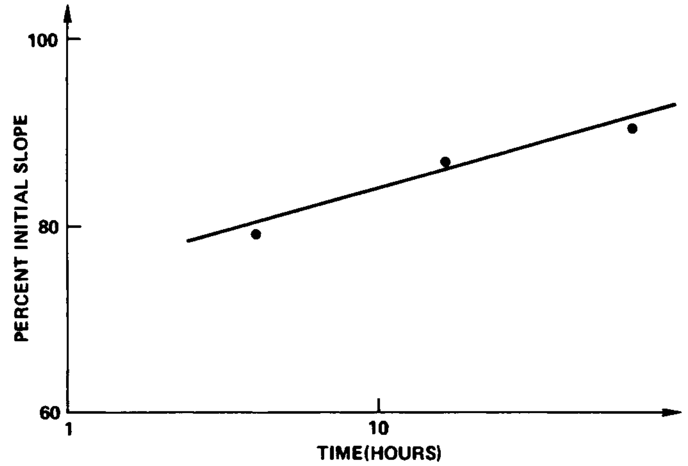


Fig. 21. Effect of rest time on creep slope recovery: initial load 5.68 kPa for 4 hr; initial slope 1.18.

higher magnification. It is seen that in fact the membrane is under a tensile stress, as indicated by the strain lines in the thin shiny section. Examination of the two foam specimens used for the 400-hr dynamic test showed that before the test there were a large number of membranes with flaws. After the test many of these membranes had ruptured. This allows more struts to buckle at a given strain, accounting for the higher creep rate of the cycled foam.

The lower creep rate after cycling resulted in an investigation of the rate of recovery of the creep rate. Several foam samples were compressed by loading in the creep tester with an initial penetration of 45% and kept in the loaded mode for 4 hr. Then, after periods of time they were retested, with the results shown in Figure 21. It can be seen that the recovery of creep rate is a semilog function, with about 92% of the initial rate recovered in 64 hr. These results suggest that samples should have at least seven days of rest before tests are conducted.

SUMMARY

The creep characteristics of flexible polyurethane foam do not fit simple elastic theory. The creep rate of these seat foams was found to go through a maximum at about 30% compression. From the results found with these samples there appears to be a correspondence of creep rates with strain but not with stress. The maximum in the creep rate is thought to be a result of very high localized strains at the onset of buckling of the foam struts. The results indicate, within the scope of the parameters investigated, that creep rate is not affected by foam density, fluorocarbon, or type of isocyanate. The creep rate is increased by increasing the water in the formulation or cure cycle and by increasing the equivalent weight of the polyol. The unopened cell walls tend to decrease the creep rate initially. However, using these foams tends to rupture the cell walls and increase the creep rate. Because of the log-linear nature of the creep recovery, samples should be allowed to rest at least one week before testing.

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