Mechanical Properties of Urea–Formaldehyde Foam

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Synopsis

The mechanical behavior of urea-formaldehyde foam was studied to evaluate its potential for energy absorption applications. The apparent elastic modulus (E_f) as a function of foam density was obtained from force-deformation tests. The values of energy absorption capacity were derived from a numerical integration technique. Poisson's ratio (ν) was determined by a method of uniaxial compression of cylindrical samples. An increase in foam density results in an increase in the apparent elastic modulus of the material and therefore in its energy absorption capacity. Poisson's ratio is independent of the foam density. The mechanical properties' values obtained can be incorporated in various analyses for predicting desired characteristics for energy absorption applications.

INTRODUCTION

Urea–formaldehyde foam (U–F) has been utilized commercially for insulating applications, and its thermal properties have been explored and documented.[1] Information pertaining to its mechanical behavior, however, is very limited. Recently, this foam was considered for an energy absorption application utilizing its mechanical characteristics.[2,3]

The objective of this study was to derive the mechanical properties of the urea–formaldehyde foam to be used subsequently in a theoretical analysis for predicting desired characteristics for maximum energy absorption.

EXPERIMENTAL

The material investigated was Rapco-Foam (Rapco Chemical, Inc., South Carolina, a subsidiary of Rapperswill Co., New York), a modified urea–formaldehyde resin formulation in accordance with the German patented Isoschaum process. It is a cold-setting resin which forms a low-density noncombustible, resilient foam. The structure has a microscopic-sized cell agglomeration interspersed with microscopic capillaries which are irregular and discontinuous (Fig. 1). The final form has 60% to 70% closed cells. The foam is generated in a continuous stream with a specially designed Isoschaum foam generator by mixing three components: air, foaming agent, and foaming resin. Air foams up the foaming agent in the foaming cylinder, and the resin is then injected in the mixing chamber. The mixing and expansion is complete after the foam travels through the foam application hose, and the formed gel is strong enough to bear its own weight until hardening has commenced. The curing process consists of a setting period which takes place 10 to 60 sec after the foam leaves the apparatus, a condensation period of 2 to 4 hr during which the foam acquires

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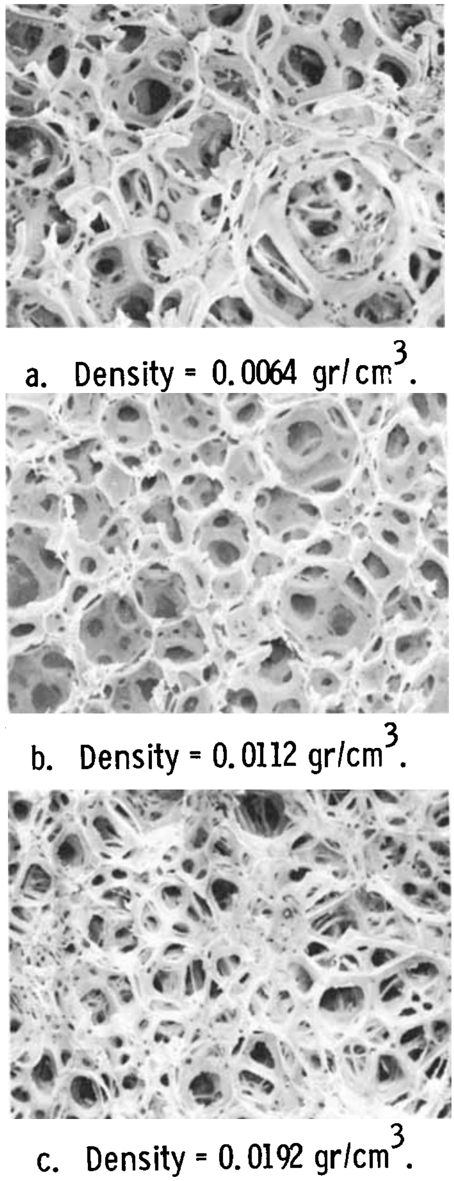


Fig. 1. Photomicrographs (magnification 100×) showing the differences in cell geometry for different densities of urea–formaldehyde foam.

its resilience, and a drying period of about one day (depending on climatic conditions) during which the foam acquires its final stable properties. The standard density of the Rapco-Foam is 0.0112 g/cm^3, but it can be varied from 0.0064 to 0.0192 g/cm^3.

The Test Specimen

Blocks of U-F foam were generated in the laboratory utilizing the Isoschaum foam generator and cut into sheets. Density of the foam was regulated by

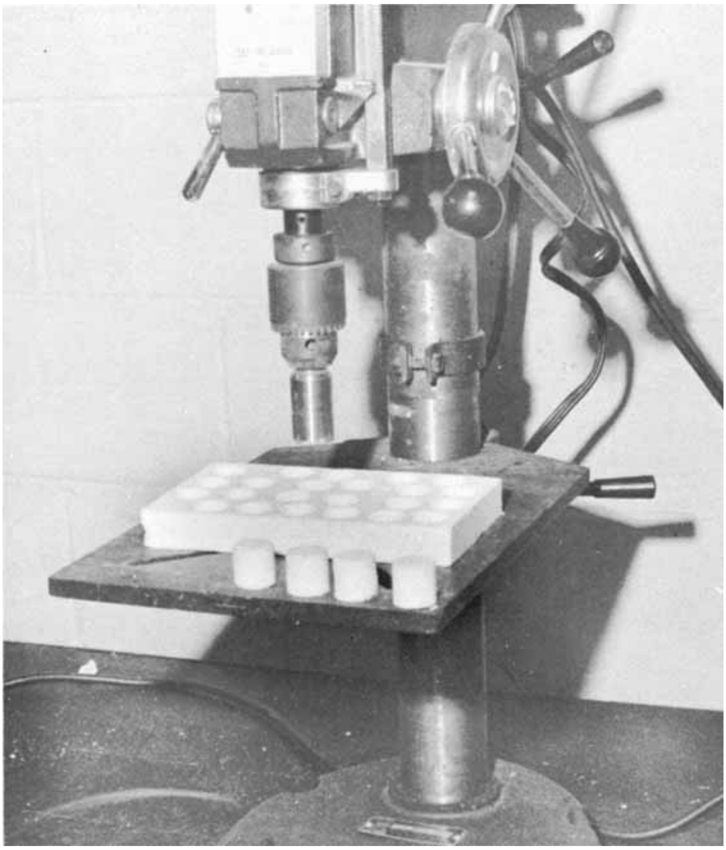


Fig. 2. Preparation of cylindrical samples of urea–formaldehyde foam. Samples were 2.54 cm in diameter.

changing the amount of flow of one of the three components to obtain two density groups: 0.0112 g/cm^3 and 0.0192 g/cm^3. A third group with a lower density (0.0064 g/cm^3) was also attempted, but the generated foam would not sustain any forces and was therefore discarded. The foam attained its final characteristics after a curing period of one to two days, and cylindrical test specimens were cut by driving a specially constructed cork borer through the sheets (Fig. 2).

The microstructure was examined from photomicrographs taken of foam samples from the different density groups to illustrate the differences in cell structure and geometry (Fig. 1). The higher density has a more dense cell structure, suggesting a higher potential for impact absorption.

The selection of suitable dimensions and a length/diameter ratio (L/D) for the samples is very significant when considered from a theoretical point of view because of the requirement to satisfy the boundary conditions. Since the results of our tests are derived on a per-unit-volume basis, it is imperative to assume uniform distribution of the argument quantity in question (energy, stresses, or displacement). The choice of dimensions was influenced by the Saint-Venant principle,[4] which suggests using a sample with a length (L) greater than its diameter (D). Therefore, cylindrical samples 5.08 cm long and 2.54 cm in diameter were investigated. The use of long samples was hindered by buckling, preventing

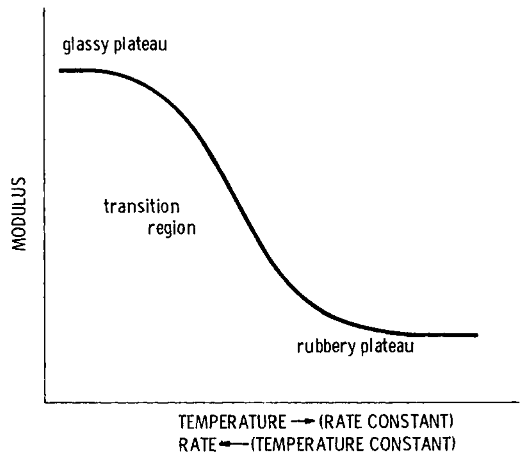


Fig. 3. Typical mastercurve of modulus vs. rate and temperature for crosslinked polymer (from Schwaber,[13] 1973).

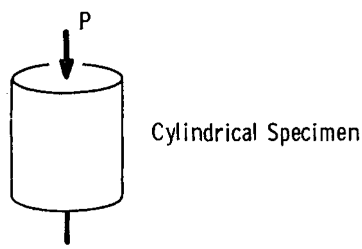
the use of Saint-Venant's approximation. Nevertheless, the buckling occurred only at large deformation (85% strain), where the struts of the foam structure begin to touch and interfere with each other's movement.[5] This region is of limited practical importance since it is desired to remain in the plateau region for optimal energy absorption. The samples were, therefore, compressed to the inflection point of the last two regions (45–50% strain), and it was hypothesized that in the region of interest the edge effects could be ignored, eliminating the need for long cylindrical samples.

To test the hypothesis, cylinders 5.08 cm or 2.54 long and 2.54 cm in diameter were employed, and the apparent modulus (E_f), measured as the initial slope of a stress–strain curve, was derived for the two regions. No significant difference was observed, and it was concluded that it is valid in this case to use the short specimens ($L/D = 1$) and to assume uniform distribution of the stress. The final samples had a diameter of 2.54 ± 0.01 cm and a length of 2.54 ± 0.1 cm.

Force–Deformation Tests

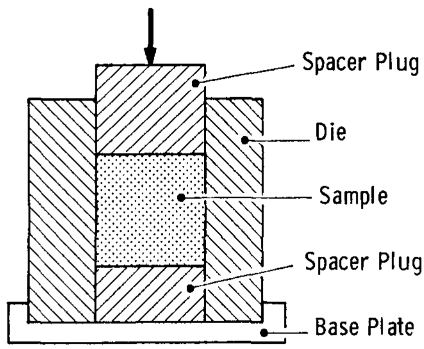
It is generally accepted that impact loading can be predicted from stress–strain data obtained at constant strain rates.[6] This method is valid only if we assume that impact velocity has no significant influence on the compressive stress–strain behavior. This assumption holds if the bulk material is in the glassy or rubbery plateau regions (Fig. 3), where its modulus is approximately rate independent. Materials in the transition region, however, are strongly rate dependent. The urea–formaldehyde foam used in this investigation is a highly crosslinked polymer and as a low glass transition temperature which makes it a typical rate-independent material. It is possible, therefore, to compare deformation energies determined at constant loading rates (e.g., Instron tests) with those obtained at different velocities (impact). Thus, the behavior of the foam during impact loading can be predicted from the area under the load–compression curve representing the energy absorption capacity of the foam.[7]

It should be noted that the urea–formaldehyde foam exhibits a pneumatic damping effect which is a rate-dependent parameter. This effect is usually of



a. Uniaxial compression of unrestrained cylindrical specimen.

(a)



b. Compression of cylindrical sample in a rigid die.

(b)

Fig. 4. Loading method used for deriving Poisson's ratio.

no significance compared with hysteresis in the strained solid phase, since even in a true closed cell-type polymer it is possible for the air to escape.[13] This is true especially with brittle foam, such as the U-F, where the pneumatic damping is ineffective once crushing of the cells is initiated. Consistent experimental results can be obtained by performing the load–deformation tests at a slow loading rate on a reasonably small sample, allowing the air to escape.[13] The experience of other investigators supports this practice. When considering brittle thermosetting materials, the impact properties may be so insensitive to speed of testing that the area under a normal, slow-speed stress–strain curve gives a good estimate of the impact strength.[8,9] Any contribution to the overall energy dissipation from the pneumatic damping effect can be considered as a bonus.

The objectives of the force–deformation tests were to derive the apparent elastic modulus for the foam, to ascertain its dependence on the foam density, and to assess the energy absorption potential as a function of the foam density. Preliminary tests were performed at various loading rates with samples of constant density (0.0112 g/cm^3) to verify the validity of the rate independence assumption and to establish the appropriate loading rate for deriving the mechanical properties. The samples were compressed coaxial with the longer axis of the sample using the Instron Universal Testing Machine. All tests were performed at ambient temperatures of 21° ± 1°C. The preliminary test compared five loading rates: 50.8 cm/min, 25.4 cm/min, 12.7 cm/min, 5.08 cm/min,

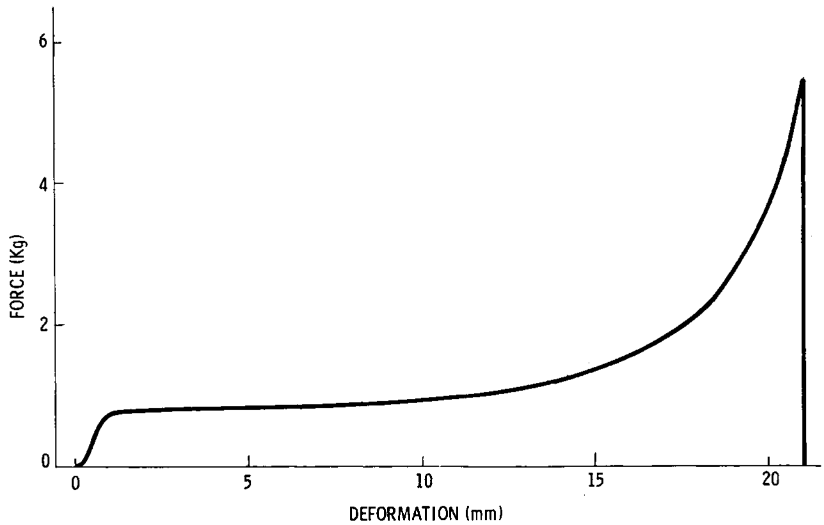


Fig. 5. Force–deformation curve of urea–formaldehyde foam subjected to compression loading.

and 2.54 cm/min, using ten samples per loading rate. The apparent modulus (E_f) was derived directly from the loading response by measuring the initial slope of the force–deformation curve.

The results confirm the assumption of rate independence, with only a slight deviation encountered at higher loading rates. The deviation was attributed to the pneumatic damping effect. A loading rate of 2.54 cm/min was chosen to minimize the pneumatic damping effect and to ensure uniform testing conditions. Twenty-five samples from each of the two density groups were loaded to 55% strain to obtain a stress–strain curve from which the apparent elastic modulus (E_f) was determined. The values of the energy absorption capacity were obtained by a numerical integration technique.

Measurements of Poisson's Ratio

Poisson's ratio was determined using a method developed by Hughes and Segerlind[10] which involved compressing two cylindrical cores of material. One sample was compressed axially while free to deform in the transverse direction. The second sample was compressed inside a rigid die to prevent lateral deformation (Fig. 4). The constitutive equation in cylindrical coordinates, when $\epsilon_{\theta\theta}$ and ϵ_{rr} are zero, is given by

$$E_f \left(\frac{\epsilon_{zz}}{\sigma_{zz}}\right) = \frac{(1+\nu)(1-2\nu)}{(1-\nu)} \tag{1}$$

This equation relates the stress and strain in the direction of the applied load, $(\epsilon_{zz}/\sigma_{zz})$, to Poisson's ratio ν, provided the value of the elastic modulus E_f is known.

The experiments were performed on cylindrical samples of foam using 25 samples from each of two density groups. All of the samples were 2.54 cm in diameter and 2.54 cm in length. The samples were loaded using the Instron

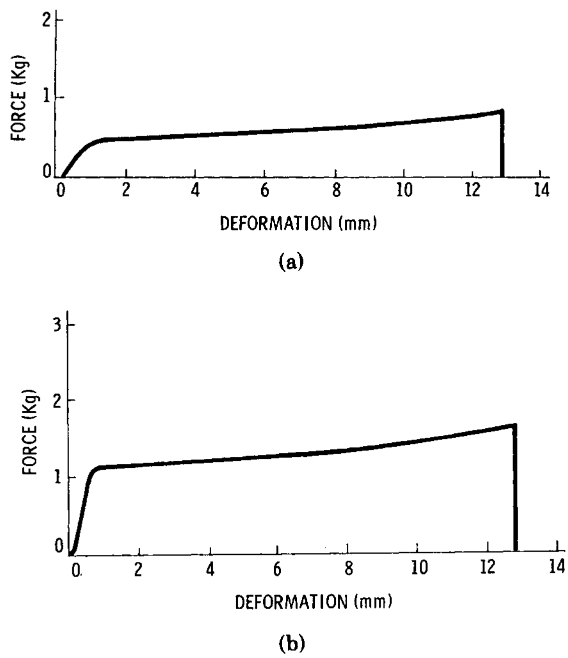


Fig. 6. Force–deformation curve of urea-formaldehyde foam of two densities subjected to a uniaxial compression load: (a) foam density 0.0112 g/cm^2; (b) foam density 0.0192 g/cm^2.

Universal Testing Machine at a loading rate of 2.54 cm/min, and force–deformation curves were obtained for both the unrestrained and the constrained tests. The initial slope of these curves yields the apparent modulus of elasticity E_f and $\sigma_{zz}/\epsilon_{zz}$ for the unrestrained and the constrained samples, respectively.

RESULTS AND DISCUSSION

The response of urea–formaldehyde foam to a compression load is shown in Figure 5. A nearly linear relationship existed at low strains until a critical value was reached, where the modulus decreased and a semiplateau region was encountered. The leveling was attributed to the buckling effect of the foam matrix at this point. The plateau region was maintained up to a strain of 45–55%, at which point the modulus increased and approached the compressive modulus of the solid material. The last region is of limited practical value, and hence stress–strain curves were obtained only for the instantaneous response and the plateau regions. Two representative curves for the two density groups are given in Figure 6a and b.

The results for the apparent elastic modulus, the energy absorption capacity, and Poisson's ratio for the U-F foam are given in Table I for two foam densities.

The apparent elastic modulus (E_f) was measured as the slope of the stress (σ)–strain (ϵ) curve for $\epsilon \rightarrow 0$ and found to be strongly dependent on the foam density. This result was expected, following previous studies by Rusch[6,11] on the load–compression behavior of brittle foams. Gent and Thomas[5] also indicated that the resistance of polymeric foams to compression depends strongly

TABLE I
Values[a] of Apparent Elastic Modulus, Energy Absorption Capacity, and Poisson's Ratio for Urea–Formaldehyde Foam Samples.

Density, g/cm^3	Apparent elastic modulus, N/cm^2	Energy absorption capacity, kg-cm	Poisson's ratio
0.0112	83.53 (14.80)	0.76 (0.12)	0.362 (0.025)
0.0192	132.41 (20.83)	1.28 (0.14)	0.367 (0.028)

[a] Mean values of 25 replications, with standard deviations in parentheses.

on the foam density. The difference in the polymer matrix for different densities can also be observed from the photomicrographs (Fig. 1), obtained with a scanning electron microscope. The results show a distinct increase in the threads—which comprise the foam matrix—with an increase in density. We can relate these photographs to the theoretical model for a foam material, envisioned by Gent and Thomas and verified subsequently through experimentation, to be comprised of a system of n randomly disposed threads. They established an almost linear relationship between a parameter associated with the threads' cross-sectional area and the foam density.

The validity of using the apparent elastic modulus of the foam as the mechanical property governing its behavior is subject to question, since the material response in the plateau region is characterized by inelastic deformation. However, the studies of Rusch[6,11] have shown that the energy absorption capacity of polymeric foam is dictated by the initial modulus and that the low modulus of the plateau region cannot be considered to sustain the impact forces. The same approach was used by Wilsea et al.,[12] who reported values of Young's modulus, for low-density forms, similar to those derived in this study. Nevertheless, it might be of value to explore this question in the future, treating the material as an elastoplastic one. However, as a first approximation, it was considered adequate to use the apparent elastic modulus as the characteristic property.

Since, in general, it is desired to maximize energy absorption using a minimum thickness of cushioning, the relationship between energy absorption potential and foam density needs to be ascertained. The results show that the energy absorption potential was significantly greater for the higher foam density. This increase is attributed primarily to the increase in the apparent elastic modulus with increase of density as noted above. In addition, the energy-absorbing efficiency is dependent also on a dimensionless function $\psi(\epsilon)$ of the compressive strain ϵ and the apparent Young's modulus. This function, although primarily dependent on the buckling of the foam matrix, is also dependent on the density of the material.

The experimental values for Poisson's ratio illustrate the lack of influence of density on Poisson's ratio, since no significant difference was found between the two density groups. These results are in agreement with the results of Gent and Thomas[5] on the mechanics of foamed elastic material; they reported no systematic trend of Poisson's ratio with foam density. The average value found in these experiments ($\nu = 0.36$) is similar to the value reported by Gent and Thomas ($\nu = 0.33$) for polymeric foams with a density similar to urea–formaldehyde. The average is also in reasonable accord with their theoretically predicted value of 0.25 for a foam model with randomly disposed threads.

SUMMARY AND CONCLUSIONS

The mechanical behavior of urea-formaldehyde foam was studied to evaluate its potential for energy absorption application.

The apparent elastic modulus and Poisson's ratio of the foam were obtained through experimentation. The apparent elastic modulus increased with increase in the foam density, thus providing a better energy absorption. Poisson's ratio was found to be independent of the foam density.

The mechanical properties derived can be incorporated in a numerical analysis to yield the optimal values for a feasible application.

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