Tensile Properties of Fiberglass-Reinforced Polyester Foams

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Synopsis

High-density structural foams and their fiberglass-reinforced versions have been characterized in tension, and the results were analyzed. The tensile modulus and strength of the nonreinforced foams can be described by the modified Kerner equation and a modified Nicolais–Narkis equation, respectively. The modulus of the reinforced foams can be predicted by using the concepts of the quasi-isotropic laminate theory. The temperature sensitivity of the reinforced foams is markedly reduced and the impact failure in a falling ball test is localized, and energy absorption is accomplished by the formation of numerous small cracks. Fiber reinforcement of foams improves also the heat sag resistance and reduces the coefficient of thermal expansion.

INTRODUCTION

Reaction injection molding (RIM) of plastics involves the use of highly reactive liquid components forming in the mold a product having a cellular core and an integral solid skin. Polyurethane, epoxy, and polyester resins can be used in the RIM process, although currently polyurethane resins are the most common ones for making automotive parts. Such structural integral skin foams are expected to be light and to have a good combination of properties, including high stiffness at low thickness and high impact resistance, a low coefficient of thermal expansion, and improved thermal resistance as measured by the heat distortion temperature. Conventional RIM polyurethanes often do not meet such a combined specification, especially the desired thermal properties. A relatively new field becoming increasingly important is the reinforced-reaction injection-molding technology (RRIM) where long, short, or milled fibers are included in the structural integral skin foam. The major positive effects of the added glass on the resulting foam properties are to reduce heat sag, increase stiffness, and decrease the coefficient of thermal expansion and mold shrinkage. While the RRIM technology is progressing rapidly due to the high commercial potential of the products, a satisfactory scientific background describing the structure-properties behavior of three-phase composites is still lacking. Fiber-reinforced polyurethane foams were investigated by several authors who made studies related to the structure and the reinforcement mechanism, fracture toughness, creep, and the temperature effects.[1–3] The present paper reports the characterization and analysis of tensile results of integral skin polyester and epoxy foams reinforced with long glass fibers.

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EXPERIMENTAL

Dumbbell shaped specimens were supplied by the SNIAL company. These specimens were cut from 10 mm thick sheets which were produced by injecting a reactive resin at room temperature into a mold already containing random glass mats. The expansion process took place in the mold by physical blowing. In some experiments the expandable reactive resin was injected into an empty mold to produce glass-free foams having different densities. A given resin formulation was always used for preparation of the fiber-reinforced foams. The glass content in the reinforced foams was determined by combustion at 600°C. Tensile properties were measured using an Instron machine equipped with a 10% strain gage extensometer and a thermostatic environmental chamber at a rate of 0.05 cm/min. Impact data were obtained by using a falling dart machine (5 kg ball falling from 4m).

RESULTS AND DISCUSSION

A simplified analysis of three-phase foams, polymer/pore/fiber, can be performed by holding one of the three variables constant and changing one of the two remaining ones. In the present work a given foamable formulation was used yielding a nonreinforced foam density of 0.6 g/mL and the reinforcing fiber loading was changed. Under such conditions the matrix (foamed polymer) properties are constant, and the fiber-reinforcement effects can be predicted by employing literature theoretical models.

During the early efforts to study the tensile properties of the nonreinforced foams it was noted that only very little information is available in the literature on the tensile behavior of stiff structural foams (density >0.5 g/mL). The tensile properties of tough foams based on polyethylene, polypropylene, and high-impact polystyrene were studied by Pramuk[4] and analyzed empirically by plotting reduced properties against reduced densities on log–log scales. Some additional general information can be found in books describing plastic foams.[5–7] Our microscopic studies have shown, as expected, that the typical shape of the pores is a function of the foam density where spherical shapes are approached by decreasing the gas content (higher density foams). This result is understandable in terms of the higher isolation of the growing bubbles and less interference with their neighbors as the gas content is reduced. Thus, stiff "high-density" foams can be approximated as rigid polymeric matrices having spherical hollow inclusions conforming with one of the cases described by the modified Kerner's equation[8,9] for the modulus prediction. The very same structure of the stiff foam conforms also to a model proposed by Nicolais and Narkis[10] for calculation of the tensile strength of brittle particulate systems. Some modification of the Nicolais–Narkis equation was found necessary, apparently to account for different stress concentration factors.

The problem of stress concentration introduced by the presence of spherical inperfections was analyzed by Goodier.[11] This theoretical analysis predicts maximum stress concentration factors of 1.5, 2, and 3 for spherical holes filled with rigid, elastomeric, or gas materials respectively. Thus air bubbles will concentrate the stress most effectively (twice compared to rigid inclusions) and an enhanced failure may be expected. In fact, the extrapolated strength value

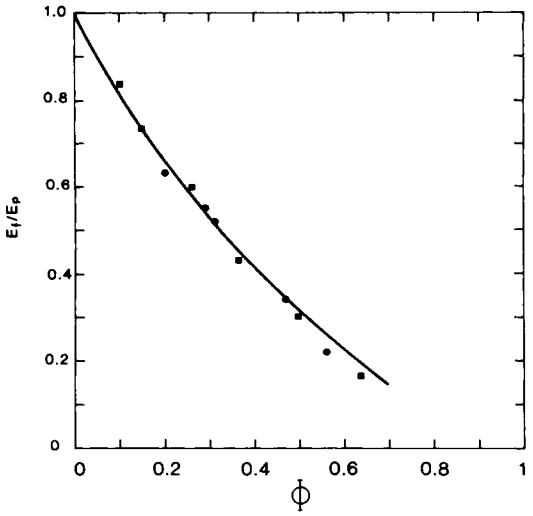

Fig. 1. Relative modulus of polyester (●) and epoxy (■) foams as function of void content. The full line represents the modified Kerner equation for $\phi_m = 0.64$.

to zero porosity (solid material) will be shown to deviate from the measured solid value by a factor of 1.65.

The modified Kerner equation is formulated as follows[9]:

$$E_r = (1 - \phi)/(1 + \phi\psi/A) \tag{1}$$

$$\psi = 1 + [(1 - \phi_m)/\phi_m^2]\phi \tag{2}$$

wnere ϕ_m is the maximum volume packing fraction of bubbles, $A = (7 - 5\nu)/(8$

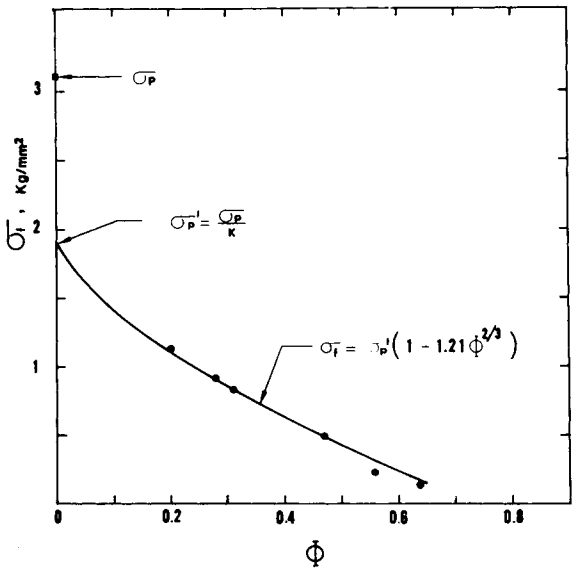

Fig. 2. Tensile strength of polyester foams as function of void content. Full line calculated for $K = 1.65$.

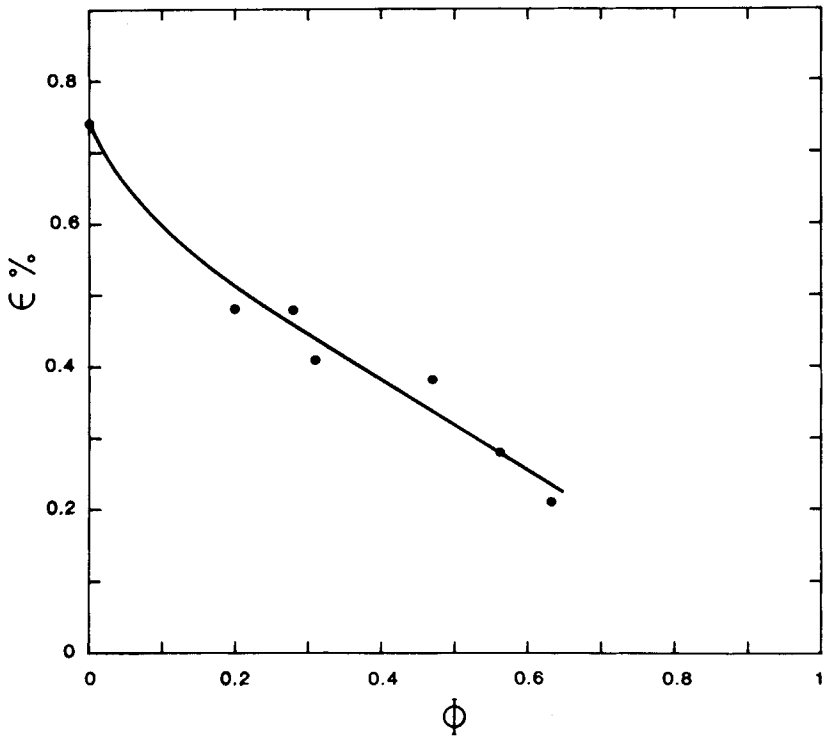

Fig. 3. Strain at break of polyester foams as function of void content.

$- 10\nu) = 1.14$, where $\nu = 0.33$ is the Poisson's ratio, ϕ is the volume fraction of spherical hollow inclusions, and E_r is the reduced modulus ($E_{\text{foam}}/E_{\text{polymer}}$).

The Nicolais–Narkis equation[10] relates the relative tensile yield stress ($\sigma_{\text{composite}}/\sigma_{\text{polymer}}$) to the volume fraction of rigid spherical inclusions, ϕ, as follows:

$$\sigma_c/\sigma_p = 1 - 1.21\phi^{2/3} \tag{3}$$

and the modified Nicolais–Narkis equation for hollow spherical inclusions is given by

$$\sigma_f/\sigma'_p = (1 - 1.21\phi^{2/3}) \tag{4}$$

where σ_f is the tensile strength of the brittle foam and $\sigma'_p = \sigma p/K$, K a modification factor accounting for the presence of spherical hollow inclusions in a brittle matrix.

Figure 1 shows a plot of the reduced modulus as function of the void content for epoxy and polyester foams. As can be seen, the data for the epoxy and polyester foams are practically indistinguishable, and they all are in a good agreement with the modified Kerner equation for $\phi_m = 0.64$. Figure 2 shows a correlation of the tensile strength σ_f as a function of ϕ. The data fit the calculated curve shown using eq. (4) for $K = 1.65$. It is important to note that eq. (4) extrapolates to $\sigma_f = \sigma'_p = \sigma_p/K$ for $\phi = 0$. This special extrapolation can be attributed to a behavior, where even upon the introduction of a small number of hollow inclusions a significant strength drop is expected. The extrapolated

Table I
Typical Properties of a Reinforced Polyester Foam

Density	0.68	(kg/L)
Glass content	24	(wt %)
Tensile strength (ISO 1926–72)	2.9	(kg/mm^2)
Tensile Modulus (ISO 1926–72)	219	(kg/mm^2)
Elongation at break (ISO 1926–72)	1.9	(%)
Flexural strength (ASTM 1621–64)	5.0	(kg/mm^2)
Flexural modulus (ASTM 1621–64)	183	(kg/mm^2)
Compression strength (ISO 1209–76)	2.5	(kg/mm^2)
Compression modulus	116	(kg/mm^2)
In plane shear strength	0.13	(kg/mm^2)
Thermal conductivity coefficient	0.03	(kcal/m·h·°C)
Specific heat	0.3	(kcal/kg·°C)
Thermal expansion coefficient	7×10^{-6}	(1/°C)
Mold shrinkage	0.08	(%)

strength value for the solid polymer based upon data measured on its expanded forms is thus expected to deviate from the real strength property (σ_p' vs. σ_p). This hypothesis cannot be tested at present since strength data on low-porosity foams are not available.

The dependence of the tensile strain at break upon the voids concentration is shown in Figure 3. By increasing the voids concentration, the strain at break gradually decreases.

Some typical properties of a fiberglass-reinforced polyester foam containing 0.24 w/w fibers are given in Table I. Noteworthy are the high modulus and strength values and the very low coefficient of thermal expansion (compared to steel 13×10^{-6} and polyurethane 50×10^{-6} $°C^{-1}$).

The next step is to estimate the elastic modulus of the reinforced foams. For fiber lengths greater than the critical aspect ratio, this calculation employs the elastic properties of the foams and the fibers and the volumetric concentration of the fibers and their distribution. For the case where continuous and parallel fibers reinforce the foam, the rule of mixtures and the Halpin–Tsai equation[12]

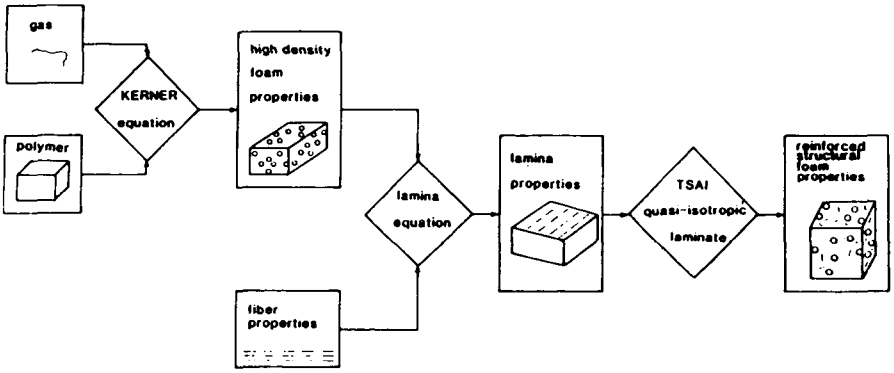

Fig. 4. Flow sheet of the calculation method used to predict the elastic modulus of the reinforced foams.

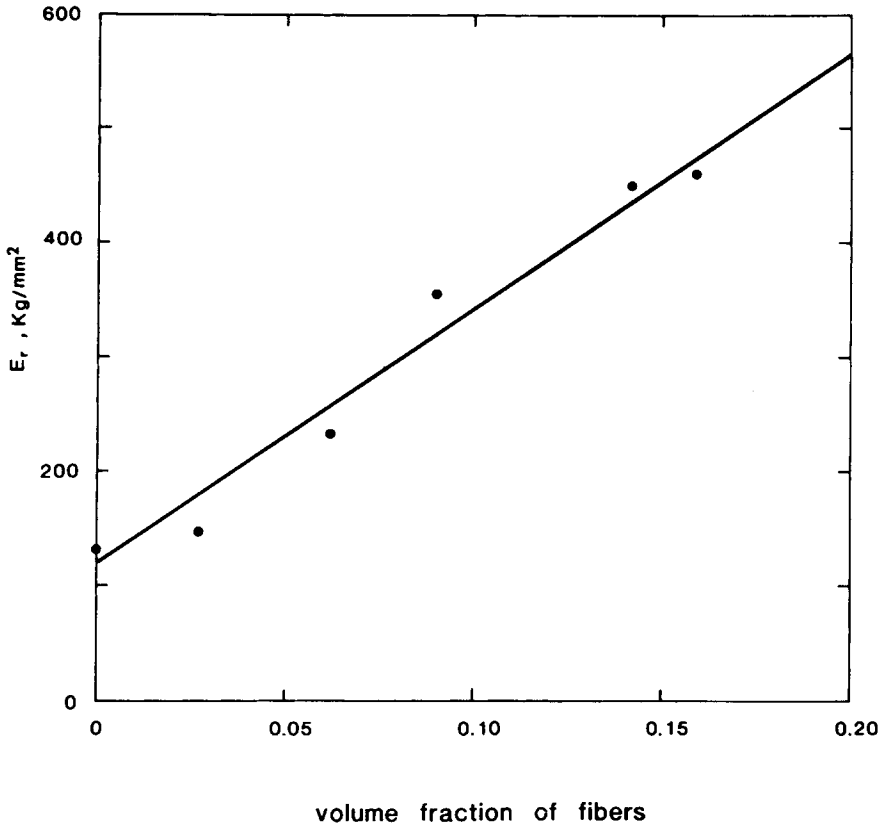

Fig. 5. Elastic modulus of the reinforced polyester foams as function of volume fraction of fibers. The full line represents the modulus predicted by the procedure outlined in Figure 4. The polyester foam density is 0.6 g/mL.

can be used to calculate respectively the longitudinal and transverse properties. If the foam is reinforced with chopped fibers randomly distributed (i.e., with fiberglass mat), it can be considered as composed by many laminae, each containing parallel short fibers arranged at different lamination angles. This description constitutes the basic concept of the quasiisotropic laminate theory.[13,14] A schematic description of the computation procedure of the elastic properties is illustrated in Figure 4. The calculated result for a fiberglass reinforced rigid foam is shown in Figure 5 and compared to the experimental data of foams reinforced with fiberglass mats containing long randomly distributed fibers. The density of the nonreinforced foam has been assumed constant and equal to 0.6 g/mL.

The temperature effects on the tensile modulus and strength of the polyester foams and fiberglass reinforced polyester foams are shown in Figures 6 and 7. The very significant effects of fiber reinforcement on the temperature sensitivity of the foams' stiffness is seen in Figure 6, where the foam's modulus declines rapidly with temperature while only moderate declines, decreasing with increasing fiber content, are exhibited for the reinforced foams. A similar tendency, although less pronounced, is seen for the tensile strength in Figure 7.

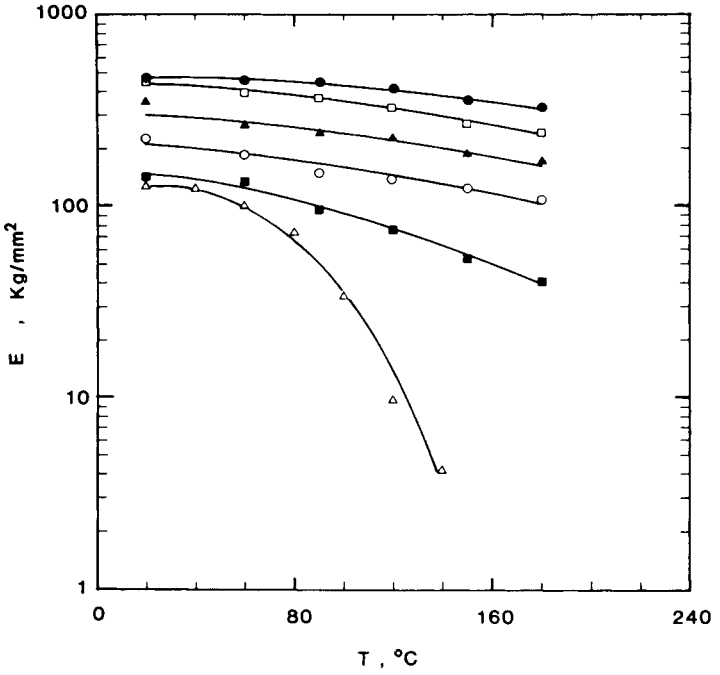

Fig. 6. Elastic modulus of the reinforced polyester foams as function of temperature for different fiber contents (w/w): (●) 0.42; (□) 0.36; (▲) 0.31; (○) 0.23; (■) 0.11; (△) 0.

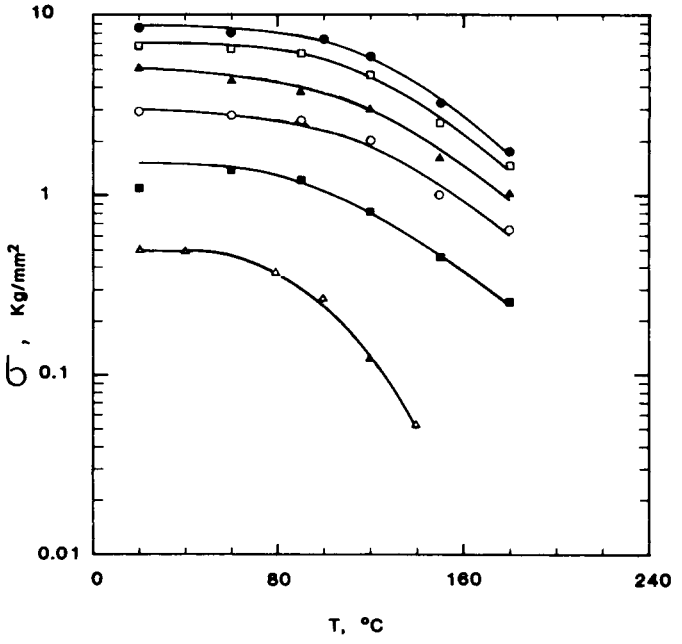

Fig. 7. Tensile strength of the reinforced polyester foams as function of temperature for different fiber contents (w/w): (●) 0.42; (□) 0.36, (▲) 0.31, (○) 0.23; (■) 0.11; (△) 0.

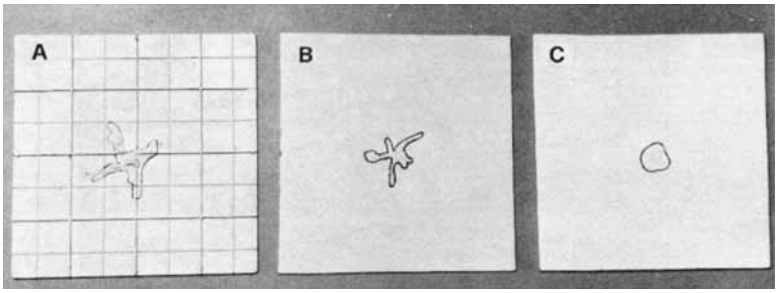

Fig. 8. Photographs of impact failure modes for glass-reinforced (A) SMC, (B) polyester, (C) polyester foam.

These results, related to the temperature sensitivity, are characteristic of fiber-reinforced plastics including fiber-reinforced foams. The difference between the temperature sensitivity of the modulus and the tensile strength can be explained in terms of initial and ultimate properties. Thus, the ultimate properties are more affected than the elastic ones by the temperature sensitivity of the resin properties and the interfacial bonding strength. The significant improvement of the heat sag resistance (deflection at a high temperature) of fiber-reinforced foams is thus a consequence of the modulus–temperature behavior shown in Figure 6.

The impact behavior, in a falling ball test, of the fiber-reinforced polyester foam is also of interest for practical applications. Figure 8 compares the impact behaviors of three different specimens all having the same stiffness. The comparison is made between a fiberglass-reinforced SMC panel, fiberglass-reinforced polyester prepared by the conventional wet compression molding method, and the fiberglass-reinforced polyester foam. The latter is shown to undergo a very localized damage restricted to the impacting ball size. The impact energy is absorbed in this case by creating numerous small cracks localized mainly in the panel bottom side subjected to tension by the falling ball. The other two nonexpanded specimens fail in impact by developing a small number of large cracks running along the surfaces and across the thickness and the damaged area is larger than the impacting ball cross section. The peculiar behavior of the reinforced foam is attributed to the presence of the small voids, causing a uniform distribution of the high instanteneous stresses within the specimen volume in the vicinity of the impacting ball.

In conclusion, the mechanical and physical properties of structural foams can be greatly improved by properly reinforcing them with fibers. The exact concentration of the fibers depends upon the performance desired. Fibers addition into structural foams is accompanied by density increase and sometimes by technological difficulties; however, an interesting and commercially attractive balance of properties can be achieved. The main possible improvements by foam reinforcement are in the stiffness, heat sag resistance, temperature sensitivity, coefficient of thermal expansion, and shrinkage on demolding.

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