

Effect of glass fiber and maleated ethylene–propylene rubber content on tensile and impact properties of Nylon 6

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Abstract

The Izod impact strength and tensile properties of blends Nylon 6 and maleated ethylene–propylene rubber (EPR-*g*-MA) reinforced with glass fiber as a function of glass fiber and EPR-*g*-MA content were examined. Materials containing 0–20 wt% glass fiber and 0–20 wt% EPR-*g*-MA were formulated. The modulus and yield strength of the unreinforced materials decreased as EPR-*g*-MA content increased. This effect can be completely counteracted by the addition of more than 10 wt% glass fiber, regardless of rubber content, with blends containing 20 wt% glass fiber showing substantially higher modulus than that of Nylon 6. Izod impact strength of super-tough blends was reduced by ~50% with the addition of small amounts of glass fiber; however, these glass fiber reinforced, rubber-toughened blends still retain a high impact strength. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Nylon 6; Rubber toughened; Glass fiber reinforced

1. Introduction

Appropriate incorporation of rubber particles into a brittle plastic matrix is a well established means of improving fracture toughness [1,2]. Under proper conditions, addition of rubber to semi-ductile thermoplastics, such as certain polyamides, polyesters, etc. can lead to super-tough blends. Unfortunately, the addition of an elastomer to a rigid matrix invariably reduces strength and stiffness relative to the unmodified material. On the contrary, incorporation of high aspect ratio rigid fillers such as high modulus fibers into a polymer matrix improves stiffness and strength [3]. Discontinuous glass fibers dispersed in a thermoplastic matrix provide injection moldable materials and eliminate the need for additional processing [4]; unfortunately, there is an inherent loss in ductility when these brittle fibers are incorporated into the more ductile polymer matrix. Some improvements in fracture energy may be realized by fiber reinforcement of brittle matrices [5,6]; however, toughness is usually markedly lower when fiber reinforcement is added to a ductile matrix.

In principle, combining fiber reinforcement with rubber toughening provides an approach to materials with high stiffness, strength, and toughness. While there is a large

body of literature addressing each individual method, the idea of combining the two has received relatively little attention [7,8]. A number of investigators have shown that the impact strength of rubber-toughened plastics drops sharply with the addition of small amounts of glass fiber and recovers somewhat as the fiber volume fraction increases [5,9–13]. Increasing the fiber loading of rubber-toughened blends has been shown to increase stiffness and strength, as expected [6,12–16]. The relatively few studies available indicate there is a trade-off between tensile properties and toughness; however, optimization of this trade-off has received almost no attention in the literature. Thus, it is not clear that materials with the best combination of stiffness, strength, and toughness have been realized yet.

This paper represents the first in a series that will explore the combined use of glass fiber reinforcement and rubber toughening of engineering thermoplastics with particular emphasis on optimizing the trade-off between stiffness/strength and toughness in these systems. This work combines Nylon 6 toughened by a maleated ethylene–propylene rubber (EPR-*g*-MA) with a commercially available glass fiber reinforced Nylon 6. The purpose is to explore the effect of glass fiber and rubber particle content on the stiffness, strength, and toughness of Nylon 6/EPR-*g*-MA/glass fiber blends. Standard impact properties, including temperature and thickness effects, and tensile properties are reported. Future papers will consider the effects of

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Table 1
Materials used in this study

Material designation	Source	Manufacturer's designation	Description
Nylon 6	Allied signal	Capron B73WP	Nylon 6, $\bar{M}_n = 22,000$ End-group content: NH ₂ = 47.9 $\mu\text{eq. g}^{-1}$ COOH = 43.0 $\mu\text{eq. g}^{-1}$
EPR-g-MA	Exxon chemical	Exxelor 1803	Ethylene-propylene rubber: 43 wt% ethylene, 53 wt% propylene, 1.14 wt% grafted maleic anhydride
BKV 30	Bayer	Durethan BKV 30	Glass fiber reinforced Nylon 6, 30 wt% well-bonded, discontinuous glass fibers
BKV 130	Bayer	Durethan BKV 130	Glass fiber reinforced Nylon 6, 30 wt% well-bonded, discontinuous glass fibers + ~ 5% impact modifier

rubber particle size and type, fiber length and adhesion, and other issues.

2. Experimental

Table 1 describes the materials used in this study. The neat Nylon 6 is Capron B73WP with $\bar{M}_n = 22,000$. BKV 30 is a glass fiber reinforced Nylon 6 containing 30 wt% discontinuous glass fiber, diameter = 13 μm . The ethylene-propylene rubber (EPR-g-MA) contains 1.14 wt% grafted maleic anhydride for reaction with the amine end groups of Nylon 6. The use of this rubber for toughening Nylon 6 has been described elsewhere [17–20].

Glass fiber reinforced rubber-toughened blends were prepared by first compounding a “mother blend”, containing only Nylon 6 and EPR-g-MA, and mixing this with BKV 30, which contains only Nylon 6 and glass fiber. The mother blend of Nylon 6 and EPR-g-MA was prepared in a Killion single-screw extruder ($L/D = 30$, $D = 1$ in.), equipped with an intensive mixing head, at 240°C using a screw speed of 40 rpm. These pellets were dry mixed with pellets of BKV 30 prior to injection molding such that the final molded part contained the proper amount of glass fiber, EPR-g-MA, and Nylon 6. The pellet mixture was injection molded in an Arburg Allrounder with a nozzle temperature of 270°C into a mold at 80°C. An injection pressure of 70 bar and a holding pressure of 35 bar were used. Screw speed was maintained at 150 rpm. ASTM D638 type I dogbone bars

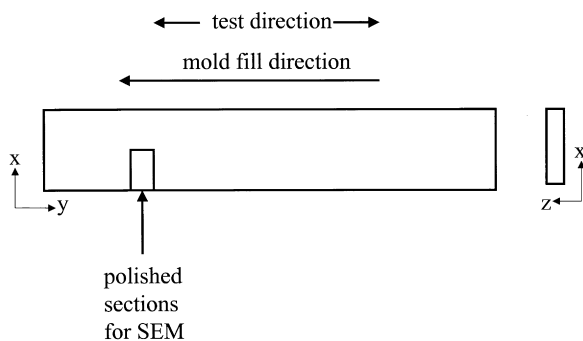


Fig. 1. Diagram of location of polished sections to determine fiber orientation and dispersion.

were molded for tensile testing and Izod bars 3.18 mm (or 6.35 mm) thick by 12.7 mm wide were molded for impact testing. This method has the limitation that a material containing large amounts of fiber and rubber cannot be made due to material balance and processing constraints. For example, a material containing 20 wt% rubber could not be made with more than 20 wt% fiber by this process.

All materials were dried at 80°C for at least 16 h prior to any melt processing. Polyamide containing materials were dried in a vacuum oven while EPR-g-MA was dried in a convection oven. After injection molding, the parts were immediately sealed in polyethylene bags and stored in vacuum desiccators for at least 24 h prior to any testing. All tests were therefore done in the dry-as-molded (DAM) state.

The morphology of the molded parts was determined by transmission electron microscopy (TEM). The molded material was cryogenically microtomed to 15 nm sections at -40°C with a diamond knife. The sections were stained using a 2% aqueous solution of phosphotungstic acid for 30 min and imaged using a JEOL 200CX transmission electron microscope at an accelerating voltage of 120 kV. Analysis of scanned TEM images was performed by Image, a computer program available from the National Institute of Health. Fiber lengths were determined by burning off the polymer matrix in a furnace at 500°C. The fibers were then dispersed in a 10 wt% solution of PMMA in toluene on a glass slide in order to fix them in place so that their lengths could be determined microscopically after the solvent evaporated. The fiber dispersion and orientation was examined by polishing molded bars, sputter coating, and viewing in a JEOL JSM35C scanning electron microscope. Polishing was accomplished using a series of successively finer abrasives. The final polishing steps made use of a 6 μm diamond paste followed by 0.05 μm alumina. Fig. 1 describes the location of the polished sections along the part. The SEM photomicrographs of these sections were taken in the x - y plane at a distance of approximately 3 cm from the far end of the 13 cm bar and half way between the surfaces of the bar in the x - z plane. This distance from the end of the bar is approximately the same position as the notch in Izod tests.

Tensile tests to determine the modulus, yield strength,

(80/20)/5 (Nylon 6/EPR-g-MA)/glass-fiber

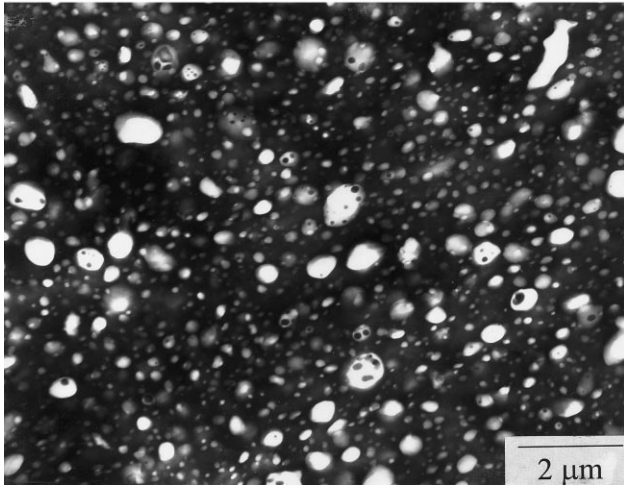


Fig. 2. TEM photomicrograph of (80/20)/5 [(Nylon6/EPR-g-MA)/glass fiber] at high magnification (10,000 \times). The polyamide phase is stained with PTA.

and elongation at break were performed according to ASTM D638 on an Instron model 1137 testing frame at a crosshead speed of 5.08 mm min⁻¹ (0.2 in. min⁻¹). An extensometer was used to accurately determine Young's modulus. The 3.18 mm thick impact bars were used for notched Izod impact tests (ASTM D256) in a TMI pendulum type tester with an insulated testing chamber for heating and cooling the specimens.

3. Results and discussion

3.1. Characterization

Fig. 2 shows a TEM photomicrograph of a fiber reinforced blends containing 5 wt% glass fiber and 20 wt% EPR-g-MA. Image analysis of these materials, summarized in Table 2, reveals that the weight average rubber particle diameter decreases from 0.23 to 0.19 μm with increasing fiber content. Other investigators have shown that the rubber particle size is relatively constant below 20 wt% rubber for similar systems [21,22]. In this case, a mother blend is created in the extrusion step and diluted during injection

Table 2
EPR-g-MA particle size for (Nylon 6/EPR-g-MA)/glass-fiber blends with a constant Nylon 6/EPR-g-MA ratio of 80:20

Fiber content (wt%)	Master blend rubber content (wt%)	\bar{d}_w (μm)	Polydispersity
0	20	0.234	1.31
5	22.8	0.231	1.36
10	27	0.223	1.29
15	34	0.199	1.33
20	48	0.193	1.20

molding. The effect of rubber composition on blend morphology for such a mixing arrangement has not been investigated. Although rubber particle size has a profound influence on impact strength, differences in particle size within the range shown here are not expected to have much effect on the toughness of Nylon 6/EPR-g-MA blends [17–20].

Fiber length has an important effect on the mechanical properties of reinforced materials, and glass fibers can be broken by melt mixing or fabrication steps [23]. Samples of injection molded impact bars at all glass and rubber compositions used in this study were examined to determine average fiber length. Prior to injection molding, the glass fiber source material, BKV 30, was determined to have a number average fiber length of 0.37 mm. After injection molding, the fiber lengths of all blends were in the range of 0.262–0.302 mm with no correlation to either glass fiber or rubber content. This gives a final aspect ratio ($=l/d$) between 20 and 24 for all blends. There is a critical aspect ratio, $(l/d)_c$, below which mechanical strength can decrease sharply. Kelly and Tyson developed the following relationship [24]:

$$\left(\frac{l}{d}\right)_c = \frac{\sigma_{uf}}{2\tau_u} \quad (1)$$

where σ_{uf} is the ultimate fiber strength and τ_u the fiber-matrix interfacial shear strength. For perfectly bonded glass fibers, the interfacial shear strength becomes the shear strength of the polymer matrix, which is 59 MPa for Nylon 6. Taking a typical value for the fiber strength of 1500 MPa, a critical aspect ratio of 13 is calculated. The observed average aspect ratios of the fibers in the materials used in this study are approximately twice this critical value.

The method used in this paper to make glass fiber reinforced, rubber-toughened blends involves dry mixing

(80/20)/10 (Nylon 6/EPR-g-MA)/glass-fiber

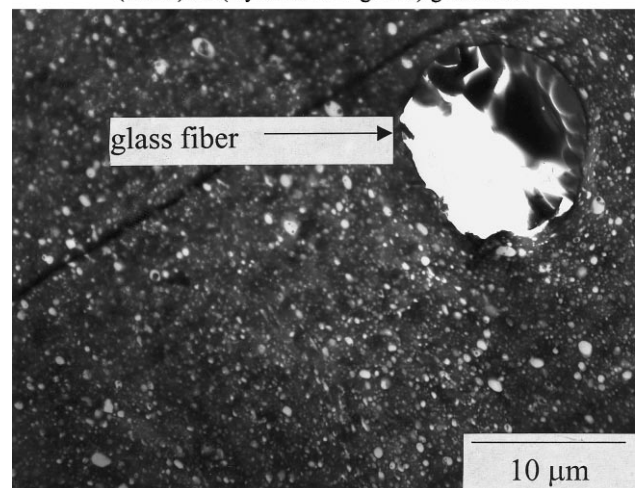


Fig. 3. TEM photomicrograph of a (80/20)/10 [(Nylon6/EPR-g-MA)/glass fiber] blend showing a glass fiber and rubber particles dispersed in the polymer matrix. The polyamide phase is stained with PTA.

of pellets containing only Nylon 6 and glass fibers with pellets containing only Nylon 6 and EPR-g-MA in the hopper of the injection molding machine. It will be shown that this procedure leads to good dispersion of glass fibers and EPR-g-MA in the final molded part. The details of this microstructure can be evaluated by SEM and TEM methods. TEM photomicrographs of blends similar to those shown in Fig. 2 do not include any glass fibers within the field of view. Because the glass fibers are of the order of 50 times larger than the rubber particles, it is unlikely to see fibers within the limited field of view for magnifications that are needed to show the rubber particles. Fig. 3 was selected to show a single glass fiber for one of the reinforced, rubber-toughened Nylon 6 materials formulated by the method discussed above. The microtoming process has shattered the fiber, and much of it has fallen out of the microtomed

section. Examination of a number of photomicrographs such as this one reveals that rubber composition is approximately the same everywhere in the blend, regardless of proximity to glass fibers. Fig. 4 shows a SEM photomicrograph of a polished surface from the interior of two glass fiber reinforced rubber-toughened blends at the location along the bar described above. A number of blends were studied in this manner and all indicated that the glass fibers were well dispersed in every case and are not present in unwetted bundles. The fibers seen on these polished surfaces are oriented in the mold fill direction as expected. Examination of the complete width of the bar reveals that the fiber orientation is highest near the surface of the molded part while a lower degree of orientation is seen in the center. The differences in fiber orientation between the material containing 5 wt% glass fiber and the material containing 20 wt% glass

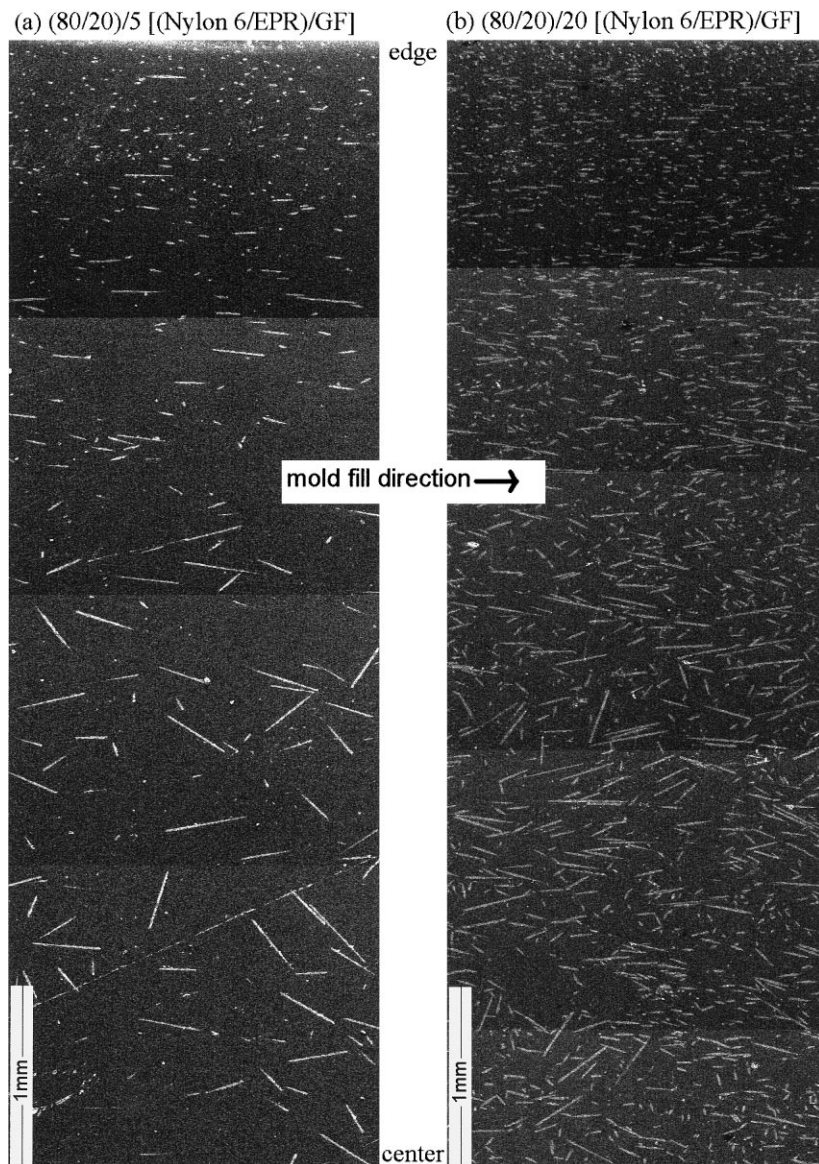


Fig. 4. SEM photomicrographs from polished sections of Nylon 6 blends containing 20 wt% EPR-g-MA and: (a) 5 wt% glass fiber; and (b) 20wt% glass fiber.

fiber are discussed below. The fiber microstructure of reinforced thermoplastics has been investigated thoroughly elsewhere [25–27]. Analysis of many photomicrographs like those shown in Figs. 3 and 4 reveal that reinforced blends formulated in the manner used here do not lead to regions that are rich or lean in either glass fibers or rubber particles.

3.2. Tensile properties

Tensile tests were used to determine the modulus, yield strength and elongation at break of the materials formed in this study. Fig. 5 shows the tensile modulus for materials containing 0–20 wt% rubber and 0–20 wt% fiber. In general, an increase in fiber content or a decrease in rubber content results in an increase in stiffness. Fig. 5b shows that the relationship between fiber content (wt%) and modulus is not linear. In particular, the initial addition of fiber (up to

5 wt%) is relatively less effective than higher fiber contents. Krenchel has proposed the following model for composite materials reinforced with discontinuous fibers [3]

$$E = \eta_o \eta_l \phi E_f + (1 - \phi) E_m \quad (2)$$

where E , E_f , and E_m are the moduli of the composite, fiber, and matrix; η_o and η_l the fiber orientation and length efficiencies, respectively, and ϕ the fiber volume fraction. This model predicts a linear relationship between composite modulus and fiber volume fraction if the reinforcement efficiencies, η_o and η_l , are not a function of fiber loading; however, a number of investigations of the microstructure of discontinuous fiber composites have shown that fiber orientation in the mold fill direction increases with increasing fiber volume fraction [26,27]. Fig. 4 shows SEM photomicrographs of a polished surface from the center of a molded bar of a Nylon 6/EPR-g-MA blend containing 5 and 20 wt% glass fiber. Although comparison is made difficult by the relatively few fibers in the material containing

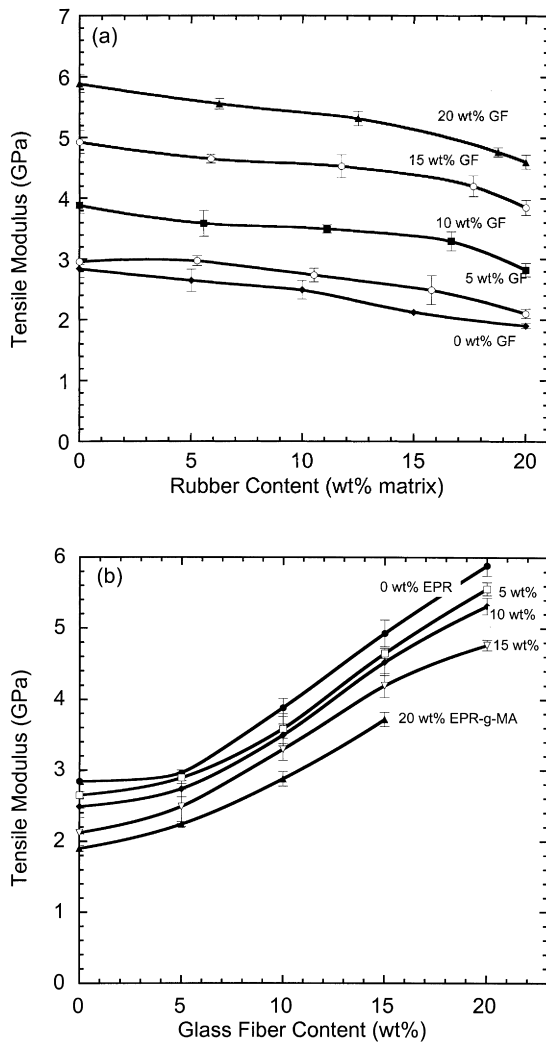


Fig. 5. Tensile modulus of Nylon 6/EPR-g-MA/glass fiber blends as a function of: (a) wt% of EPR-g-MA in the polymer matrix; and (b) wt% of glass fiber based on total mass of polymer and glass. Rubber content (wt%) in (b) is based on total mass of polymer and glass.

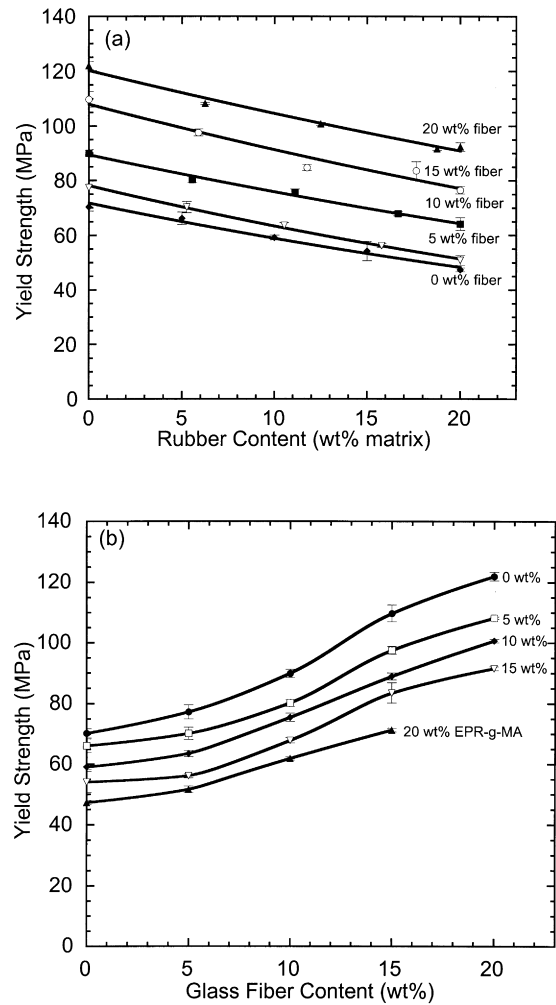


Fig. 6. Yield strength of Nylon 6/EPR-g-MA/glass fiber blends as a function of: (a) wt% of EPR-g-MA in the polymer matrix; and (b) wt% of glass fiber based on total mass of polymer and glass. Rubber content (wt%) in (b) is based on total mass of polymer and glass.

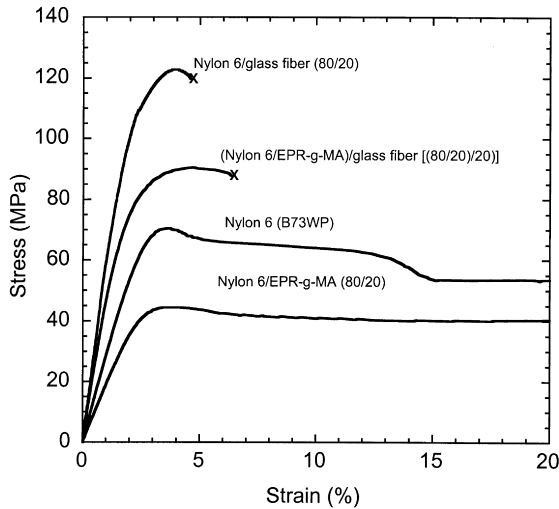


Fig. 7. Stress–strain diagrams for neat Nylon 6, Nylon 6/EPR-g-MA (80/20), Nylon 6/glass fiber (80/20), and (Nylon 6/EPR-g-MA)/glass fiber [(80/20)/20]. Nylon 6 and Nylon 6/EPR-g-MA continue elongating until strains are above 75%.

5 wt% glass fiber, there are observations that can be made about fiber orientation. The fibers are oriented nearly parallel to the mold fill direction near the edge and are somewhat more random in the center, consistent with the observations of others [26,27]. Further, some degree of orientation in the mold fill direction persists throughout the bar containing 20 wt% glass fiber, while in the material containing 5 wt% glass fiber the fiber orientation is more random towards the center of the bar. In this case, the mold fill direction is the same as the testing direction. This means that the reinforcing effectiveness of the fibers is less at lower fiber contents due to the dependence of fiber orientation on fiber content, which explains the trends observed.

Tensile strength of these materials shows similar trends

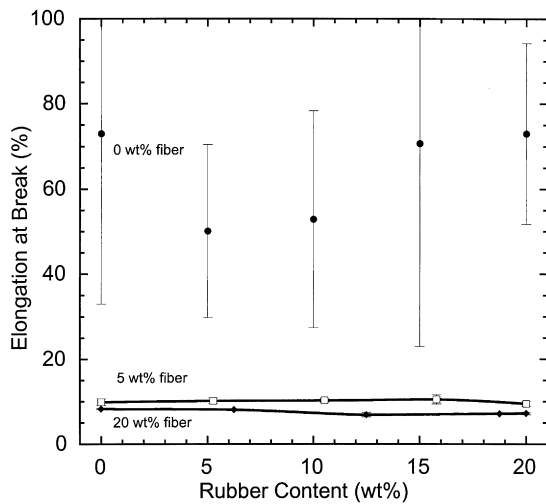


Fig. 8. Elongation at break as a function of content of rubber in the polymer matrix at various fiber content levels.

(see Fig. 6) as noted above for modulus. The tendency for lower reinforcement efficiency below 5 wt% glass fiber, relative to higher levels of reinforcement, is evident here also. Substantial improvements in stiffness and strength, relative to neat Nylon 6, are possible at moderate fiber content even when the rubber content is high. The stress–strain diagrams in Fig. 7 demonstrate this fact. As the rubber content of the Nylon matrix is increased to 20 wt%, the modulus and yield strength are decreased relative to the unmodified material. On the contrary, the modulus and yield strength are greatly improved when 20 wt% glass fiber is incorporated into neat Nylon 6. When 20 wt% glass fiber is used to reinforce the blend containing 20 wt% EPR-g-MA, the yield strength and modulus are significantly higher than neat Nylon 6. Fig. 8 shows the effect of glass fiber and rubber on the elongation at break for these materials. Prior to the addition of glass fiber, all of these materials are very ductile in slow speed tensile tests.

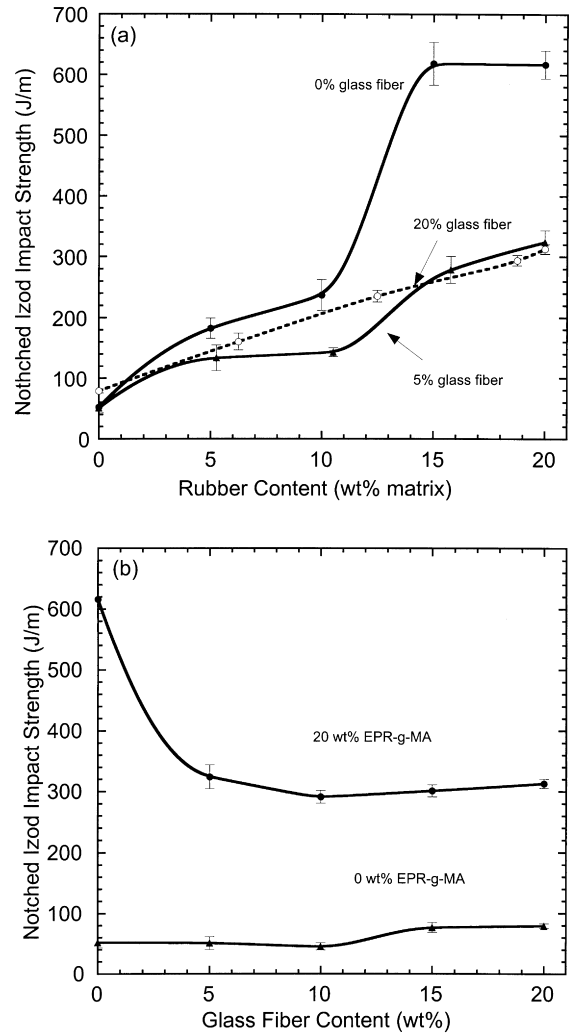


Fig. 9. Notched Izod impact strength of 3.18 mm thick specimens as a function of: (a) wt% EPR-g-MA in the polymer matrix; and (b) wt% of glass fiber based on total mass of polymer and glass for blends containing 0 and 20 wt% EPR-g-MA based on polymer matrix mass.

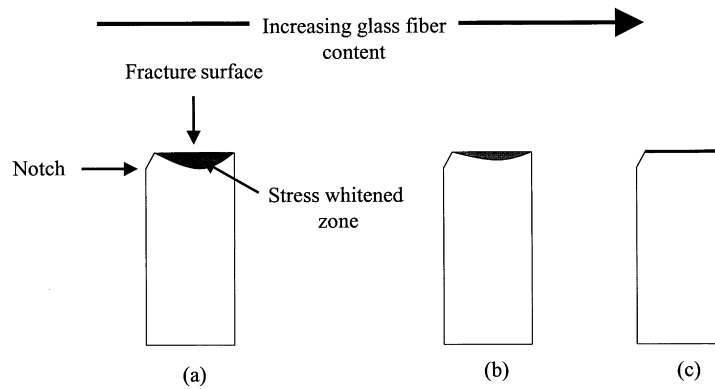


Fig. 10. Schematic representation of stress whitened zones of materials containing 20 wt% EPR-g-MA and: (a) 0 wt% glass fiber; (b) 5 wt% glass fiber; and (c) greater than 10 wt% glass fiber.

With the addition of only 5 wt% glass fiber, the elongation at break drops sharply to about 10% and falls slightly more to about 8% at high glass fiber loading.

3.3. Izod impact strength

Notched Izod impact tests were performed on the materials described above with the results shown in Fig. 9. In Fig. 9a, the Izod impact strength is plotted as a function of rubber content, while in Fig. 9b, impact strength is shown as a function of glass fiber content. For the unreinforced material, there is a marked increase in toughness between 10 and 15 wt% EPR-g-MA, as frequently observed in such systems [28]. The materials containing 5 wt% glass fiber show similar behavior, but at lower absolute Izod values. The fracture energy of the Nylon 6 material without rubber modification increases with increasing fiber content. The addition of even small amounts of glass fiber (5 wt% glass fiber) to the rubber-toughened matrix dramatically reduces the energy absorbed by the specimen compared to the blend containing no glass fiber, but these materials are still tougher than neat Nylon 6. The loss of impact energy seems to have a minimum near 10 wt% glass fiber and recovers somewhat at higher glass fiber contents. Other investigators have shown that the impact strength of rubber-toughened and neat Nylon 6 or Nylon 66 continues to increase at fiber contents beyond those investigated here [11,12].

The behavior of these materials can be understood by examining the stress-whitened zones near the fracture surface. A number of studies correlate the size of the stress-whitened zone with the energy absorbed by these materials in impact tests [29]. Fig. 10 shows schematically how the stress whitened zones of fractured specimens containing 20 wt% EPR-g-MA changes with the addition of glass fiber. In the absence of glass fibers, there is a large zone of deeply whitened material below the fracture surface. When the material contains 5 wt% glass fiber, this stress whitened zone is much smaller and not as deeply white. Beyond 5 wt% glass fiber, stress whitening exists only on a very thin layer below the fracture surface. The

reduction in size of the stress whitened zone correlates well with the decreases in fracture energy and elongation at break observed with the addition of glass fiber. This seems to indicate that the presence of even small amounts of glass fiber may restrict the deformation of the polymer matrix. The decrease in fracture energy that results from the addition of small amounts glass fiber is no doubt a result of the loss of ductile energy dissipation caused by the micro-mechanical constraints imposed by the fibers. As the glass fiber content increases beyond 10 wt%, the fracture energy of the rubber modified materials may be enhanced in the same manner as the glass fibers toughen the brittle, unmodified Nylon 6 material.

It is informative at this point to examine the combinations of stiffness and toughness that can be achieved by this method. In Fig. 11, Izod impact strength is plotted against the modulus for selected blends from this study as well as examples of commercially available materials. The leftmost line represents what is achieved in the absence of fiber reinforcement when the rubber composition is varied from

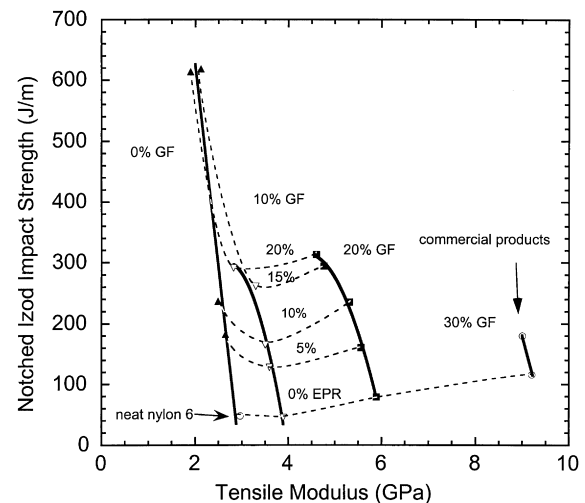


Fig. 11. Plot of modulus against notched Izod impact strength for selected blends. Each curve represents a series of materials containing the same amount of glass fiber.

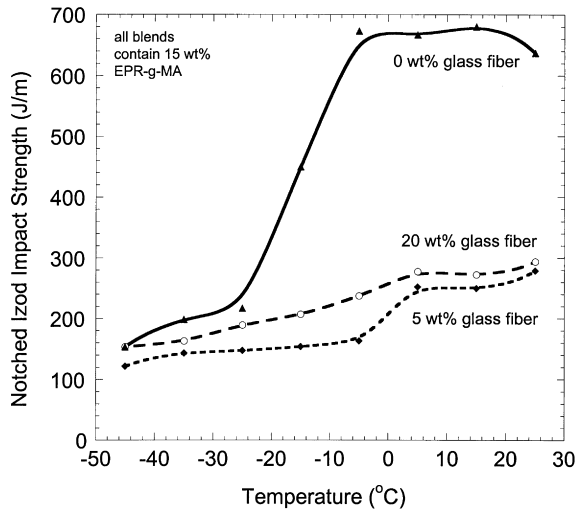


Fig. 12. Notched Izod impact strength of 3.18 mm thick specimens as a function of temperature for blends containing 15 wt% EPR-g-MA.

0 to 20 wt%. When these blends contain sufficient amounts of rubber (>15%), they are super-tough; however, their modulus is lower than the unmodified material as explained earlier. The next series of materials to the right contain 10 wt% glass fiber. At this level of glass fiber loading, the material containing 20 wt% EPR-g-MA has recovered nearly all of the modulus lost due to the addition of rubber, relative to neat Nylon 6. The toughness of these materials does not qualify as super-tough; however, they are very tough, especially when compared to Nylon 6. All the materials containing 20 wt% glass fiber are much stiffer than neat Nylon 6, and there is no further degradation in toughness. The two materials on the far right are commercially available products from Bayer marketed under the names Durethan BKV 30 and BKV 130; because they contain 30 wt% glass fiber, their stiffness is, of course, much higher than any of those formulated here. The impact modified material, BKV 130, contains a small amount of what appears to be a core-shell impact modifier (~5%) which accounts for the increase in toughness and decrease in stiffness.

Low temperature toughness is important for many materials applications. Fig. 12 shows the Izod impact strength of Nylon 6 materials containing 15 wt% rubber as a function of temperature. The material without glass fiber undergoes a ductile-to-brittle transition at -15°C . The material containing 5 wt% glass fiber has a similar drop in impact strength between 5 and -5°C . Beyond 5 wt% glass fiber, these materials do not exhibit a sharp drop in toughness but gradually lose toughness as temperature decreases. When the blend contains 20 wt% EPR-g-MA, the ductile-to-brittle transition temperature of the unmodified material is -40°C as shown in Fig. 13. Fig. 14 shows the impact strength of a series of materials containing 15 wt% glass fiber as a function of temperature; in each case, there is a gradual loss of toughness as the temperature decreases

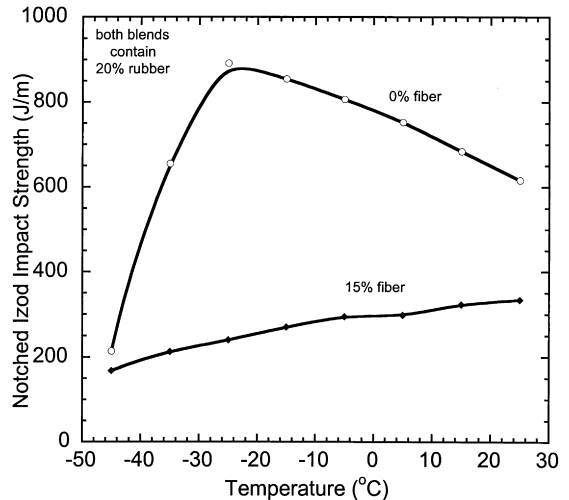


Fig. 13. Notched Izod impact strength of 3.18 mm thick specimens as a function of temperature for blends containing 20 wt% EPR-g-MA.

rather than an abrupt transition. The addition of rubber to the reinforced material improves toughness at all temperatures.

Specimen thickness can affect the toughness of thermoplastic polymers in the absence of glass fibers. Fracture energy may decrease with increasing thickness due to a transition from plane stress to plane strain conditions in the vicinity of the notch. The addition of rubber modification usually reduces this effect. When glass fibers are employed, this thickness effect may be enhanced by the decrease in fiber orientation resulting from the injection molding thicker specimens [25]. Fig. 15 compares the Izod impact strength of specimens 6.35 and 3.18 mm thick. For the unreinforced material containing 20 wt% EPR-g-MA, the 6.35 mm specimen has virtually the same impact strength as the thinner specimen. For all materials

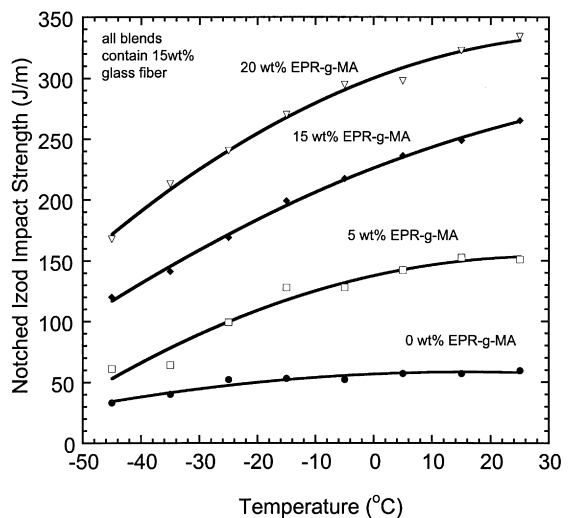


Fig. 14. Notched Izod impact strength 3.18 mm thick specimens as a function of temperature for blends containing 15 wt% glass fiber.

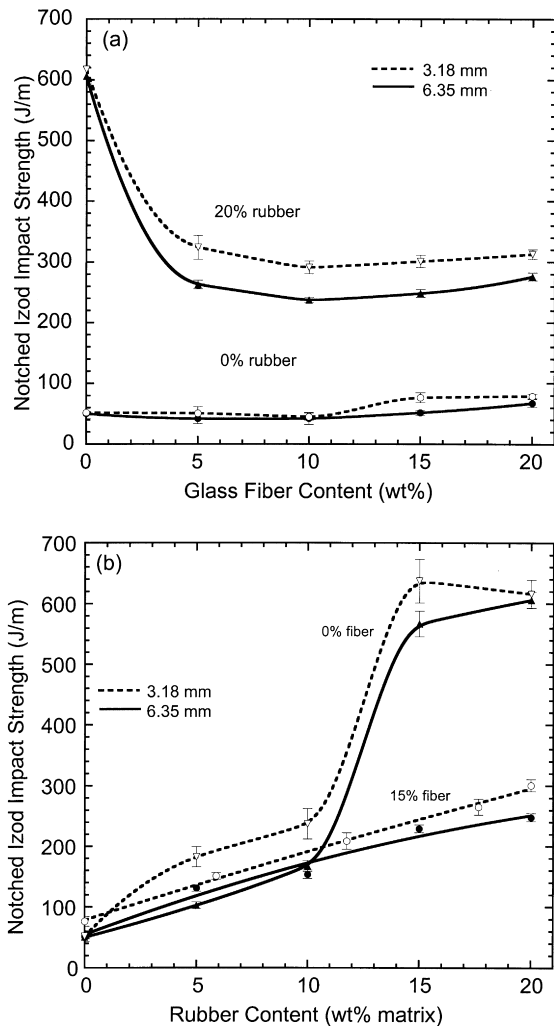


Fig. 15. Notched Izod impact strength for 6.35 and 3.18 mm thick specimen as a function of: (a) glass fiber content (wt%) and (b) rubber content (wt% matrix).

containing no rubber, the normalized Izod impact strength is slightly higher for the thinner bars; however, there is a significant difference in fracture energy between the two thicknesses for rubber containing materials. Similar differences are seen in Fig. 15b, where Izod impact strength is shown as a function of rubber content. With the exception of the unmodified Nylon and the unreinforced material containing 20 wt% rubber, the 6.35 mm thick specimens had lower impact strength than the 3.18 mm specimens in every case. The decrease in fiber orientation associated with molding a thicker specimen and a transition in the stress state in the vicinity of the notch are both likely to decrease the fracture energy of the thicker specimens.

4. Conclusions

The effects of glass fiber and EPR-*g*-MA contents on the tensile and Izod impact performance of blends based on

Nylon 6 were examined. Incorporation of the rubber into Nylon 6 leads to a super-tough blend but reduces modulus and yield strength as expected. The loss in modulus and yield strength can be completely reversed by addition of glass fibers. In fact, the stiffness and strength of the glass fiber reinforced, rubber-toughened material can be much higher than neat Nylon 6 if a sufficient amount of glass fiber is used; however, the elongation at break and Izod impact strength of the rubber-toughened material is reduced when glass fibers are introduced. Even a small amount of glass fiber (<5 wt%) is sufficient to cause a 50% reduction in room temperature Izod impact strength. Although the fracture energy of the glass fiber reinforced rubber-toughened materials does not rival that of the super-tough unreinforced blends, the toughness of these materials is still quite high (>300 J m⁻¹). At low temperatures, the Izod impact energy of the reinforced, rubber-toughened materials is improved at all glass fiber loadings, relative to the material containing no rubber. The fracture energy of these materials decreases gradually as temperature is decreased, in contrast to unreinforced materials, which lose their high level of toughness dramatically at a ductile-to-brittle transition temperature.

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