Glass Fiber Reinforced Polypropylene/EPDM Blends. II. Mechanical Properties and Morphology

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SYNOPSIS

Tensile and impact properties of the ternary system polypropylene (PP)/ethylene propylene diene elastomer (EPDM)/glass fiber (GF) and the corresponding binary systems PP/EPDM blend and PP/GF composite are studied. Results are presented and analyzed as functions of compositional variables, viz., (i) matrix PP/EPDM blending ratio at constant GF loadings and (ii) GF loading at constant matrix blending ratios for the ternary system and (iii) EPDM content for PP/EPDM binary system and (iv) GF content for the binary system PP/GF, respectively. The role of individual components EPDM and GF in these mechanical properties is discussed and their combined effects are inspected at certain composition ranges. Theoretical analysis of tensile data is presented which reveals the effect of EPDM on the reinforcing effect of GF. Unlike the conventional role of an elastomer, increase of EPDM content in the presence of GF increases the modulus of the ternary system. Impact strength of the ternary system increases with increasing GF content both in the presence and absence of EPDM, showing a distinct minimum at matrix blending ratio PP/EPDM 90/10. Scanning electron micrographs of impact-fractured surfaces are presented to illustrate the dispersion of the two phases of the polyblend matrix, fiber alignment, and the fiber interface.

INTRODUCTION

Blending of thermoplastics with elastomers produces improvement in impact properties, processability, etc. On the other hand, the deterioration in tensile strength and modulus is a drawback to such blending. Incorporation of reinforcing fillers into such blends may produce useful combination of properties, for example, the improved impact toughening of it with good stiffness and strength. Improvement of properties on addition of reinforcing filler as a third component to a polymer blend has been reported for several systems, for example, talc-filled elastomer modified polypropylene,[1-3] glass-fiber-filled PP/HDPE (high density polyethylene) blend,[4] glass-fiber- and talc-filled PP/LDPE (low density polyethylene),[5,6] and calcium-carbonate-filled polyethylene/EVA (ethylene vinyl acetate copolymer) blend.[7] This subject seems to have received much less attention than it deserves, probably due to experimental complexities and difficulties in interpretation of the results on ternary systems where two components act as variables instead of one in the usual case of binary composites.

With this in view, we have undertaken a study of the PP/EPDM/GF ternary system. Measurements are made not only on the ternary system but also on the corresponding binary system to serve as the necessary reference for identification of the role of the respective third component of the ternary composite PP/EPDM/GF.

Melt rheological behavior of this ternary system reported in a previous publication[8] showed a change in the melt viscosity and melt elasticity around a critical shear rate due to the interaction of glass fibers and dispersed EPDM elastomer domains, and the randomness of the alignment of glass fibers.

Tensile and impact properties and morphology of the PP/EPDM/GF ternary composite will be presented in this paper. The experimental variables of composition of the ternary systems used in this study are: (1) the matrix blending ratio (varying

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from 0 to 30% EPDM) at several constant GF loadings and (2) the GF loading (varying from 0 to 30 wt %) at several constant matrix blending ratios.

EXPERIMENTAL

Materials

Polypropylene and EPDM elastomer used in this work were Koylene M 0030 (MFI 10) from Indian Petrochemicals Corporation Ltd. and Nordel 1040 from DuPont (Mooney viscosity 40 and ethylene and diene contents 75 and 4%, respectively). Glass fibers (chopped strands of 3 mm length) were of grade FGP-1651 of Fibreglass Pilkington, coated with a proprietary coupling agent compatible with PP.

Preparation of Blends and Composites

PP/EPDM blend was prepared by melt mixing in a single screw extruder (Windsor SX-30) using a screw speed of 20 rpm with temperature 200–220°C of the various zones. The binary and ternary composites PP/GF and PP/EPDM/GF were prepared by mixing the appropriate quantities of all the components in one step, under the above-stated experimental conditions. Nomenclatures and compositions of the various samples are shown in Table I.

Test Specimens

Test specimens for tensile and impact tests were prepared by injection molding on an SP-1 injection molding machine from Windsor at temperature 210–220°C. Dumbbell-shaped specimens conforming to ASTM-D-638 were used for tensile, and rectangular bar shapes conforming to ASTM-D-256 were used for impact tests. A notch 2.5 mm deep and at a 45° angle was cut on the impact specimens.

Measurements

Tensile measurements were made on an Instron universal tester (Model 1112) at a strain rate of 5 cm/min and initial gauge length of 5 cm. The Izod impact test on notched samples was carried out on a pendulum-type impact tester (FIE impact tester Model 042). Impact strength was calculated from the difference of pendulum potential energy before and after the impact per unit width of the samples.

At least five samples were tested for each composition, and average values are reported; the deviation was less than 5% in all cases.

Scanning electron micrographs of impact fractured surfaces were recorded on a Stereoscan S4-10 from Cambridge Scientific Instruments Ltd. The samples were etched with xylene at room temperature to dissolve out EPDM domains from the fractured surface.

Table I Nomenclature and Composition of the Samples Studied

Sample Designation	Description	Composition (wt %)			
		PP	EPDM	PP/EPDM	GF
A	PP	100	—	—	—
E	EPDM	—	100	—	—
P1	PP/GF (90/10)	90	—	—	10
P2	PP/GF (80/20)	80	—	—	20
P3	PP/GF (70/30)	70	—	—	30
B1	PP/EPDM (90/10)	90	10	—	—
B2	PP/EPDM (80/20)	80	20	—	—
B3	PP/EPDM (70/30)	70	30	—	—
C1	B1/GF (90/10)	—	—	90	10
C2	B1/GF (80/20)	—	—	80	20
C3	B1/GF (70/30)	—	—	70	30
C4	B2/GF (90/10)	—	—	90	10
C5	B2/GF (80/20)	—	—	80	20
C6	B2/GF (70/30)	—	—	70	30
C7	B3/GF (90/10)	—	—	90	10
C8	B3/GF (80/20)	—	—	80	20
C9	B3/GF (70/30)	—	—	70	30

RESULTS AND DISCUSSION

Tensile Properties

Stress–strain curves for the various samples are shown in Figures 1–4. Unblended PP shows a distinct yield peak followed by a small variation of stress up to the breaking point (Fig. 1). Incorporation of GF narrows down the yield peak and increases the yield stress (i.e., stress at yield peak), decreases yield strain (i.e., strain at yield peak), and increases modulus (which is proportional to the slope of the initial linear part of the curve), as seen in Figure 1.

In the case of the PP/EPDM binary blend (Fig. 2), the yield peak broadens and the yield stress decreases with increasing EPDM content. Note the difference of the scales used on the strain axis in Figures 1 and 2. On addition of GF to the binary blend B1 the yield peak narrows down and the yield stress increases with increasing GF content, as shown in Figure 3. The breaking strain, which was 326% for the binary system B1, reduces to less than 5% for the ternary composite sample C3 containing 30 wt % GF.

As a function of matrix blending ratio at constant GF loading, the yield peak reduces in width and breaking strain is almost the same (i.e., 30–40%) for all the three samples shown in Figure 4.

These four sets of stress–strain curves (Figs. 1–4) indicate that the yield peak narrows down considerably with increasing GF loading. The elastomer EPDM broadens the yield peak, without showing much difference in the yield strain with varying EPDM content, both in the absence of GF (see Fig. 2) and at constant GF content (see Fig. 4). However, yield stress decreases with increasing EPDM content

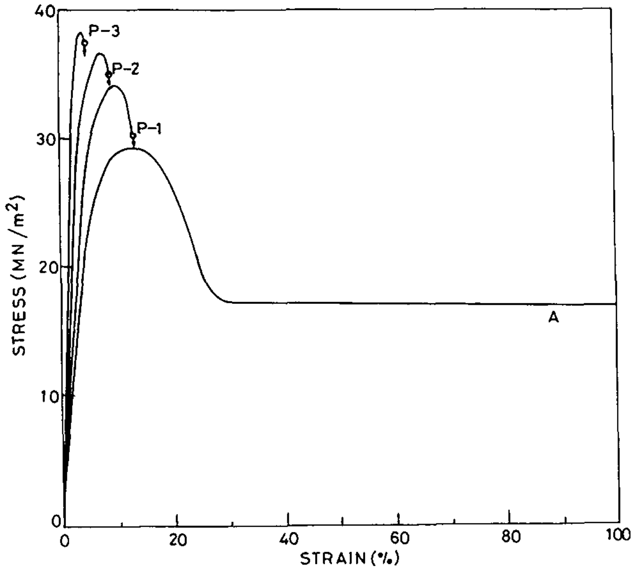

Figure 1 Tensile stress-strain curves for PP(A), and PP/GF composites at varying GF loading (wt %): (P-1) 10; (P-2) 20; (P-3) 30. Breaking strain for PP is 240%, not shown in the figure.

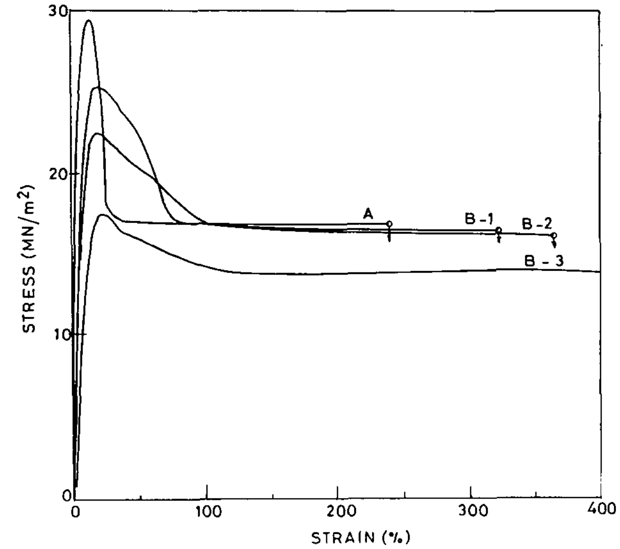

Figure 2 Tensile stress-strain curves for PP(A) and PP/EPDM blend at varying EPDM content (wt %): (B-1) 10; (B-2) 20; (B-3) 30. Breaking strain of B-3 is 516%, not shown in the figure.

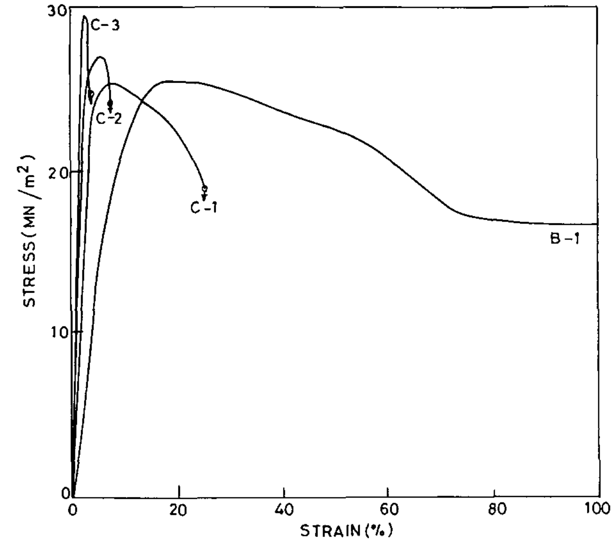

Figure 3 Tensile stress-strain curves for the ternary composite PP/EPDM/GF at constant blending ratio of the matrix and varying GF loading (wt %): (C-1) 10; (C-2) 20; (C-3) 30; (B-1) the corresponding binary blend matrix PP(90)/EPDM(10) Breaking strain of B-1 is 326%, not shown in the figure.

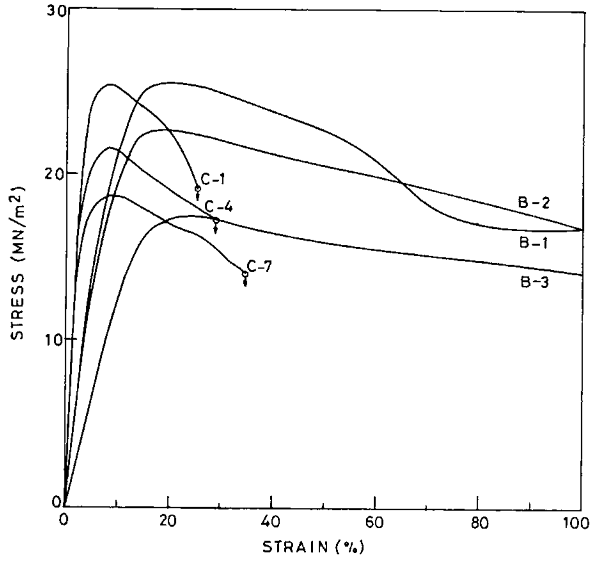

Figure 4 Tensile stress–strain curves for ternary composite PP/EPDM/GF at constant GF loading (10 wt %) and varying blending ratio of the polyblend matrix (wt % EPDM): (C-1) 10; (C-4) 20; (C-7) 30. Curves for the polyblend matrices are also shown at the respective blending ratios (wt % EPDM): (B-1) 10; (B-2) 20; (B-3) 30.

both in the absence and in the presence of GF (Figs. 2 and 4).

Variations of yield stress, yield strain, elastic modulus, and work of yield with the compositional variables of these binary and ternary systems are discussed below to distinguish the effects of the individual components on the tensile properties of these systems. Work of yield is defined as the area under the stress–strain curve up to the end of yield region, to represent the total energy absorbed in the process of yielding. The data are presented in Figures 5–8, as a function of two variables: (i) matrix blending ratio (PP/EPDM ratio) at fixed values of GF loading and (ii) GF loading at fixed values of matrix blending ratios. The observed effects are discussed in the following subgroups.

PP/EPDM Blend

For the case of PP/EPDM blend in the absence of GF, yield stress (Fig. 5) and modulus (Fig. 7) decrease while the yield strain (Fig. 6) and work of yield (Fig. 8) increase with increasing EPDM content of the blend.

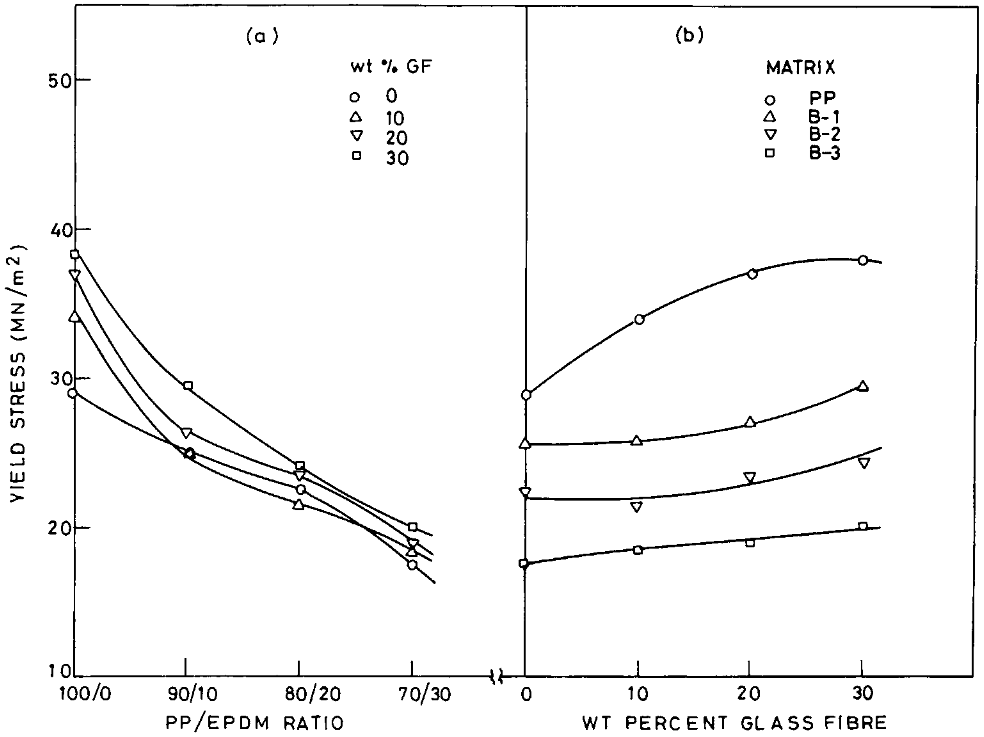

Figure 5 Yield stress of PP/EPDM/GF ternary system: (a) as a function of matrix blending ratio with GF content as the variable; (b) as a function of GF loading with matrix blending ratio as the variable.

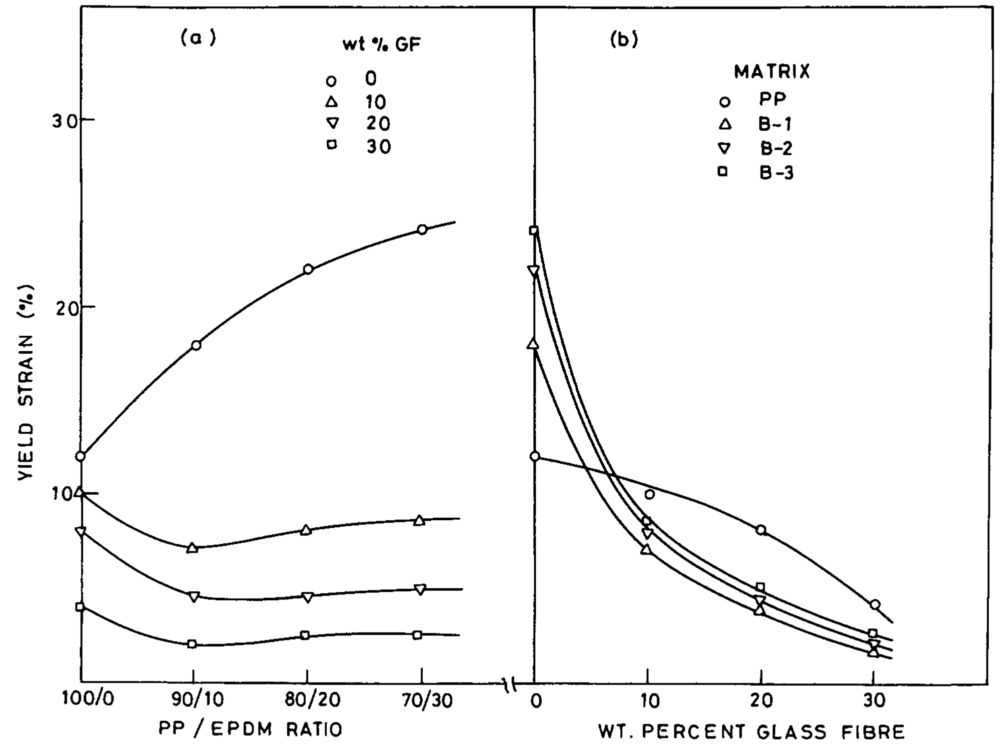

Figure 6 Yield strain of PP/EPDM/GF ternary system (a) as a function of matrix blending ratio with GF loading as the variable; (b) as a function of GF loading with matrix blending ratio as the variable.

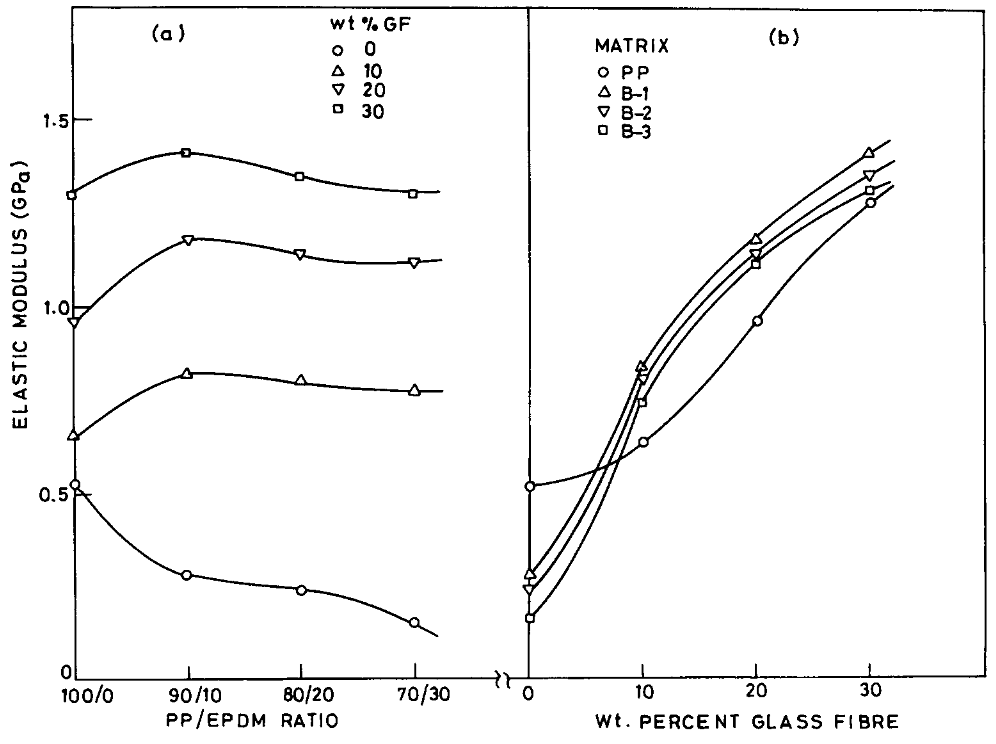

Figure 7 Tensile elatic modulus of PP/EPDM/GF ternary system: (a) as a function of matrix blending ratio with GF loading as the variable; (b) as a function of GF loading with matrix blending ratio as the variable.

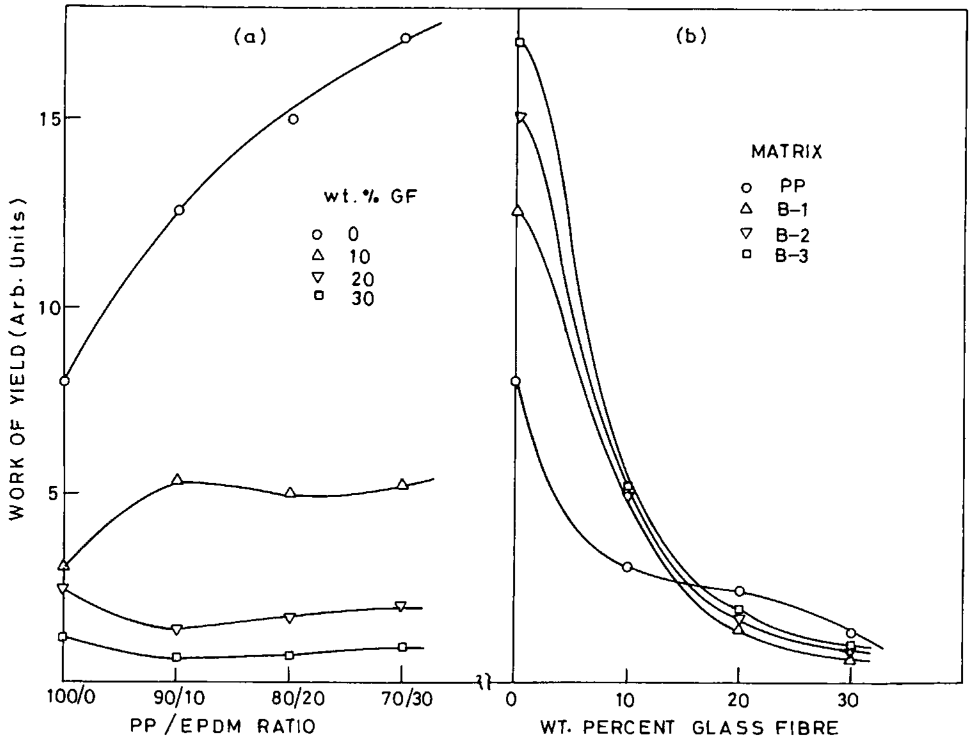

Figure 8 Work of yield of PP/EPDM/GF ternary system: (a) as a function of matrix blending ratio with GF loading as the variable; (b) as a function of GF loading with matrix blending ratio as the variable.

The decrease of both yield stress and elastic modulus are slightly sharper in the regions 0–10% and 20–30% EPDM content than in the middle region of 10–20% EPDM content. Yield strain and work of yield, on the other hand, increase monotonically in the entire range of blend composition.

PP/EPDM/GF Composite

The results for the ternary composite are discussed below for the effects of (i) variation of matrix blending ratio at constant GF loading and (ii) variation of GF loading at constant blending ratio.

At Constant GF Loading. In the presence of GF, an increase of EPDM content of the polyblend matrix decreases yield stress and yield strain and increases modulus. Work of yield retains its tendency to increase with increasing EPDM content of the polyblend matrix only at low GF loading (i.e., 10%), and thereafter the curve shows a decreasing trend. Total change in the range of measurements is twofold for yield stress and 1.5 times for modulus and yield strain.

The characteristic feature of yield stress versus matrix blending ratio curve at 0% GF, namely, the less sharp variation in the middle zone of matrix blending ratio (i.e., 10–20% EPDM), disappears gradually with increasing GF loading in the ternary system. This suggests that the EPDM domains in the middle zone of composition, acquire an average size appropriate for countering the effect of GF on the shear yielding of the matrix. The observed absence of this effect in the abundance of GF (i.e., at high GF content) supports this explanation.

Variations of elastic modulus, yield strain, and work of yield (at GF loading > 20%) with blending ratio follow opposite trends for the PP/EPDM/GF ternary composite than the corresponding binary system at 0% GF. These variations have similar shapes of the curves at all the GF loadings, except in the case of work of yield, where the curve at 10% GF shows an upward trend while those at 20 and 30% GF show downward trends [see Figs. 5(a), 6(a), and 8(a)].

Modulus of the ternary system [see Fig. 7(a)] shows a higher value at 10% EPDM content compared to pure PP, and thereafter it decreases slightly with increasing EPDM content of the matrix. Yield strain of the ternary system [see Fig. 6(a)], which is much lower for the blend at 10% EPDM, increases with increasing EPDM content of the matrix above 10% EPDM. The ternary composite PP/EPDM/

GF has a higher modulus than the corresponding binary system at 0% EPDM. At a constant GF loading, modulus of the composite is higher in case of 10% EPDM content than 0% EPDM content, and then decreases with increasing EPDM content of the matrix beyond 10% EPDM. The initial region between 0 and 10% EPDM and/or GF on the curves may not be representative of the true behavior in the absence of data points in this region, owing to uncertainities about the clustering of GF. Furthermore, the morphological studies, presented in a subsequent section clearly indicate that there is no clustering of GF in these composites. Sharpness of the maxima in the modulus versus blending ratio curve decreases with increasing GF loading [see Fig. 7(a)], which suggests that the role of EPDM becomes less significant with increasing GF loading.

At Varying GF Loading. At constant matrix blending ratio, yield stress increases with increasing GF loading at all the blending ratios of the matrix [see Fig. 5(b)]. The overall increase of yield stress for the ternary system is less than that for the corresponding binary system at 0% EPDM; the ratio of extreme values being 1.3 for the binary system and around 1.1 for the ternary system at the various matrix blending ratios studied. This indicates that EPDM, which facilitates yielding, suppresses the effect of GF on yield stress. The yield peak increases in height and narrows down on incorporation of GF, which reflects a substantial decrease in work of yield with increasing GF loading at any given matrix blending ratio [see Fig. 8(b)]. Work of yield decreases initially quite sharply and then levels off to a very low value at high GF loadings. This suggests that GF prevents shear yielding of the major matrix component PP and changes its character from ductile to brittle.

Yield strain of the ternary composite PP/EPDM/GF decreases with increasing GF loading more sharply than that of the corresponding binary system at 0% EPDM [see Fig. 6(b)]; and so does the work of yield [see Fig. 8(b)]. The decrease of yield strain (and also work of yield), which is quite sharp initially up to 10% GF loading, becomes quite slow at higher GF loadings, implying that the effect of GF reaches saturation when GF loading exceeds 20%. It may be emphasized that the addition of elastomer (i.e., EPDM) decreases the yield strain and work of yield of PP in the presence of GF, which is contrary to the role of elastomer added to a thermoplastic, in the absence of GF.

Modulus increases with increasing GF loading at each blending ratio of the matrix. The overall increase is greater in case of the ternary systems than the corresponding binary system at 0% EPDM [see Fig. 7(b)]. Astonishingly, the addition of EPDM, which produced a decrease in modulus at 0% GF, causes an increase of modulus in presence of GF [see Fig. 7(b)]. Such a reversal in the role of elastomer due to the presence of GF is apparently a combined effect of dispersed EPDM domains and the GF.

The observed increase of reinforcement effect on addition of EPDM in the presence of GF suggests that EPDM domains help in imparting the GF the necessary property for reinforcement, namely, the alignment along the direction of applied tensile stress, and/or preventing the randomization of fiber alignment during the tensile deformation. The rubbery nature of EPDM domains may facilitate the alignment of GF by providing flexible medium around them and/or by holding the fibers in position due to good adhesive property of elastomer so as to reduce the tendency towards misalignment during tensile deformation.

Furthermore, the addition of EPDM in presence of GF facilitates yielding [yield stress decreases, see Fig. 5(b)]. The role of elastomer domains on the yield behavior is generally associated with the deformation of the dispersed elastomer domains which induce shear yielding of the adjacent matrix. Thus the EPDM seems to play a dual role in these ternary composites: First, it helps in maintaining the alignment of the glass fibers during tensile deformation, and, second, it induces/facilitates shear yielding of the matrix.

Theoretical Analysis

Analysis of these tensile data on the basis of simple first power law equations suggested for binary systems by Piggott and Leidner[9] reveals some systematic differences in the reinforcement effect and the role of each individual component in reinforcement. This equation has the advantage over the various others used previously by Gupta and Purwar,[10] in that it represents both reinforcement and weakening by simply varying the sign or the relative magnitudes of the parameters used. This has been used by other authors.[11] The reinforcement effect could be positive or negative, depending on whether GF or EPDM, respectively, is treated as the inclusion and the remaining part of the respective binary or ternary system as the matrix for this analysis. According to Piggott and Leidner's equation[9]

$$(\sigma/\sigma_0) = a - b \cdot V_f \tag{1}$$

where σ is the yield stress (or any other mechanical property) of the composite and σ_0 that of the matrix,

V_f is the volume fraction of the filler and a and b are constants. The constant a takes account of the weakening of the matrix due to stress concentration. This parameter will be less than unity or greater than unity, depending upon whether the matrix is weakened by the stress concentration effect or strengthened by reinforcement, respectively. The constant b, which represents the effect of inclusion, would be "positive" for the inclusion, producing decrease of strength (or any other mechanical property), and "negative" for the inclusions, producing reinforcement effects.

Analysis of these data on tensile yield stress versus volume fraction of the respective inclusion leads to the values of a and b shown in Table II, for the four systems considering GF as inclusion in two of these, i.e., systems 1 and 2 and EPDM as inclusion in systems 3 and 4.

The value of a is equal to unity in systems 1 and 3 where the matrix is a single component one. The systems containing two-component matrices (viz., systems 2 and 4) show $a = 0.72$ when the matrix has a weakening component such as EPDM and $a = 1.5$ when it has a reinforcing component such as GF.

The sign of the constant b is quite consistent with the reinforcing or weakening character of the inclusion. It is negative for the case of the reinforcing filler, i.e., GF (systems 1 and 2 in Table II), and positive for the case of the weakening filler EPDM (systems 3 and 4 in Table II). The magnitude of b depends on the matrix for any given filler. For example, for GF as the filler, $b = -3.4$ for PP as the matrix and $b = -0.24$ for the PP/EPDM matrix. On the other hand, in the case of the weakening filler, the value of b is higher when the filler EPDM is added to PP/GF (treated as the matrix) instead of the single-component PP matrix. Thus, it is clear that the second component of the matrix produces its own reinforcement (or the weakening effect), which ultimately controls the rate of increase (or decrease) of the tensile properties with the volume fraction of the component treated as the filler in eq. (1).

Impact Properties

Izod impact strength of notched samples varies with the composition variables of these PP/EPDM/GF composite and PP/EPDM blend shown in Figure 9. Results are discussed below for the binary blend and the ternary composite.

PP/EPDM Blend

Impact strength of PP/EPDM blend increases with increasing EPDM content of the blend as shown in Figure 9(a). The impact strength increases rather slowly up to 20% EPDM content and then quite sharply at higher EPDM content. The curve has qualitative similarities with that found for the blends of PP with other elastomers.[12] The total increase of impact strength in the studied range of blending ratio is five times the value for unblended PP. This is larger than the increase observed in the case of other blends of PP,[13-15] suggesting greater suitability of EPDM for impact toughening of PP.

PP/EPDM/GF Composite

At Constant GF Loading. As a function of matrix blending ratio at constant GF loading, the impact strength increases with increasing EPDM content of the polyblend matrix, as shown in Figure 9(a). However, with respect to the case of unblended PP matrix, the binary blend matrix at 10% EPDM imparts a lower impact strength to the composite. The impact strength shows a distinct minimum at matrix

Table II Parameters a and b of Eq. (1) Fitting the Tensile Yield Stress Data

System No.	Description	Component Treated as Matrix	Component Treated as Inclusion	a	b
1	PP/GF	PP	GF	1.00	−3.40
2	PP/EPDM/GF	PP/EPDM	GF	0.72	−0.24
3	PP/EPDM	PP	EPDM	1.00	1.17
4	PP/GF/EPDM	PP/GF	EPDM	1.50	1.70

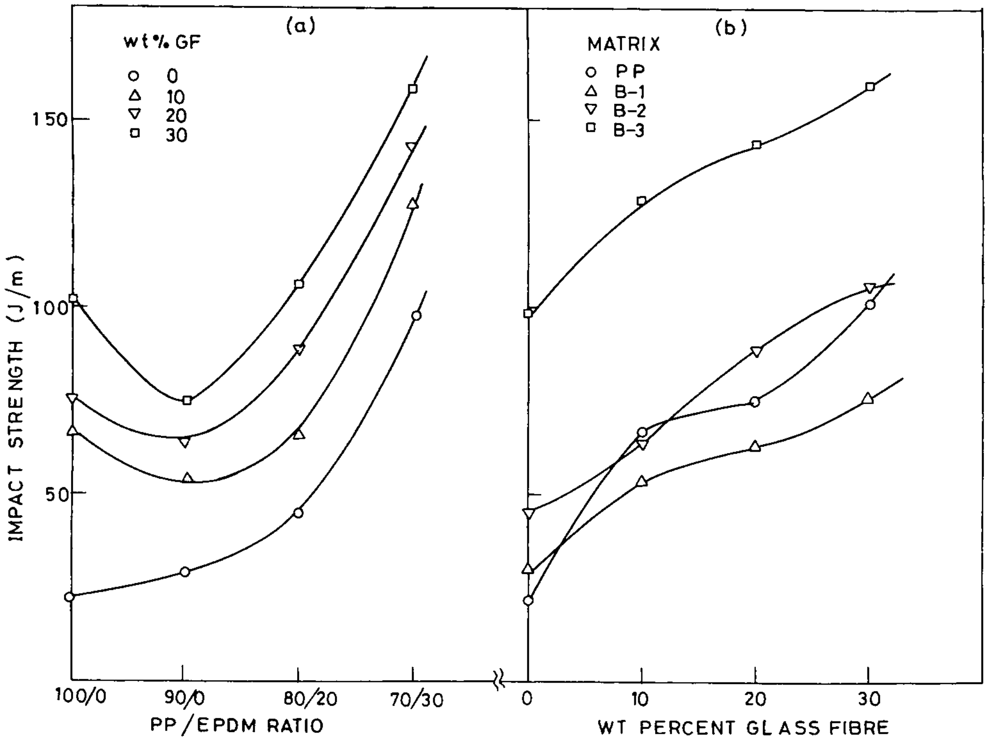

Figure 9 Impact strength of PP/EPDM/GF ternary system: (a) as a function of matrix blending ratio with GF loading as the variable; (b) as a function of GF loading with matrix blending ratio as the variable.

blending ratio consistent with 10% EPDM only in the presence of GF. At 0% GF no such minimum in impact strength is seen. Moreover, the slope of the impact strength versus matrix blending ratio curve in the initial 0–10% EPDM region changes gradually from a positive value at 0% GF to a high negative value at 30% GF loading. This gradual change of slope indicates an active role of GF in the impact behavior at low EPDM content of the matrix of the ternary composite. This also implies that at low EPDM content of the matrix the role of elastomer in the impact toughening is greatly suppressed by the GF, or the conjunction of GF and EPDM toughening in both PP and PP/EPDM blend matrix, as evident from the fact that the impact strength is always superior for the sample containing higher GF loading.

At Varying GF Loading. As a function of GF loading at constant matrix blending ratio, the impact strength increases in a manner shown in Figure 9(b). The total increase in the range of measurements, which is five times that for the case of the unblended PP matrix, reduces to the increase by factors of 2.5, 2.3, and 1.6 for the cases of matrix with 10, 20, and 30% EPDM content, respectively.

The curve for the case of unblended PP matrix is quite nonlinear with a flat portion in the region of 10–20% GF [see Fig. 9(b)]. This flat portion gradually tends to disappear with increasing EPDM content of the matrix. At low EPDM content (or at small average domain size of the elastomer), as well as in the absence of EPDM, the impact toughening effect of the GF is somewhat suppressed, only up to 10 wt % EPDM in the polyblend matrix. At higher EPDM contents, impact toughening effects of EPDM and GF act in conjunction with each other. This suggests that when EPDM droplets are bigger than a critical size, they act cooperatively with GF in enhancing the impact strength.

Morphology

PP/EPDM Blend

Scanning electron micrographs of impact fracture surfaces of PP and PP/EPDM blend at different blending ratios are shown in Figure 10. The fracture surface has a different kind of roughness in PP/EPDM blend than in PP. The fracture surface looks

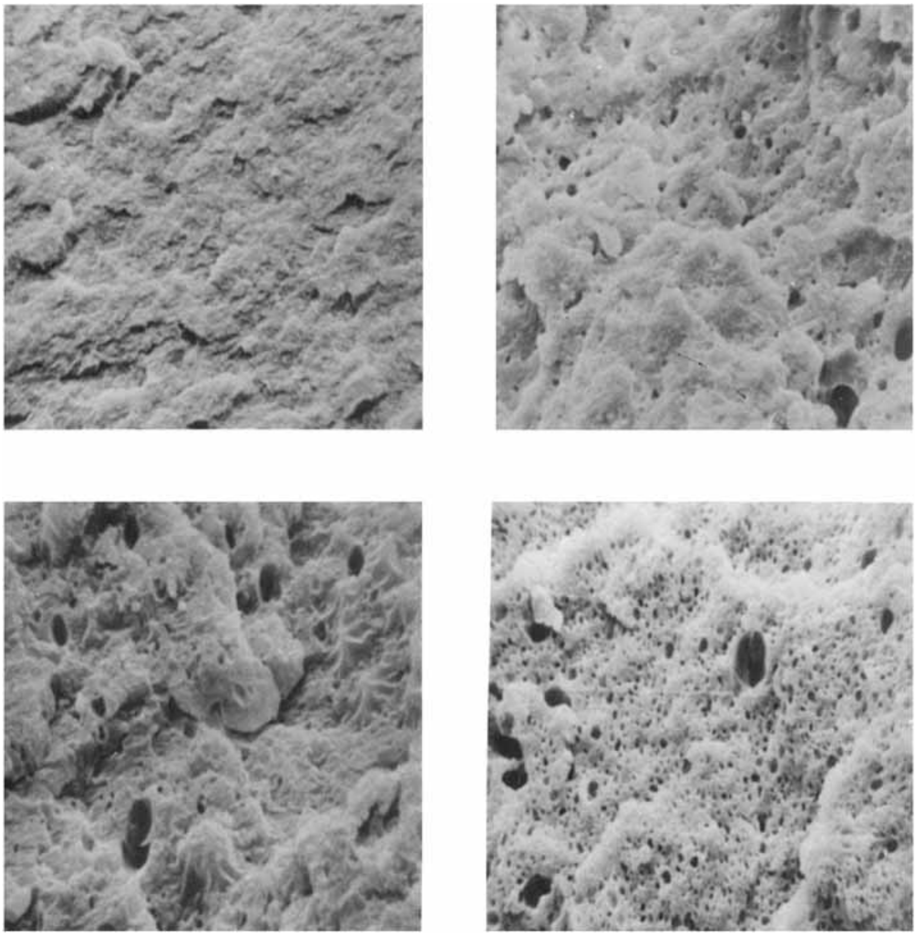

Figure 10 Scanning electron micrographs of impact fractured surfaces of PP(a) and PP/EPDM blend at various blending ratios: (b) 90/10; (c) 80/20; (d) 70/30.

like hills and valleys in case of the blend and like a rough plane in case of PP. Presence of EPDM droplets seems to give rise to localized toughened zones in PP, which in turn form hilly regions on fracture.

EPDM droplets dispersed in the matrix are clearly visible as deformed circular or elliptical voids. The dispersion of EPDM droplets is quite homogeneous. The number of droplets seems to increase with increasing EPDM content of the blend. The sample containing 30 wt % EPDM shows quite uniform and fine dispersion of EPDM in PP matrix.

PP/EPDM/GF Composite

Scanning electron micrographs of the three samples of PP/EPDM/GF composite with varying GF content at constant composition of the matrix (i.e., 80/20 blend of EPDM) are shown in Figure 11. In these micrographs of impact fracture surfaces, the glass fibers are seen projecting out from the matrix in all three cases. The glass fibers are well separated and show no clustering in any region of these fracture surfaces. This was observed on all the micrographs of all the three GF contents studied. The glass fibers are tightly held by the matrix. However, in some cases, gaps between GF and matrix are visible. Such gaps are apparently created due to the displacement of glass fibers by impact forces, since the gaps are on the same side of the GF on all the fracture surfaces. Furthermore, if the gaps were due to differences in thermal contraction of the matrix and GF, then it should occur uniformly on all sides of the GF and should be seen around fibers in all the samples.

Polymer adhering on GF surface is visible at very high magnification, as shown in Figure 12. This sticking phase does not seem to be the major component of the matrix, i.e., PP, because in that case

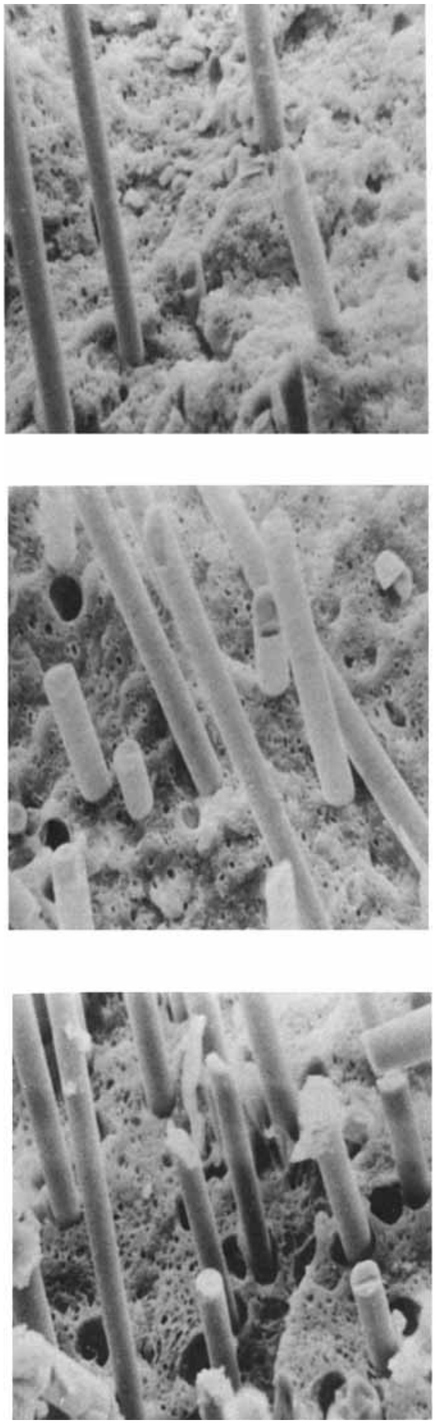

Figure 11 Scanning electron micrographs of impact fractured surfaces of PP/EPDM/GF ternary system ay various compositions (refer to Table I for nomenclature): (a) sample C-4; (b) sample C-5; (c) sample C-6.

a greater surface area of GF should have been covered by the polymer. The EPDM elastomer might be stickier and may have greater affinity to GF.

Figure 12 Scanning electron micrographs of impact fractured surfaces of PP/EPDM/GF ternary system at a high magnification to illustrate the details of the fiber–matrix interface and the fiber surface.

CONCLUSION

Addition of EPDM to PP increases elongation at break and yield strain and decreases the yield stress and modulus. GF, on the other hand, produces an opposite effect on the modulus, yield stress, and yield strain and decreases the elongation at break considerably. The same general trends are observed also for the effect of GF in the presence of EPDM and for the effect of EPDM in the presence of GF.

EPDM, which is notorious for its effect of decreasing the modulus, acts completely the opposite in the presence of GF. At any given GF content the modulus is higher in the case of the PP/EPDM matrix at all blending ratios than in the case of the PP matrix. EPDM plays a dual role in these ternary composites: First it helps in maintaining the alignment of GF during tensile loading, and, second, it induces shear yielding of the matrix.

GF produces an increase of impact strength in the presence of EPDM, which may be seen as a combined effect of GF and the elastomer domains. However, the polyblend matrix at 10% EPDM gives lower impact strength to the composite than unblended PP matrix.

The dispersion of EPDM in PP matrix is quite homogeneous and fine, and glass fibers are tightly held in the matrix, without any gaps due to differences in thermal contraction of matrix and the fiber.

REFERENCES

1. J. E. Stamhuis, *Polym. Compos.*, **5,** 202 (1984).
2. J. E. Stamhuis, *Polym. Compos.*, **9,** 72 (1988).
3. J. E. Stamhuis, *Polym. Compos.*, **9,** 280 (1988).

4. A. K. Gupta, V. B. Gupta, R. H. Peters, W. G. Harland, and J. P. Berry, *J. Appl. Polym. Sci.*, **27**, 4669 (1982).
5. M. Arroyo and F. Avalos, *Polym. Compos.*, **10**, 117 (1989).
6. M. Arroyo Ramos and J. P. Vigo Matheu, *Polym. Compos.*, **9**, 105 (1988).
7. A. Mitsuishi, S. Kodama, and H. Kawasaki, *Polym. Compos.*, **9**, 112 (1988).
8. A. K. Gupta, P. Krishna Kumar, and B. K. Ratnam, *J. Appl. Polym. Sci.*, **42**, 2595 (1990).
9. M. R. Piggott and J. Leidner, *J. Appl. Polym. Sci.*, **18**, 1619 (1974).
10. A. K. Gupta and S. N. Purwar, *J. Appl. Polym. Sci.*, **29**, 3513 (1984).
11. L. Nicolais, E. Drioli and R. F. Landel, *Polymer*, **14**, 21 (1973).
12. A. K. Gupta and S. N. Purwar, *J. Appl. Polym. Sci.*, **31**, 535 (1986).
13. A. K. Gupta and S. N. Purwar, *J. Appl. Polym. Sci.*, **30**, 1799 (1985).
14. A. K. Gupta and B. K. Ratnam, *J. Appl. Polym. Sci.*, **42**, 297 (1991).
15. A. K. Gupta, A. K. Jain, B. K. Ratnam, and S. N. Maiti, *J. Appl. Polym. Sci.*, **39**, 515 (1990).

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