

# Poly(butylene Terephthalate)/High Density Polyethylene Alloys. II. Mechanical Properties and Rheology

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## SYNOPSIS

Alloys of poly(butylene terephthalate) (PBT) and high density polyethylene (HDPE) in 80 : 20 ratio were prepared using a polyethylene-based ionomer as a compatibilizer. The effect of the addition of this compatibilizer on mechanical and rheological properties of the PBT/HDPE blends was examined. The mechanical properties studied were tensile, flexural, and impact properties as a function of ionomer content. Ultimate mechanical properties showed significant improvement on addition of ionomer. This has been attributed to an increase in the interfacial adhesion between the two phases in the presence of the compatibilizer. Rheological measurements showed that shear viscosity increased for the blend with the addition of the compatibilizer. An explanation for this behavior is presented on the basis of the theory of emulsions.

## INTRODUCTION

Melt blending of two or more polymer components generally leads to either total or partial incompatibility.<sup>1</sup> For most multicomponent systems the result is then a heterogeneous product that has a relatively weak interfacial adhesion and accordingly results in relatively poor mechanical behavior. Physical and chemical interaction across the phase boundaries are known to control the overall performance of immiscible polymer blends. Strong interactions result in good adhesion and efficient stress transfer from the continuous to the dispersed polymer phase in the blends. Although interfacial adhesion controls primarily mechanical properties such as strength and toughness, rheological and processing characteristics, environmental resistance, sorption, diffusion, etc. are also affected by the nature and extent of the wetting and adsorption phenomenon that are usually associated with adhesion.<sup>1,2</sup> Methods to improve adhesion between two immiscible phases that are chemically and physically different have been a subject of considerable research, often of proprietary

nature.<sup>3-5</sup> Out of several approaches proposed to strengthen interfacial adhesion between two immiscible phases and thus enhance overall mechanical properties, the following two are more successful<sup>2</sup>:

1. Addition of a third component (compatibilizer) which is capable of specific interactions and/or chemical reactions with the blend constituents. Block and graft copolymers fall in this category. An A-B block or graft copolymer will tend to accumulate at, orient, and bridge the interface between polymers A and B. This results in reducing the interfacial tension thus improving the compatibility and adhesion between the components.
2. Blending suitably functionalized polymers capable of enhanced specific interactions and/or chemical reactions.

It has been reported by Teyssie and co-workers<sup>6</sup> that additions even in small amounts of polystyrene/hydrogenated polybutadiene block or graft copolymers to mixtures of polystyrene (PS) with various polyolefins is very efficient in improving the ultimate properties of the original blends. Investigations on these polyblends have emphasized on significant re-

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ductions in domain size and increased interfacial adhesion. Similar observations have been reported by Locke and Paul<sup>7,8</sup> for polyethylene and poly(vinyl chloride) blends with chlorinated polyethylene.

Poly(butylene terephthalate) (PBT), a thermoplastic polyester and high density polyethylene (HDPE), a polyolefin are expected to form an immiscible blend as seen from their widely different solubility parameter values which are 10.7 (cal/cc)<sup>1/2</sup> for PBT and 9.03 (cal/cc)<sup>1/2</sup> for HDPE. An ionomer that is a copolymer based on PE containing ionic groups can be added to this blend system in order to improve interfacial adhesion and thus improve ultimate mechanical properties. The mode of compatibilization and the effect of ionomer on morphological characteristics of this blend have been reported in an earlier paper.<sup>9</sup> In the present paper, the role of ionomer as a compatibilizer in modifying the mechanical and rheological properties of PBT/HDPE blend has been investigated. The state of dispersion (i.e., morphology of a two-phase polymer blend) is influenced by processing conditions, for example, extrusion temperature, which in turn influences the rheological properties. Hence an attempt has been made to relate the rheological properties of the blend to their state of dispersion in flow.

## EXPERIMENTAL

PBT under the trade name ARNITE T-006 ( $M_v = 55,000$ ) was obtained from Cenka Plastics Ltd. (India). HDPE used was Hostalen-G with a melt flow index of 10.0, a molding grade material obtained from Polyolefins Industries Ltd. (PIL) (India). The ionomer used was poly(ethylene-co-sodium methacrylate), which is a random terpolymer consisting of roughly 80% PE and 20% of mixture of methacrylic acid partially neutralized with zinc. Ionomer under the trade name Surlyn-8660 was obtained from DuPont (USA).

**Preparation of Blends.** All blends were prepared by melt mixing on a single screw extruder (Betol BM1820) of  $L/D = 20$ , in a temperature range 230–240°C with the screw speed at 30 rpm. The present work involves the preparation of the binary blend of PBT/HDPE and ternary blends of PBT/HDPE/ionomer. In all blend systems the ratio of PBT to HDPE was 80 : 20 by weight. The amount of ionomer in ternary blend was taken to be 2, 4, and 8 wt %. Composition of various blends taken for study are as shown in Table I. Pure PBT and HDPE were also made to pass through the same

**Table I Blend Composition**

Sample No.	Sample Name	PBT	HDPE (wt %)	Ionomer
1	A	80	20	—
2	B	—	96	4
3	C	78.4	19.6	2
4	D	76.8	19.2	4
5	E	73.6	18.4	8
6	F	100	—	—
7	G	—	100	—

process of extrusion so that they would have the same thermal history as the blend samples.

**Preparation of Test Specimens.** The test specimens for the evaluation of mechanical properties were prepared by injection molding on a Windsor SP-1 screw type machine using the screw speed of 30 rpm and injection pressure of 150 kg/cm<sup>2</sup>. Mold was kept at ambient temperature (30 ± 2°C). The granule samples were dried thoroughly at 80–100°C in a vacuum oven.

**Measurement of Mechanical Properties.** Tensile properties were measured on an Instron Universal Tester Model 1121 using injection molded dumbbell-shaped samples, according to ASTM D638 (type 1) test procedure. The testing conditions were as follows: gauge length 6 cm, crosshead speed 10 mm/min, and chart speed 200 mm/min. The Izod impact strength of unnotched and notched samples was measured on a FIE Impact Tester Model IT-0.42 (falling hammer type) in accordance with the ASTM D256 test procedure. Impact strength is expressed in terms of the energy absorbed per unit width of the specimen and reported as energy per meter of notch. Flexural measurements were done on a tensiometer with 3-point loading system according to ASTM D790 test procedure. The support span length was 7 cm. At least five samples were tested in each case, and the average value was reported. All the tests were performed at ambient temperature, i.e., 30 ± 2°C.

**Measurement of Rheological Properties.** Rheological data were generated on Rheograph 2001 (Gottfert, Germany) using round hole die of diameter ~ 1 mm and an  $L/D$  ratio of 30 at temperatures of 240, 250, and 260°C. The comparison interval was 8 s and the initial melting time was 1 min. The instrument was set at constant speed/shear rate mode. Desirable shear rate is obtained by feeding in varying piston speeds. A maximum of eight piston speeds in the range 0.04–2.40 mm/sec. were used. Rheograph 2001 is microprocessor controlled and

the computer evaluates the data applying Rabinowitsch and Bagley correction factors and also using a mirror relationship.<sup>10</sup> Rabinowitsch correction is applied to get the true wall shear rate  $\dot{\gamma}_w$  from the apparent shear rate ( $\dot{\gamma}_{app}$ ),

$$\dot{\gamma}_w = [(3n + 1)/4n] \dot{\gamma}_{app} \quad (1)$$

where  $n$  is the power law flow index and  $(3n + 1)/4n$  is the Rabinowitsch correction factor. The melt viscosity is given by the ratio of shear stress and shear rate:

$$\eta = \tau_w / \dot{\gamma}_w \quad (2)$$

The viscous drag that occurs in the region is independent of the length of the capillary and considered as increasing the effective length of the die. To account for this effective increase in length in terms of the die radius, the Bagley correction factor is applied to get the true wall shear stress.<sup>11,12</sup> The end correction term  $n$  is given by the negative intercept of the plot of  $P$  vs.  $L/R$  in a range of shear rates. Now

$$\begin{aligned} \tau_w \text{ (true shear stress)} &= \frac{\Delta PR}{2(L + nR)} \\ &= \frac{\Delta P}{2(L/R + n)} \end{aligned} \quad (3)$$

Since  $\Delta P = 2\tau(L/R + n)$  at  $\Delta P = 0$ ,  $n = -L/R$ . The viscous, elastic, and time-dependent quantities directly calculated from the viscosity function  $\eta(X_w)$  are:

1. The normal stress coefficient  $\Theta(X_w)$
2. The first normal stress difference ( $\tau_{11} - \tau_{22}$ )
3. The swelling ratio  $(D/d)^2$ .

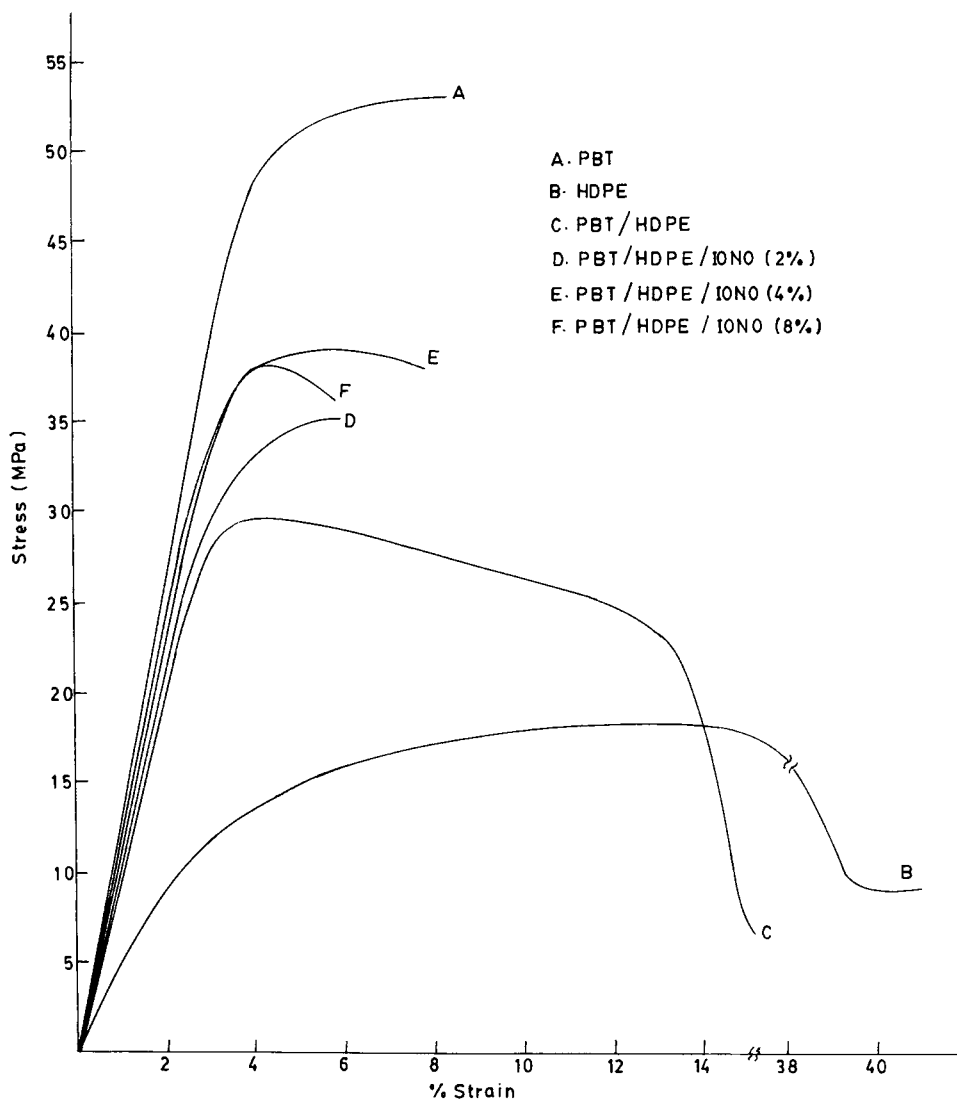
## RESULTS AND DISCUSSION

### Mechanical Properties

**Tensile Properties.** Stress-strain curves for PBT/HDPE and PBT/HDPE-ionomer blends are as shown in Figure 1. From these stress-strain curves, various tensile properties, namely, tensile strength, tensile modulus, and % elongation-at-break (%) have been calculated and are presented in Table II. The values of pure PBT and HDPE are also included for comparison. From the stress-strain curves it can

be observed that pure PBT as well as pure HDPE show ductile failure. The blend PBT/HDPE also shows a ductile failure, but the blends with ionomer show less ductile type failure, with the curves ending at or just after the yielding point. It can be seen that blending of HDPE with PBT lowers the strength as well as modulus values. Morphological studies reported in our earlier paper<sup>9</sup> on these blends show that HDPE domains are dispersed in the PBT matrix. Domain size shows a reduction on adding ionomer as compared to the blend without ionomer.<sup>9</sup> It is widely accepted that in such systems the particle of the dispersed phase acts as a stress concentration point, introducing weak points in the matrix material.<sup>13</sup> As a result, an intrinsically tough matrix breaks at a lower stress and at lower elongation compared to pure matrix free of these particles. However, although an isolated crack can rapidly propagate through a polymer matrix, resulting in a fracture with only a small amount of energy, if a larger number of cracks are present, their stress fields can interfere when they pass near one another. This type of interaction can strongly reduce the stress at the tips of the cracks and can stop their growth. Since more cracks are formed during the fracture process, more energy would be absorbed in breaking the material and the tensile strength, and tensile modulus values would be higher in blends containing ionomer, where a larger number of domains per unit volume are seen.

The tensile strength values show an increase on addition of ionomer as compared to the blend without ionomer (Table II). The maximum increase ( $\approx 25\%$ ) is obtained at 4% ionomer content. This composition showed a maximum value of crystallinity as determined from X-ray.<sup>9</sup> Tensile modulus values increase by 15% as the ionomer content increases from 2% to 8%. The elongation at break decreases significantly on addition of ionomer to the PBT/HDPE blend. Figure 2 shows the variation of various tensile properties with ionomer content. The interfacial tension and adhesion between the two phases also plays a critical role in determining the mechanical behavior.<sup>14</sup> Thus tensile strength and tensile modulus values of the compatibilized blends have been found to deviate positively from additivity as compared to the PBT/HDPE blend. The PBT/HDPE blend shows inferior properties because of poor adhesion and high interfacial tension between the two polymers owing to their widely different polarities. On addition of ionomer, which is a copolymer of (polyethylene-co-sodium methacrylate) to the PBT/HDPE blend, interactions at the interface improve, and thus interfacial adhesion is improved.



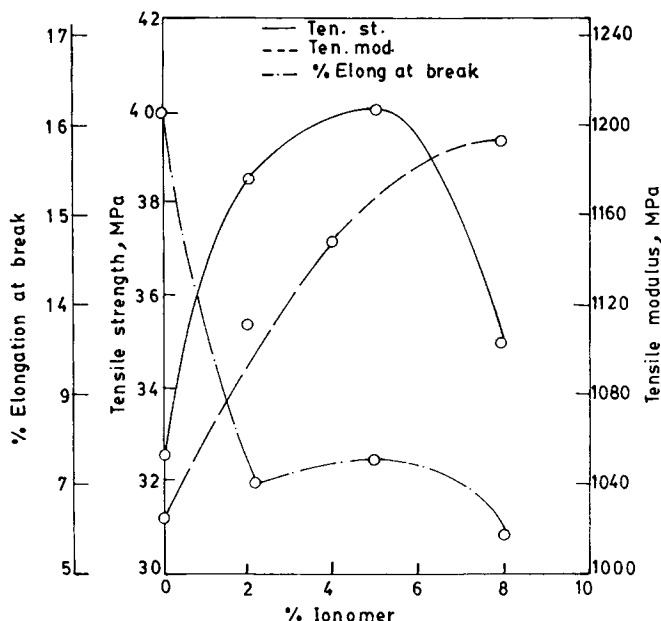
**Figure 1** Stress-strain plots for PBT, HDPE, PBT/HDPE, and PBT/HDPE/ionomer blends.

At the same time reduction in interfacial tension in the presence of a compatibilizer permits a finer dispersion of HDPE in the PBT matrix during mixing,

leading to better mechanical properties. Heikens and co-workers<sup>4,5</sup> have also reported similar increase in yield strength and tensile strength for PS/LDPE

**Table II** Mechanical Properties of PBT/HDPE/Ionomer Blends

Sample No.	Blend Composition (wt %)			Tensile (MPa)			Flexural (MPa)		Izod Impact (kg m/m)	
	PBT	HDPE	Iono	Str.	Mod.	% Elon.	Str.	Mod.	Not.	Unnot.
1	80	20	0	32.7	1025	15.3	50.5	1285	5.45	30.3
2	78.4	19.6	2	38.5	1112	7.05	61.0	1698	3.52	39.9
3	76.8	19.2	4	40.2	1150	7.64	60.6	1837	4.05	48.9
4	73.6	18.4	8	35.3	1175	5.89	57.1	1621	4.20	56.5
5	100	—	—	52.2	1375	8.96	79.5	2122	5.20	—
6	—	100	—	18.5	462.5	37.4	23.7	740	4.40	—



**Figure 2** Plot of tensile properties vs. % ionomer content for PBT/HDPE/ionomer blends.

blend on addition of a graft copolymer of the two polymers.

For immiscible blends such as PBT/HDPE, polarity mismatch between the two components results in a weakening of the interface reflecting in poor mechanical properties and problem of weld lines during molding. The effects of mismatch of poorly adhering components at the interface can be considered by way of a simple model. This model was developed by Nolley and co-workers<sup>15</sup> to analyze the problem of weld lines in a binary blend of PP/LDPE. They developed the model in a general way first and reduced it to the specific case of a binary blend.

It is assumed that the adhesive strength of a bond (formed in the melt) between the polymers  $i$  and  $j$  in tension is  $\sigma_{ij}$ . For the random case, the adhesion resulting from this  $i$ - $j$  contact would be  $\sigma_{ij}f_i f_j$ , where  $f_i$  and  $f_j$  are surface fractions of the components  $i$  and  $j$ . The total tensile strength of the interfaces (TS) is then the sum over all possible types of contacts, i.e.,

$$TS = \sum_{ij} \sigma_{ij} f_i f_j \quad (4)$$

In general, this sum will contain  $N^2$  terms, where  $N$  is the number of components. For a binary blend system, it can be assumed that the surface area fraction is equal to bulk volume fraction  $f_i = \phi_i$ ,  $f_j = \phi_j$ . This reduces the terms in eq. (4) since  $\sigma_{ij} = \sigma_{ji}$ ; hence eq. (4) reduces to

$$TS = \sigma_{11}\phi_1^2 + 2\sigma_{12}\phi_1\phi_2 + \sigma_{22}\phi_2^2 \quad (5)$$

where  $\sigma_{11}$  and  $\sigma_{22}$  refer to the "adhesive" strengths of pure components to themselves. In the limit of poor adhesion of component 1 to component 2, i.e., PBT/HDPE blend,  $\sigma_{12} = 0$ ; thus eq. (5) reduces to

$$TS = \sigma_{11}\phi_1^2 + \sigma_{22}\phi_2^2 \quad \text{with } \phi_1 + \phi_2 = 1 \quad (6)$$

The binary PBT/HDPE blend data is remarkably in good agreement with this prediction, indicating that the assumption  $\sigma_{ij} = 0$  is probably valid for this case (Table III). It is also seen that tensile strength values for corresponding PBT/HDPE blend with compatibilizer lie above the theoretically calculated values. This suggests that in ionomer-containing blends, a finite positive  $\sigma_{12}$  adhesion strength exists brought about by the addition of the third component which is an ionomer in this case, through terms  $\sigma_{13}$  and  $\sigma_{23}$ .

Using eq. (4),  $\sigma_{12}$  values were calculated for the blends with the ionomer as the compatibilizer and are shown in Table III. It can be seen that  $\sigma_{12}$  values show a sharp increase as ionomer content increases from 2 to 4%, whereas at 8% ionomer content the increase is only marginal. It has been reported<sup>16</sup> that, at higher ionomer concentration, excess ionomer molecules may concentrate at the interface and lead to flocculation arising due to strong interparticle interactions (Ion clusters). This effect can be detri-

**Table III Comparison of Tensile Strength (TS) Values Obtained Experimentally with the TS Values Predicted using Nolley et al's. Model<sup>15</sup>**

Sample	Tensile Strength (Exptl) (MPa)	Tensile Strength (Theoret) Assuming $\sigma_{12} = 0$ (MPa)	Average Strength $\sigma_{12}$ (M Pa)
PBT + HDPE	32.7	32.73	0
PBT + HDPE + Iono 2%	38.5	30.09	24.27
PBT + HDPE + Iono 4%	40.2	28.68	34.99
PBT + HDPE + Iono 8%	35.3	25.30	35.66

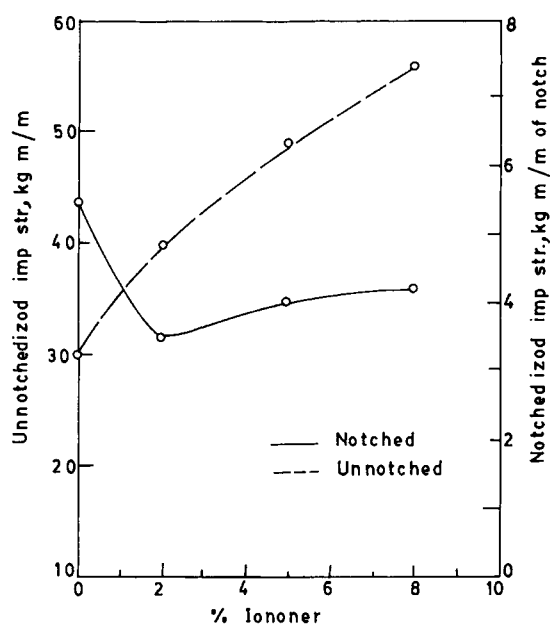
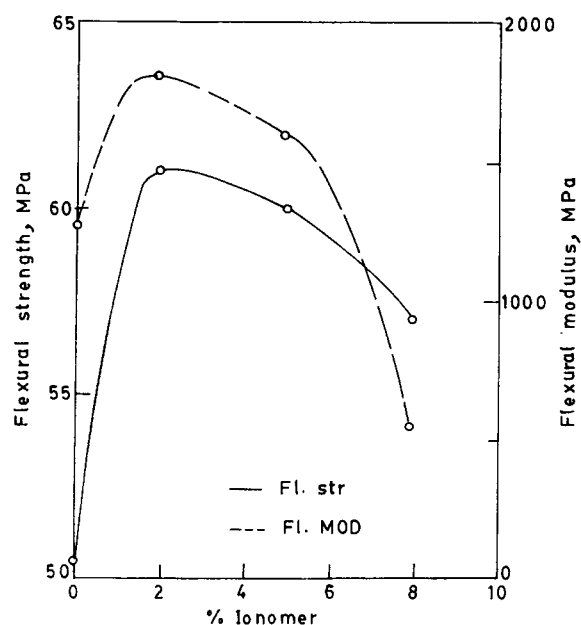
mental on blend properties. Perhaps this may be the reason for lower tensile strength value at 8% ionomer content compared to that at 4%. Thus it can be said that 4–5% ionomer content is optimum to achieve uniform dispersion and excess quantities of ionomer is not necessary.

**Impact Properties.** Unnotched and notched impact strength values of the PBT/HDPE/Ionomer blends are as shown in Table II. Unnotched impact strength of the PBT/HDPE blend is lower than either of the pure polymers. This is because HDPE, a lower impact strength material, forms a sleeve around the PBT core.<sup>9</sup> On addition of increasing amount of ionomer, a gradual increase (about 86% at 8% ionomer content) in the unnotched impact strength values is observed. This may be due to sheath-core morphology becoming less distinct as the ionomer is added to the blend as also seen in SEM studies reported earlier.<sup>9</sup> The notched impact

strength value of compatibilized blend is lower than the uncompatibilized blend, but the values gradually increase with increasing amount of ionomer (Fig. 3). The explanation for this behavior is not obvious in this case.

**Flexural Properties.** Flexural strength and modulus measured for pure components and the blends of PBT/HDPE/Ionomer are shown in Table II. Flexural strength as well as modulus values improve significantly on the addition of ionomer to the incompatible PBT/HDPE blend. The maximum values are obtained at 2% ionomer content, after which the values show a decreasing trend, however, remaining higher than the uncompatibilized blend. The variation of flexural properties with ionomer content is shown in Figure 4.

The substantial improvements observed in the mechanical properties of modified immiscible blend of PBT/HDPE might be attributed to an increase

**Figure 3** Plot of impact properties vs. % ionomer content for PBT/HDPE/ionomer blends.**Figure 4** Plot of flexural properties vs. ionomer content for PBT/HDPE/ionomer blends.

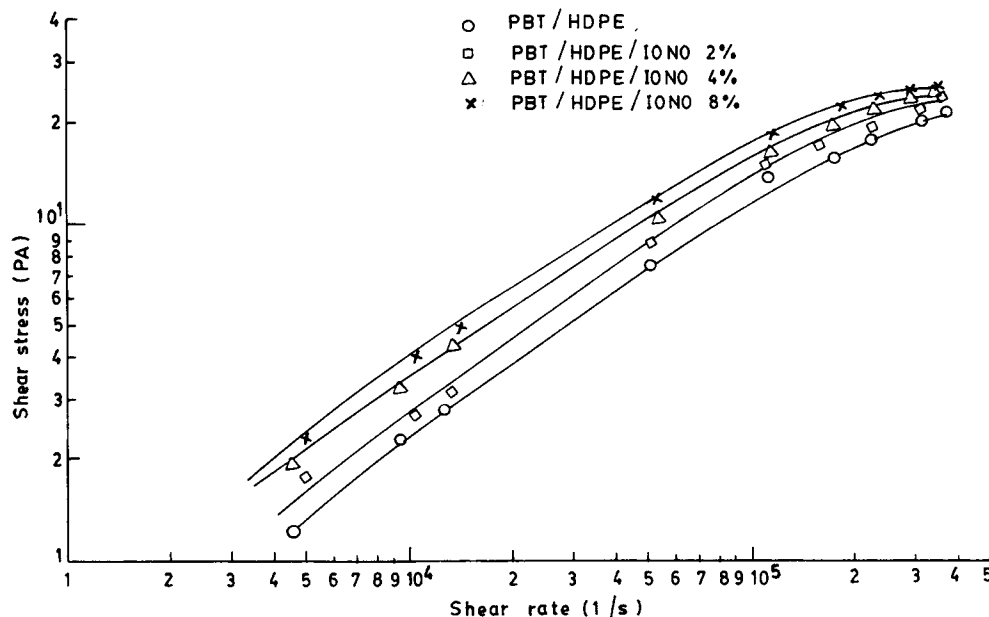


Figure 5 Plots of shear stress vs. shear rate for PBT/HDPE/ionomer blends at 240°C.

in the interfacial adhesion between the two polymer phases in presence of the compatibilizer. The ionomer must adhere rather well to each of the corresponding homopolymers, which display only a poor mutual affinity. Calculation of adhesive strength of the two polymers ( $\sigma_{12}$ ) in the presence of the ionomer also supports this observation.

**Rheological Properties.** The plots of shear stress vs. shear rate at 240°C for pure PBT, HDPE, and the blend samples are shown in Figure 5. It is seen that the dependence of shear stress on shear rate is linear for lower and medium shear rates with slope less than 1 (Table IV) for all the blend compositions studied, which is indicative of the power law behavior and the pseudoplastic nature of these blends, as is typical for thermoplastics.

**Viscosity Shear Rate Behavior.** Figure 6 gives the viscosity vs. shear rate plot at constant temperature (240°C) for PBT, HDPE, and the blends with

different ionomer compositions. It is seen that blending HDPE with PBT greatly reduced the viscosity of PBT at the processing temperature. This considerable drop in viscosity has important implications in processing and can be explained by the fact that at 240°C HDPE is a relatively low viscosity liquid, since this temperature is much higher than its melting point. This low viscosity component in the blend contributes to lowering of the viscosity of the blend. The addition of the ionomer to the PBT/HDPE blend increases the viscosity as seen from Figure 6. Figure 7 gives the plot of viscosity vs. ionomer composition at constant temperatures and selected shear rates. It is seen that at both temperatures (240 and 260°C), the blend without ionomer has the lowest viscosity. At 2% ionomer content, viscosity is higher and the viscosity increases as ionomer content is further increased to 4 and 8%. It is also seen that changes in viscosity on addition of ionomer are more significant at lower shear rate. These observations can be explained in terms of the morphology of the heterogeneous polymer blends in the molten state, which may be considered very similar to that of concentrated emulsions.<sup>17</sup> As discussed in the earlier related paper,<sup>9</sup> SEM and PM studies have shown that PBT/HDPE blend is an incompatible one where the lower viscosity HDPE component is dispersed as spherical domains into the more viscous PBT component, which forms the matrix/continuous phase. SEM studies also show that, on adding ionomer, the size of the HDPE domains decreases as ionomer content increases. Blend

Table IV Rheological Parameters of PBT/HDPE/Ionomer Blend

Sample No.	Sample Name	Power Law Exponent $n$
1	PBT + HDPE	0.7073
2	PBT + HDPE + IONO 2%	0.7045
3	PBT + HDPE + IONO 4%	0.6591
4	PBT + HDPE + IONO 8%	0.6320
5	PBT	0.7714
6	HDPE	0.7142

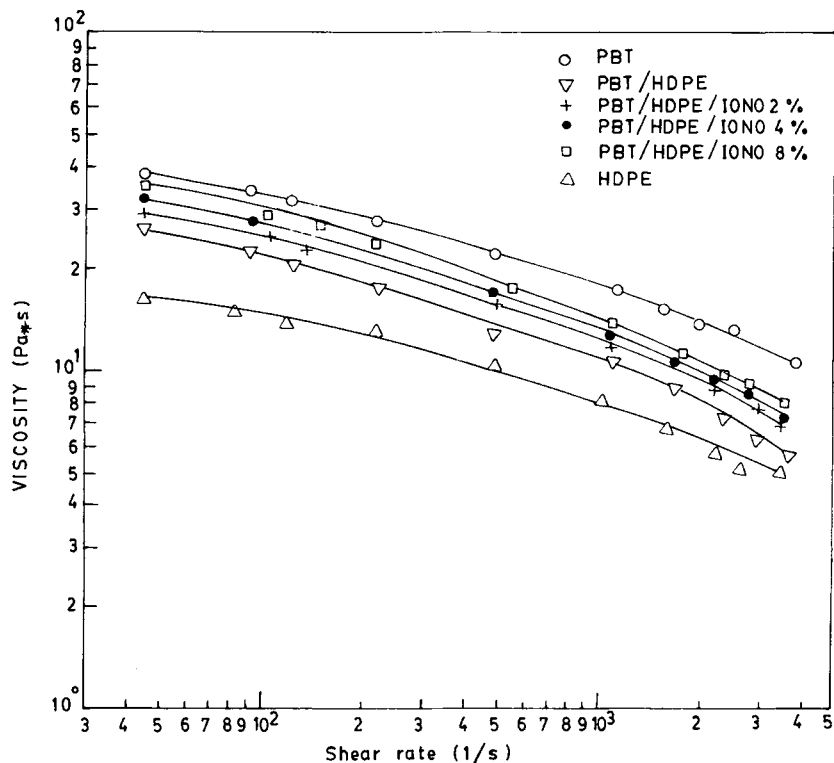


Figure 6 Plots of viscosity vs. shear rate for PBT, HDPE, and their blends at 240°C.

without ionomer has larger domains as compared to the blends with ionomer. Since larger domains are easily deformed in a flow field, there are less chances of interaction, hence lowering the viscosity for the

blend without ionomer. This is in accordance with Taylor's theory for emulsion,<sup>17</sup> which says that droplet deformation increases as droplet size in-

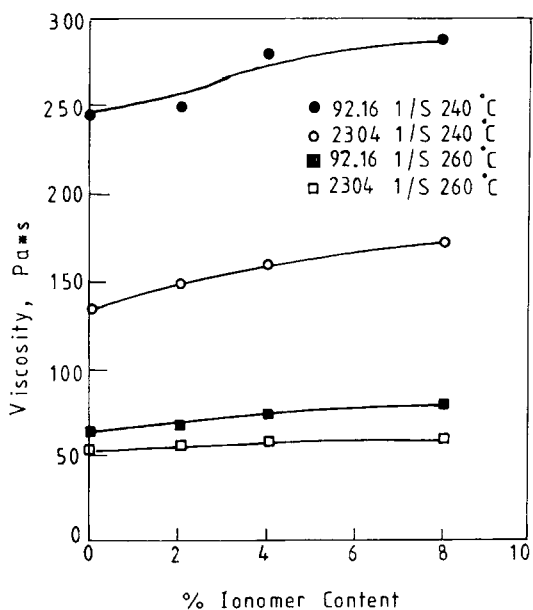


Figure 7 Plots of viscosity vs. % ionomer content at two different shear rates and temperatures.

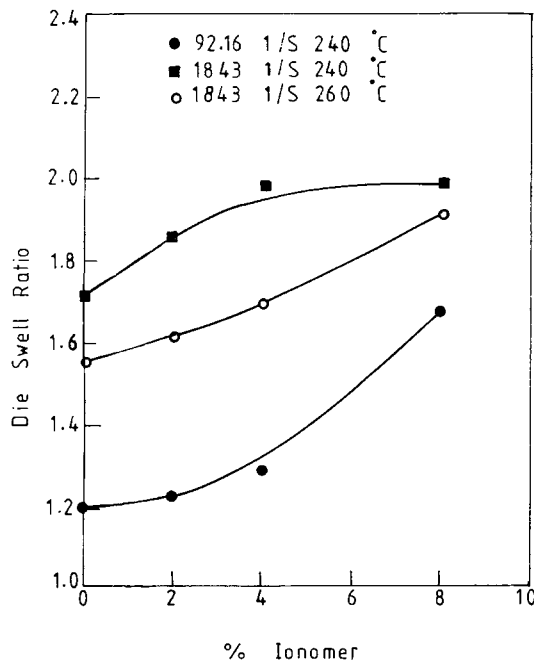


Figure 8 Plots of die-swell vs. % ionomer content at two different temperatures and shear rates.

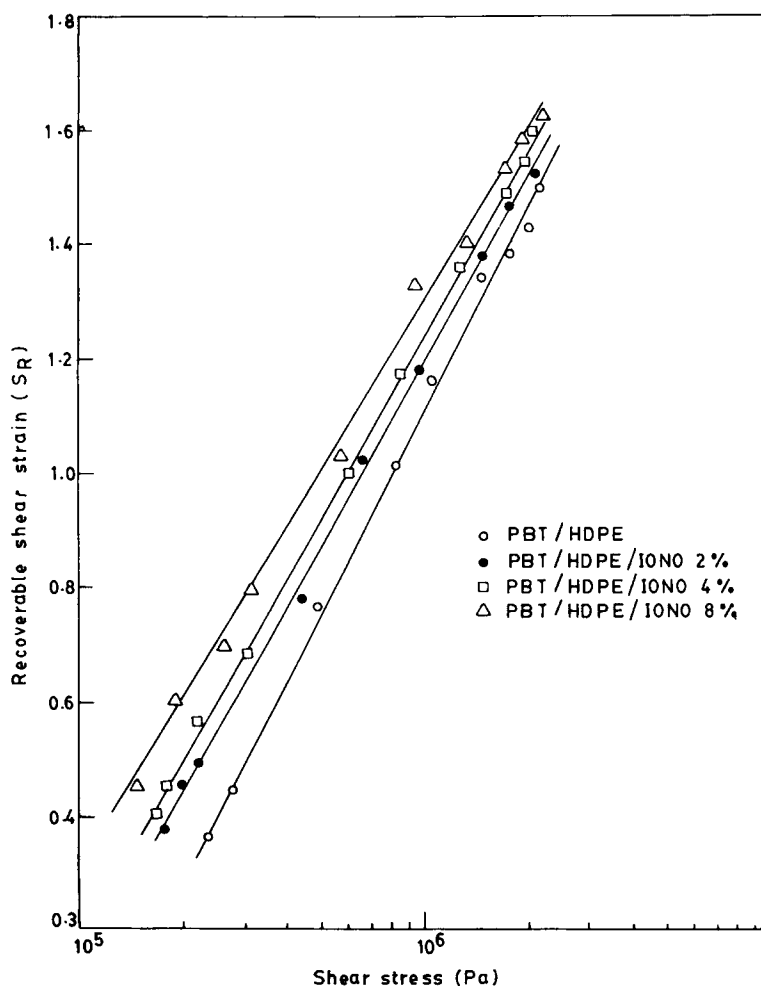


creases. As the ionomer is added, the droplet size reduces, making it less deformable; hence, there are more chances of interaction, leading to higher viscosity for the blends with ionomer. SEM studies reported in the earlier paper,<sup>9</sup> also show that in the blend without ionomer HDPE domains have a clean surface, indicating no interaction between the two phases. This may be the reason for interlayer slip giving rise to lower viscosity. As ionomer is added, a more homogeneous dispersion of one phase into another is obtained, and the interface is not so clear, indicating more interactions at the interface between the two polymers and hence less slippage at the interface in the presence of ionomer. This may be the reason for higher viscosities of the blend on addition of ionomer. Similar observations have been reported for polyolefin/polyamide blends<sup>16,18</sup> and HDPE/PS blends<sup>19</sup> on addition of a compatibilizer.

**Die Swell vs. Ionomer Content.** Die swell is defined as the extruded strand diameter divided by the diameter of the die. It is the manifestation of the normal stresses caused due to viscoelastic behavior. Die swell here is calculated using a mirror relationship<sup>10</sup> between the normal stress coefficient and viscosity. It has been observed by some authors<sup>10</sup> that a mirror relationship exists between (1) viscosity function  $\eta(\dot{\gamma})$  and stress viscosity  $\eta_0(t)$  and (2) steady normal stress coefficient at a shear rate  $\dot{\gamma}$  and normal stress coefficient  $\Theta_0$  at small rates at a time  $t$ , if  $\dot{\gamma}$  is equal to a constant  $k$  divided by the time  $t$ . These mirror relationships for viscosity and the normal stress coefficient of viscoelastic fluids can be represented as follows:

Viscosity:

$$\eta = \tau / \dot{\gamma} \quad (7)$$



**Figure 9** Plots of recoverable shear strain ( $S_R$ ) vs. shear stress for PBT/HDPE/ionomer blends.

$$\eta(\dot{\gamma} = 1/t) = \eta_0(t) \quad (8)$$

Normal stress coefficient:

$$\Theta = (\sigma_1 - \sigma_2)/\dot{\gamma}^2 \quad (9)$$

$$\Theta = (\dot{\gamma} = k/t) = \Theta_0(t) \quad (10)$$

where  $2 \leq k \leq 3$ . Plots of die swell vs. ionomer composition at different temperatures and shear rate are shown in Figure 8. The die swell increases with ionomer content, which shows that there is a consistent increase in the elastic contribution of this viscoelastic fluid with increase in ionomer content. The values of power law flow exponent  $n$  were calculated from Figure 5 and are given in Table IV. The value of  $n$  gives an idea about the viscoelasticity of the blend. The interaction of compatibilizer can be compared with small amount of crosslinking action in rubbery polymers, which leads to an increase in elasticity. Therefore, the better the action of compatibilizer in homogenizing the blend, the higher will be the pseudoplasticity and hence the lower will be the  $n$  values, as has been observed. Recoverable shear strain ( $S_R$ ) is another viscoelastic parameter defined as<sup>17</sup>

$$S_R = (\tau_{11} - \tau_{22})/2\tau_w \quad (11)$$

Figure 9 shows the  $S_R$  vs. shear stress plot for the PBT/HDPE alloy system. It is seen that  $S_R$  values are higher for blends with ionomer and the value increases as ionomer content increases, similar to normal stress behavior. The magnitude of the recoverable shear strain is a measure of the stored elastic energy of deformation in flow. Dispersion of viscoelastic droplets have an additional mode for the accumulation of the free energy for deformation, since large droplets (blends without ionomer) can be deformed to a greater extent during flow<sup>17</sup>; hence the blend would exhibit lower recoverable free energy of deformation (lower  $S_R$  value) after cessation of flow. The reverse is true for blends with ionomer.

It can be concluded that the blend system PBT/HDPE can be compared to negative deviation blends as per Utracki's<sup>20,21</sup> classification of blends from a rheological point of view. Viscosity measurements show negative deviation from the additivity line (Fig. 10). This is due to little interaction between the two phases, i.e., lack of adhesion between the segregated domains of the two polymers. As the amount of ionomer increases in the blend, deviation from additivity line decreases (Fig. 10). In other words, the blend with ionomer show lesser negative deviation, which again suggests better interfacial interactions be-

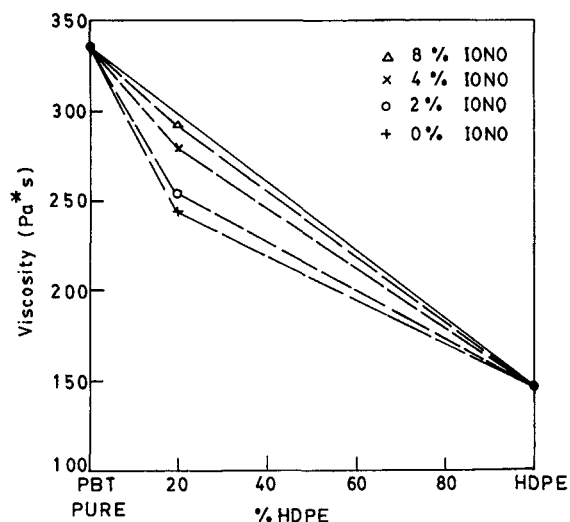


Figure 10 Viscosity vs. % HDPE for PBT/HDPE/ionomer blends at varying ionomer content and fixed shear rate.

tween the two polymers in the presence of the ionomer.

## CONCLUSION

The main conclusions drawn from this study are:

1. PBT/HDPE is an incompatible blend. Inferior performance of this blend is due to lack of adhesion at the interface between the two polymers.
2. Mechanical properties show an overall improvement on addition of ionomer as a compatibilizer to the blend of PBT and HDPE.
3. Superior performance of compatibilized blends can be attributed to improved interfacial bonding between the two polymers in the presence of compatibilizer. The results are supported by the earlier morphological studies.
4. Tensile strength values obtained for this system fit the Nolley and co-worker's model<sup>15</sup> for a binary system. A finite positive  $\sigma_{12}$  (adhesive strength between polymers 1 and 2) suggest better interfacial adhesion in the presence of ionomer.
5. Viscosity of blends with ionomer is higher than the blend without ionomer. As the ionomer content increases, viscosity increases due to greater compatibilization as explained using theory of emulsions.
6. First normal stress difference ( $\tau_{11} - \tau_{22}$ ) as

well as die-swell values are higher for the blends with ionomer.

7. Viscoelastic parameters  $S_R$  (recoverable shear strain) values are higher for the blends with ionomer, indicating an increase in viscoelasticity on addition of ionomer.

Both mechanical and rheological properties indicate formation of PBT/HDPE alloy in the presence of ionomer. In brief, it has been shown that a PE-based ionomer is an effective compatibilizer for alloying PBT and HDPE, two dissimilar polymers. Such alloys have superior properties and would be less expensive, making them commercially viable for engineering application.

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