i-PP/HDPE Blends. III. Characterization and Compatibilization at Lower i-PP Contents

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SYNOPSIS

The mechanical properties of high-density polyethylene (HDPE)-rich i-PP/HDPE blends were studied. Two grades of HDPE were investigated, one with a melt viscosity close to that of the polypropylene (PP) and the other having a much lower melt viscosity. Compatibilization of the 10/90 i-PP/HDPE blend with three copolymers (an ethylene/propylene/diene [EPDM] copolymer and two ethylene/vinylacetate [EVA] copolymers, differing in their VA content) was also investigated. Blends of PP with the low melt viscosity HDPE displayed poor mechanical properties. It was not possible to improve these properties sufficiently with EPDM or EVA. In the case where viscosity matching was achieved between PP and HDPE, addition of i-PP (up to 30%) to HDPE resulted in a large drop in the impact strength of the blends, compared to that of the neat HDPE. A large drop (>50%) was also observed in the ultimate tensile elongation. However, the flexural modulus, yield stress, and ultimate tensile strength all increased with the introduction of i-PP into HDPE. Modification of these blends with an EPDM resulted in the return of all properties to values very close to those of the neat HDPE. The ultimate tensile elongation of the EPDM-modified i-PP/HDPE blend even exceeded that of the virgin HDPE. It was also found that although EVAs can be used to compatibilize these blends these additives were not as effective as was the EPDM. © 1996 John Wiley & Sons, Inc.

INTRODUCTION

In the first two parts of this series,[1,2] attention was focused on the characterization and compatibilization of polypropylene (PP)-rich PP/high-density polyethylene (HDPE) blends. Addition of HDPE to PP resulted in a material with poor ultimate tensile properties.[1] Compatibilization with the ethylene/propylene/diene copolymer or with the ethylene/vinyl acetate copolymer improved the Charpy impact strength and the tensile properties.[2]

However, a significant portion of the HDPE on the market finds its way into blow-molding applications for articles like milk jugs, water jugs, and detergent bottles. A problem arises when attempts are made to recycle these parts. Very often, the spout or the closure on these bottles is produced from injection-molding-grade PP. Thus, the HDPE waste stream from blow-molding applications will likely have some contamination from PP.[3,4] Generally, the presence of excessive amounts of PP will lead to poor mechanical properties of the recycled HDPE, and, thus, it becomes difficult to make durable articles from this recycled material.

For this reason, it is important to investigate HDPE-rich i-PP/HDPE blends. If the incompatibility of PP and HDPE can be overcome by the introduction of a suitable compatibilizer, then a way is opened for the manufacture of parts with good mechanical properties. We have, therefore, undertaken to characterize blends of virgin i-PP and HDPE resins and to modify these blends with an ethylene/propylene/diene copolymer (EPDM) and an ethylene/vinyl acetate copolymer (EVA). We report the results herein.

EXPERIMENTAL

Materials

Two HDPE resins were supplied by Novacor Chemicals Ltd. Injection-molding-grade isotactic polypropylene (i-PP) was supplied by Montell Canada Inc. The ethylene/propylene/diene copolymer (EPDM) was supplied by Bayer Rubber Inc. and had an ethylene content of $\sim$ 80%, as determined by high-field NMR analysis. Two ethylene/vinyl acetate copolymers (EVA) were supplied by AT Plastics. EVA-28 has a vinyl acetate (VA) content of 28%, and EVA-33 has a VA content of 33%. Molecular weight data,[5] densities, and melt-flow properties are outlined in Table I.

Sample Preparation

Blending

All materials were tumble-blended prior to melt-blending on a Buss laboratory kneader, Type PR 46. This consisted of a kneading screw and an extruding screw at right angles to each other. The barrel temperature varied from 145°C at the feed port, up to 190°C at the last zone, and to 180°C at the die. The feed hopper auger speed setting was 6, the kneader screw speed was set to 12, and the extruder screw speed was set between 7 and 9. The extruded strands were frozen in cold water, air-dried, and pelletized. The compositions of the binary and ternary blends studied are given in Table II. A 10/90 i-PP/HDPE blend was chosen for the compatibilization study with EPDM and EVA.

Injection Molding

Impact bars (6.2 × 12.7 × 76 mm^3) and dumbbell tensile specimens (ASTM D638, Type I) were in-

Table II Compositions of the Blends Studied

Wt % i-PP	Wt % HDPE-5	Wt % HDPE-65	Wt % Copolymer
0	100	—	—
5	95	—	—
10	90	—	—
20	80	—	—
30	70	—	—
0	—	100	—
5	—	95	—
10	—	90	—
20	—	80	—
30	—	70	—
9.5	85.5	—	5.0
9.5	—	85.5	5.0

jection-molded on a Battenfeld BSKM 50 ton press. The barrel temperature ranged from 190 to 210°C, the injection pressure was 3.22 MPa, the mold temperature was 40°C, and the injection time was 1.2 s. The impact specimens were notched (30°) to a depth of 2.0 mm the day that they were molded. Thin-walled containers were injection-molded on an Engel ES-125 injection molder containing a reciprocating screw and fitted with a thin-wall container mold (635 micron thickness). The barrel temperature varied from 230°C at the feed port to 270°C at the nozzle. The average injection velocity was 14.7 cm/min, with an injection pressure of 12.4 MPa. The mold temperature was set at 30°C. All samples were aged in air at room temperature for 1 week prior to testing.

Annealing

Annealing was performed in an hot air oven set at 75°C for 1 week. Impact specimens were notched before annealing.

Table I Properties and Molecular Characteristics of Polymers Employed in This Investigation

Resin	M_n	M_w	M_z	MFI (deg/min)	ρ (g/cm^3)
PP	22,000	166,000	509,000	20[a]	0.91
HDPE-5	16,000	72,600	256,000	5[b]	0.96
HDPE-65	9,200	36,300	98,000	65[b]	0.959
EPDM	65,700	165,000	379,000	50[c]	0.87
EVA-28	19,700	76,900	219,000	3[b]	0.952
EVA-33	12,200	53,400	167,000	43[b]	0.952

[a] 230°C, 2.16 kg.
[b] 190°C, 2.16 kg.
[c] Mooney viscosity (D6146) ML 1+8 (125°C).

Mechanical Testing

Impact testing was performed on an instrumented Charpy impact tester designed in our laboratory.[6] Results reported in this study were averages of 10 specimens. Impact strengths were calculated from the kinetic energy loss of the hammer during the impact event. Tensile testing was performed on an Instron tensile tester at a crosshead speed of 25.4 cm/min and an initial jaw separation of 10 cm. Results reported herein were averages of seven specimens. The gate puncture test was developed by Shell Canada Ltd. to determine the gate strength of injection-molded thin-walled containers.[7] The gate puncture strengths reported in this study were averages of 10 specimens.

Environmental Stress Crack Resistance

The environmental stress crack resistance (ESCR) was determined on an instrument designed in our laboratory according to ASTM D 2552—with some modifications. It comprised a 35°C constant temperature bath filled with a 15 wt % solution of Igepal (^{TM}) CO-630 in water. Specimens ($8.5 \times 1.27 \times 0.16$ cm^3) were prepared by compression molding at 200°C and controlled slow cooling (30°C/h) in the press. Edge notching (0.13 ± 0.02 cm) was performed on both edges with a jig fitted with a new razor blade. The initial applied stress was 56 kg/cm^2. Eight specimens were run in each batch of testing. The failure time was detected by microswitches and recorded with a computer. The F_{50} failure time for the eight samples tested per run was calculated in accordance with ASTM D 2552, Section 10.

Dynamic Mechanical Analysis

Melt-blended pellets were introduced between the 25 mm-diameter plates of a Rheometrics 605 dynamic mechanical spectrometer and compression-molded into a disc of 2 mm thickness at 190°C. The environment was continually purged with nitrogen gas to minimize thermo-oxidative degradation. Dynamic mechanical properties were obtained at a strain of 30%, and the frequency was varied between 0.1 and 100 rad/s (equivalent to 0.625 to 625 s^{-1}). The strain of 30% was chosen because the blends exhibited linear behavior at this strain.

RESULTS AND DISCUSSION

Binary Blends of *i*-PP and HDPE

It is well known that to obtain a good dispersion of polymer A in polymer B the melt viscosities of the

two materials should be similar. We must also bear in mind that postconsumer resins will have varying compositions, both in terms of polymeric constituents as well as polymer grades. In light of this, we investigated the addition of *i*-PP to two HDPE grades: one with a low MFI (HDPE-5) and one with a higher MFI (HDPE-65).

The variation of impact strength with PP content for *i*-PP/HDPE-5 blends is shown in Figure 1. Addition of PP to HDPE-5 resulted in a significant increase ($\sim 70\%$ at 30% *i*-PP content) in the flexural modulus and a drastic reduction ($\sim 70\%$ at 30% *i*-PP content) in the impact strength. The effects of PP content on tensile yield and ultimate tensile properties are shown in Figures 2 and 3, respectively. The yield stress increased slightly with addition of PP, while the yield strain decreased slightly. A greater effect was seen in the ultimate tensile properties. At 30% PP content, the ultimate tensile strength (UTS) increased by about 50%, whereas the elongation at break decreased by 50%. All samples exhibited yield as well as necking. None of the samples actually experienced cold-drawing at the deformation rate employed. However, as the PP content was increased, the change in extension between the yield and failure decreased, so that at 30% PP, the sample was seen to fail immediately after
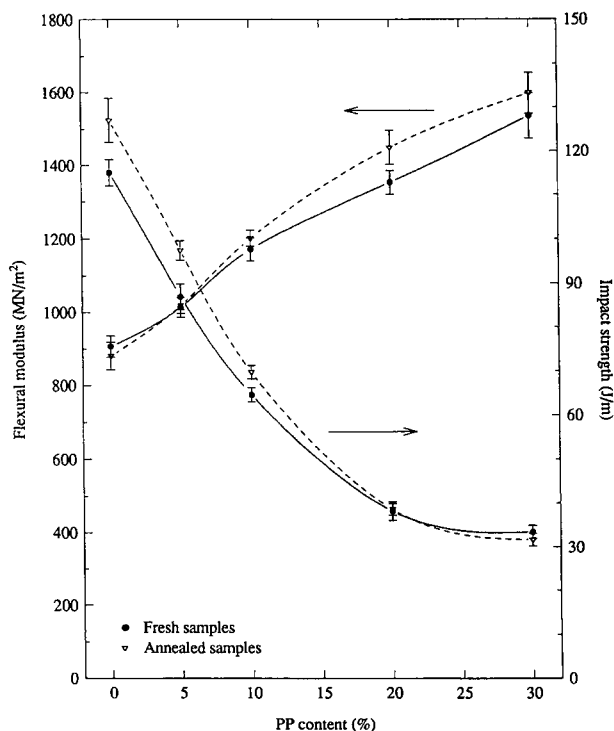
Figure 1 Effect of *i*-PP content on the impact properties of *i*-PP/HDPE-5 blends.
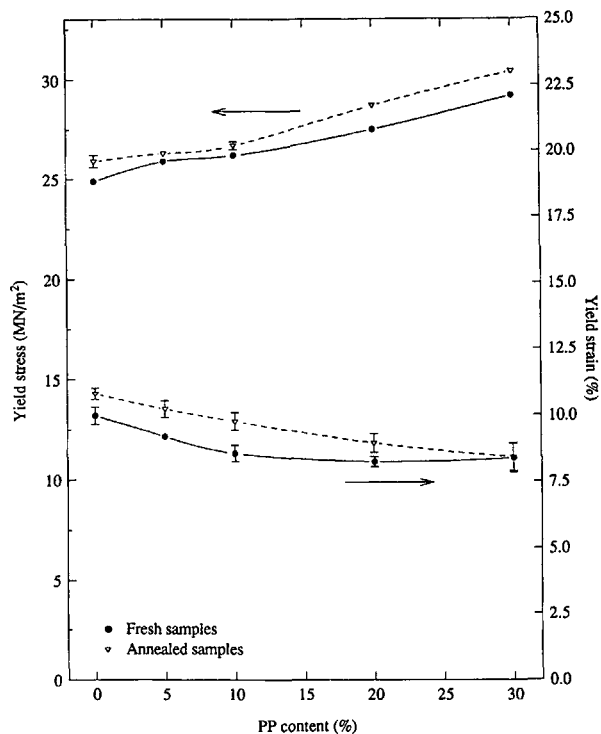
Figure 2 Effect of i-PP content on the tensile yield properties of i-PP/HDPE-5 blends.

the first sign of necking was observed. In general, the properties of the blends were found to fall in between those of the neat homopolymers, as shown by the data given in Table III and in Figures 1–3.

These results are consistent with earlier results published by several authors. Deanin and Sansone,[8] Lovinger and Williams,[9] and Bartlett et al.[10] all reported that the addition of PP to HDPE resulted in a decrease in impact strength and in elongation at break.

The behavior of the annealed blends is more complex than that observed in the PP-rich i-PP/HDPE blends. However, in general, it may be concluded that annealing increased the impact and tensile properties slightly, although there were some minor deviations with variation in blend compositions.

Addition of 10% PP to HDPE-5 resulted in a slight decrease in the environmental stress crack resistance of the material (from 14.0 h for HDPE to 13.2 h for the 10/90 i-PP/HDPE blend). There are a number of factors which are known to effect the ESCR behavior of polyethylene. Isaksen et al.[11] showed that ESCR improved with increasing molecular weight (as measured by the melt-flow index) and with a narrower molecular weight distribution, as shown by addition of a low molecular weight hy-

drocarbon to PE. The degree of crystallinity also affects the ESCR. In general, increased crystallinity resulted in improved ESCR (in the constant stress tests), although large crystalline structures appeared to aggravate the problem. In the bent-strip test, in which the strain is constant (initially), the opposite result was obtained.

Li et al.[12] investigated the effect of the addition of 10% PP to HDPE on the ESCR of the HDPE. They found that the addition of PP increased the failure time by about 25%. The flexural strength remained unchanged and the impact strength was slightly reduced.

The fact that we observed a slight decrease in the ESCR failure time should not be seen as a contradiction of the results of Li et al.,[12] since they used a bent-strip test. As was shown by Isaksen et al.,[11] different ESCR test procedures can result in the same materials being ranked differently. Further, Li et al. compression-molded their specimens at 175°C, followed by quench-cooling in a cold press. This differs from our experiments, in which the samples were slow-cooled in the press. What is clear from our results is that addition of PP to HDPE did not result in a gross deterioration of the ESCR behavior.

In the case of blends of HDPE-65 and i-PP, different results were observed. Only a slight increase
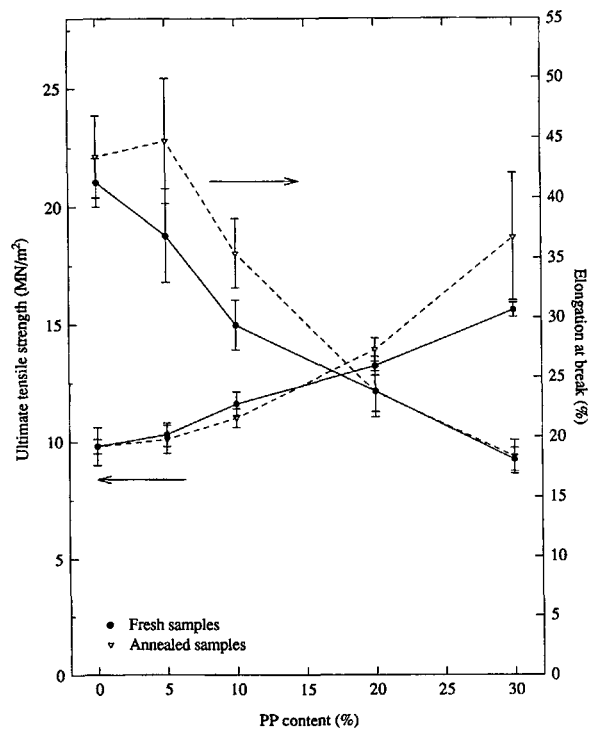
Figure 3 Effect of i-PP content on the ultimate tensile properties of i-PP/HDPE-5 blends.

Table III   Impact and Tensile Properties of the Neat Homopolymers

| Property	*i*-PP	HDPE-5	HDPE-65
Flexural modulus (MN/m^2)	1864 ± 140	907 ± 29	959 ± 76
Impact strength (J/m)	18.7 ± 1.1	115 ± 3	28.9 ± 1.8
Yield stress (MN/m^2)	35.4 ± 0.5	24.9 ± 0.1	26.6 ± 0.2
Yield strain (%)	7.5 ± 0.5	10.0 ± 0.3	8.1 ± 1.0
Ultimate tensile strength (MN/m^2)	29.9 ± 1.0	9.8 ± 0.3	17.8 ± 3.2
Elongation at break (%)	14.3 ± 1.6	41.3 ± 2.0	23.2 ± 2.1
ESCR F_{50} (h)	—	14.0	—

in the flexural modulus with increasing PP content (Fig. 4) was observed. The impact strength was greatly reduced (75%) upon addition of PP to HDPE-65. The tensile properties changed with PP content as shown in Figures 5 and 6. Again, the yield properties do not change greatly with PP content. However, for the fresh samples, we noted that addition of 30% PP to HDPE-65 resulted in a material that failed before yielding under a tensile load. As far as the ultimate tensile properties are concerned, we can see that a stepwise change occurred in both the UTS and the elongation at break. Addition of 5% PP to HDPE-65 increased the UTS by 45%, after which this property remained unchanged with respect to PP content. The reverse is true for the

ultimate elongation. A small amount of PP reduced the elongation at break by 57%. Addition of more PP had no further effect. The effect of PP content on the gate puncture strength of these blends is shown in Table IV. It is clear that addition of PP to HDPE-65 resulted in a steady decline in the gate puncture strength (15.0 kg$_f$ for neat HDPE-65 to 3.6 kg$_f$ for the 30/70 *i*-PP/HDPE-65 blend). The environmental stress crack resistance of these blends was not determined due to the brittleness of the materials. Notching resulted in cracks of random size and shape.
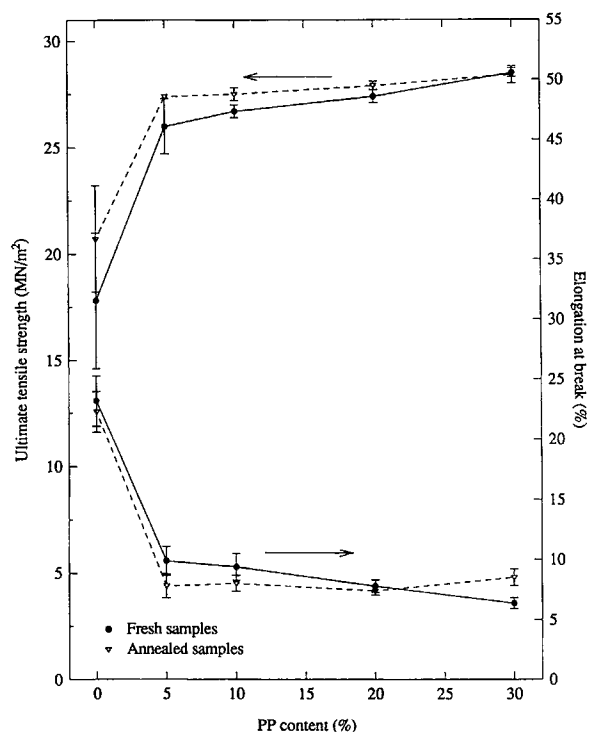
Once again, annealing of these blends is not a straightforward phenomenon. The most noticeable effect of annealing can be seen in the yield proper-
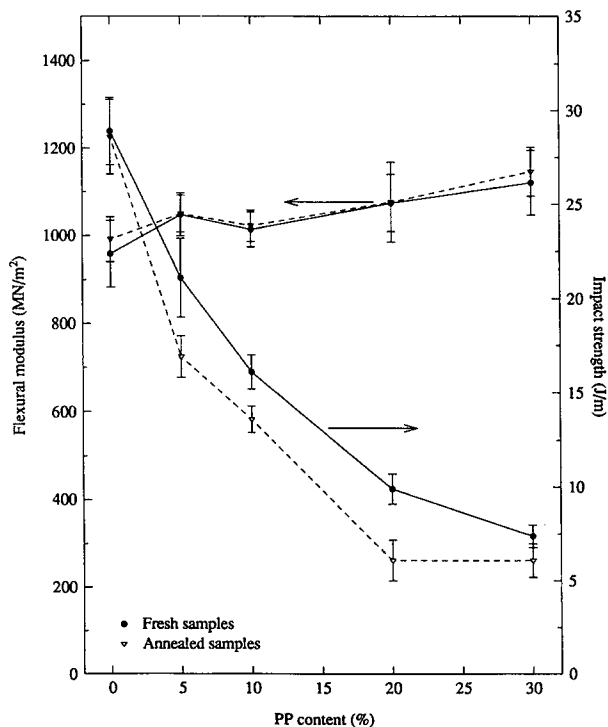
Figure 4   Effect of *i*-PP content on the impact properties of *i*-PP/HDPE-65 blends.
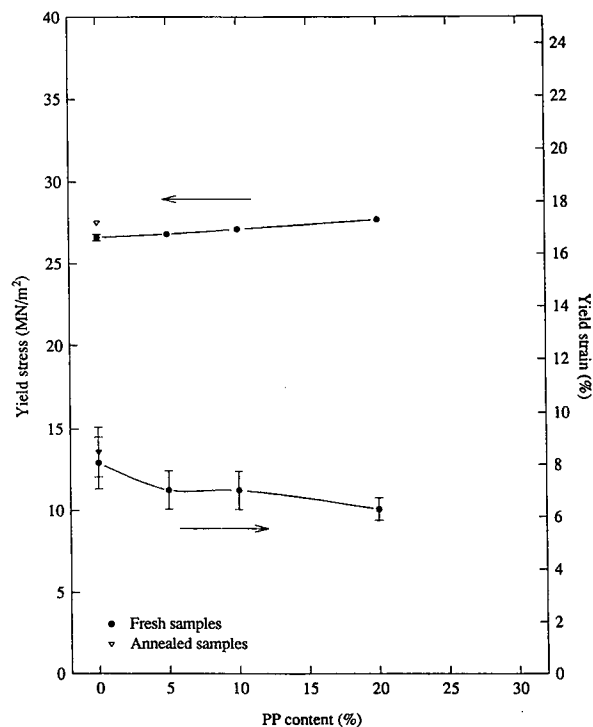
Figure 5   Effect of *i*-PP content on the tensile yield properties of *i*-PP/HDPE-65 blends.

Figure 6 Effect of i-PP content on the ultimate tensile properties of i-PP/HDPE-65 blends.

ties. Whereas samples containing between 5 and 20% PP displayed a yield point in the fresh samples, annealing resulted in a material which failed before yielding. Only the pure HDPE-65 still displayed a yield point after annealing. Annealing of the thin-walled containers resulted in large losses in gate puncture strength (Table IV).

Figure 7 shows the melt-flow behavior of i-PP, HDPE-5, HDPE-65, and i-PP/HDPE blends at 190°C. The equivalent shear rates for the frequency range studied is 0.625 to 625 s^{-1}. It is estimated that the shear rate at the gate in the injection molder was of the order of 10^2 s^{-1} (6.3 rad/s), although the

melt had the opportunity to relax in the mold before solidification occurred. At these moderate shear rates, there exists a good viscosity match between i-PP and HDPE-5, and one would expect a good dispersion of the PP phase in the HDPE-5 matrix. However, in the case of i-PP and HDPE-65, it is clear that a large discrepancy exists between the melt viscosity of the two materials at moderate shear rates. Thus, one would expect the PP to be very poorly dispersed in the HDPE-65 matrix. This accounts for the observation that i-PP has a more adverse effect on the tensile properties of the i-PP/HDPE-65 blends than on the i-PP/HDPE-5 blends.

Compatibilization of PP/HDPE Blends

Compatibilization of the 10/90 i-PP/HDPE-5 blends was attempted with a high ethylene content EPDM, EVA-28, and EVA-33. Ternary blends were prepared containing 1, 3, and 5% of these materials. In general, properties varied monotonically with increasing compatibilizer. Hence, the following discussion will focus on the 10/90 i-PP/HDPE-5 blend containing 5% compatibilizer. The results for the impact and tensile properties are given in Table V. Focusing first on the impact properties, we see that whereas addition of 10% i-PP to HDPE-5 resulted in an increase in the flexural modulus, addition of EPDM or EVAs brought this property back to the neat HDPE-5 values. EPDM was more effective at neutralizing the stiffness imparted by the PP than were the EVAs, although these latter materials were also quite effective at reducing the flexural modulus. In the case of the impact strength, we can see that EPDM was very effective at improving the impact strength of the i-PP/HDPE-5 blend. The 70% drop in this property resulting from addition of PP is recovered with addition of 5% EPDM, so that the ternary blend has an impact strength only slightly ($\sim$ 8%) below that of the neat HDPE-5. Both EVA-

Table IV Gate Puncture Strength of i-PP/HDPE-65 Blends

Blend Composition i-PP/HDPE-65/Copolymer	Gate Puncture Strength (kg$_f$) (Fresh Samples)	Gate Puncture Strength (kg$_f$) (Annealed Samples)
0/100/0	15.0 ± 1.3	13.0 ± 2.1
5/95/0	14.0 ± 2.3	8.3 ± 4.6
10/90/0	12.9 ± 2.3	8.7 ± 3.4
20/80/0	7.3 ± 4	3.3 ± 2.6
30/70/0	3.6 ± 1.2	2.2 ± 0.7
9.5/85.5/5.0 (EPDM)	11.8 ± 2.5	9.6 ± 3.2
9.5/85.5/5.0 (EVA-28)	12.9 ± 2.9	10.2 ± 3.8
9.5/85.5/5.0 (EVA-33)	9.2 ± 1.7	9.5 ± 4.6
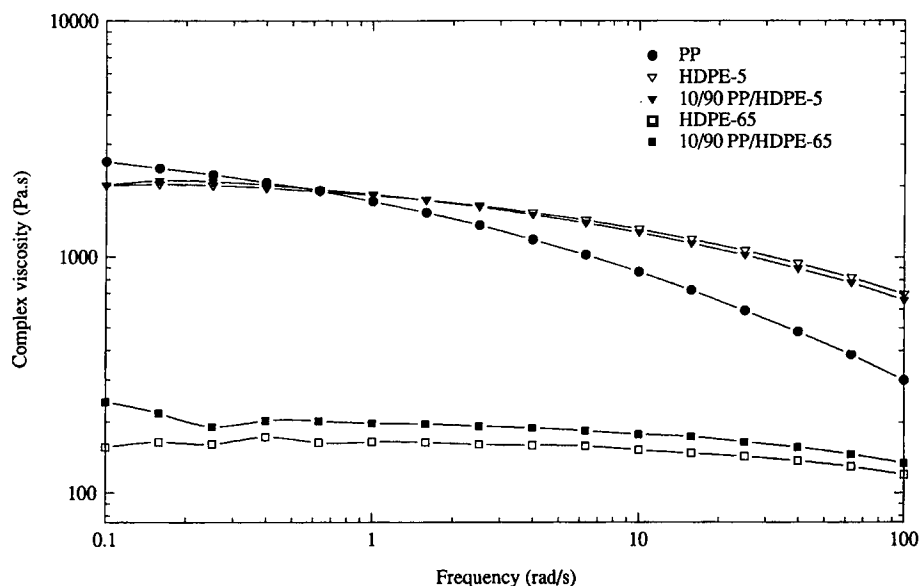
Figure 7   Flow behavior of neat polyolefin resins and of PP/HDPE blends.

28 and EVA-33 also improved the impact strength of the 90/10 HDPE-5/PP blend. However, they were still ~ 30% below the neat HDPE-5 level.

The tensile yield properties were only slightly affected by addition of copolymer. In essence, all three materials (EPDM, EVA-28, and EVA-33) were able to return the tensile yield properties back to neat HDPE levels.

Addition of 10% *i*-PP to HDPE-5 resulted in an increase in the UTS, as mentioned above. Subsequent addition of the copolymer reduced this property back to near neat HDPE levels. EVA-28 only slightly reduced the UTS, and EVA-33 effected the largest reduction in this property. More important for the ultimate tensile properties, however, is the ultimate elongation, where addition of 10% of PP caused a 50% drop in this property. Both EVAs brought the elongation at break back up to the neat HDPE-5 levels, within experimental error. The

EPDM, on the other hand, was more impressive, where the ultimate elongation was enhanced to a level ~ 30% higher than that of the neat HDPE.

The effect of the addition of a copolymer to the 10/90 *i*-PP/HDPE-5 blend on the ESCR performance is shown in Table V. Only a slight decrease in this property was observed for all three copolymers. Modification with EPDM resulted in the largest decrease, from 13.2 h for the 10/90 *i*-PP/HDPE-5 blend to 10.3 h for the EPDM-modified system.

It has been known for some time that both EVA and EPDM can improve the ESCR behavior of HDPE. Spenadel[13] investigated the effect of various elastomeric materials on the ESCR properties of low- and high-density PE. He found that butyl rubber and polyisobutylene were very effective at improving the stress-crack resistance of both HDPE and LDPE. Some EP rubbers also improved this property, but to a lesser extent.

Table V   Impact and Tensile Properties of the Compatibilized Blends of *i*-PP and HDPE-5

Property	10/90 *i*-PP/HDPE-5	9.5/85.5/5.0 *i*-PP/HDPE-5/ EPDM	9.5/85.5/5.0 *i*-PP/HDPE-5/ EVA-28	9.5/85.5/5.0 *i*-PP/HDPE-5/ EVA-33
Flexural modulus (MN/m^2)	1173 ± 31	898 ± 33	952 ± 27	970 ± 29
Impact strength (J/m)	64.6 ± 1.6	106 ± 6	84.3 ± 3.5	78.6 ± 1.9
Yield stress (MN/m^2)	26.2 ± 0.1	24.1 ± 0.2	23.5 ± 0.1	23.5 ± 0.1
Yield strain (%)	8.58 ± 0.31	9.79 ± 0.21	10.2 ± 0.23	9.50 ± 0.32
UTS (MN/m^2)	11.6 ± 0.5	10.3 ± 1.0	10.7 ± 0.8	9.1 ± 0.5
Elongation at break (%)	29.4 ± 2.1	54.7 ± 2.8	41.8 ± 4.9	37.5 ± 5.0
ESCR F$_{50}$ (h)	13.2	10.3	11.5	11.2

Fang et al.[14] studied the modification effect of several elastomers on HDPE. These authors observed that EVA improved the ESCR performance of the HDPE dramatically. They postulated that the EVA was able to connect crystalline regions with other crystalline regions as well as with amorphous regions, thereby strengthening the amorphous/crystalline interface. Li et al.,[12] who also reported an ESCR improvement upon addition of EVA to HDPE, conjectured that this enhancement came about because the longer side chains of the EVA prevents it from being incorporated into the HDPE crystallites. This was believed to result in more intercrystalline links, which are thought to improve the ESCR performance of the HDPE. A number of patents[15-17] have also been published outlining the ability of EVA to improve the ESCR behavior of HDPE. It would seem that our results indicate that the presence of PP prevents the EVA from improving the ESCR of the HDPE.

It is clear, therefore, that based on the results of the blends of virgin resins of HDPE-5 and PP, the presence of 10% i-PP in HDPE-5 is undesirable. However, this can be rectified with addition of 5% EPDM to yield a material with similar impact properties and improved tensile properties, compared to the neat HDPE-5. EVA-28 and EVA-33 can also be used to compatibilize these i-PP/HDPE blends, but with a slight drop in impact strength. This may or may not be important, depending on the application.

The effect of modification of the 10/90 i-PP/HDPE-65 blend is shown in Table VI. Addition of EPDM, EVA-28, or EVA-33 to the 10/90 i-PP/HDPE-65 blend had only a slight effect on the flexural modulus. The ternary blends possessed similar rigidity compared to that of the neat HDPE-65. These copolymers also had little effect on the impact strength, and, hence, the impact strength of the ternary blends were still very much inferior to that of the neat HDPE-65.

Ternary blends of i-PP and HDPE-65 containing 5% EPDM did not exhibit any yield. EVA-28 and EVA-33 reduced the yield stress of the blend slightly and left the yield strain unchanged compared to the 10/90 i-PP/HDPE-65 blend. Thus, these ternary blends have a slightly reduced yield stress and a greatly reduced yield strain compared to the neat HDPE-65.

All three copolymers reduced the UTS slightly, to values closer to that of the neat HDPE-65. However, they were completely inefficient in improving the ultimate elongation. In fact, EPDM further reduced the elongation at break. EVA-33 performed the best, but it only gave a 14% improvement, which is still far from the 150% improvement required to return this property to the neat HDPE-65 level.

Very little work has been reported on the compatibilization of HDPE-rich PP/HDPE blends. Bartlett et al.[10] employed an ethylene–propylene elastomeric additive (semicrystalline) to modify the PP/HDPE blends. They found that this EP copolymer (at a 20% loading, at all PP/HDPE compositions) improved the impact strength and the elongation at break, but reduced the tensile strength and the tensile modulus of the injection-molded samples. Qualitatively similar results were obtained for compression-molded specimens. No indication was given as to the manner in which this EP rubber affected these PP/HDPE blends.

It has been suggested that in the case of a well-blended ternary blend that EP rubbers reside at the PP/HDPE interface, thereby reducing the interfacial tension and improving the mechanical properties of the material. Stehling et al.[18] who investigated the PP-rich PP/HDPE blends, found that the EPDM and HDPE formed either a core–shell system, with HDPE as the core, or an interpenetrating network.

There are a number of possible morphologies that can be expected in our ternary systems. The first is

Table VI   Impact and Tensile Properties of the Compatibilized Blends of i-PP and HDPE-65

Property	10/90 i-PP/HDPE-65	9.5/85.5/5.0 i-PP/HDPE-65/ EPDM	9.5/85.5/5.0 i-PP/HDPE-65/ EVA-28	9.5/85.5/5.0 i-PP/HDPE-65/ EVA-33
Flexural modulus (MN/m^2)	1014 ± 40	905 ± 40	930 ± 45	967 ± 60
Impact strength (J/m)	16.1 ± 0.9	19.3 ± 1.1	18.1 ± 0.7	20.3 ± 1.3
Yield stress (MN/m^2)	27.1 ± 0.1	—	25.0 ± 0.1	24.6 ± 0.1
Yield strain (%)	7.02 ± 0.73	—	7.03 ± 0.97	7.17 ± 0.54
UTS (MN/m^2)	26.7 ± 0.3	23.0 ± 0.2	24.7 ± 0.5	23.8 ± 0.4
Elongation at break (%)	9.4 ± 1.1	4.3 ± 0.2	9.1 ± 1.8	10.7 ± 1.4

that both the *i*-PP and the copolymer will disperse separately in the HDPE phase. Another possibility is that the *i*-PP and the copolymer will form some joint structure, which could be either a core–shell structure, an interpenetrating-type structure, or a less regular structure such as a "joined droplet" arrangement. The structure that forms in a given system will depend on the relative viscosity of the components, on the intensity of the mixing process, and on whether the copolymer has a greater affinity for the HDPE or the *i*-PP.

It would be expected that all the copolymers studied in this investigation will have a greater affinity for the HDPE than for the *i*-PP, since the copolymers have high ethylene contents. This would rule out the possibility of a core–shell arrangement with the copolymer as the core and the *i*-PP as the shell. It is also unlikely that the copolymers and the *i*-PP would form an interpenetrating network structure, due to the affinity of the copolymers for the HDPE phase. Thus, we would expect either a core–shell arrangement with PP as the core and the copolymer as the shell or a separate dispersion of PP and the copolymers.

Figure 8 outlines the melt-flow characteristics of the various homopolymers and copolymers. The EPDM has the highest complex viscosity of the neat materials. The *i*-PP, HDPE-5, and EVA-28 are an order of magnitude lower in viscosity, and the HDPE-65 and EVA-33 are another order of magnitude lower. This would suggest that EPDM would be poorly dispersed in the *i*-PP/HDPE blends, due to its high viscosity. EVA-28 should be well dispersed

in the *i*-PP/HDPE-5 blend, and the EVA-33 should disperse well in the *i*-PP/HDPE-65 blend and in the *i*-PP/HDPE-5 blend.

As far as the HDPE-5 blends are concerned, it has been shown that the best impact strength improvement could be achieved with the EPDM. This is probably a result of the elastomeric character of the EPDM imparting a good impact strength enhancement to the HDPE-5. It seems possible that the EPDM and *i*-PP form a core–shell morphology, with EPDM as the shell. EPDM was also the most effective at improving the elongation at break of the 10/90 *i*-PP/HDPE blend. However, EVA-28 performed the best in terms of improving the yield strain and the ultimate tensile strength.

In the case of the HDPE-65 blends, the EVAs were able to improve the properties of the 10/90 *i*-PP/HDPE blend better than was the EPDM. The only exception is the impact strength, in which case the EPDM performed better than did the EVA-28, but still worse than the EVA-33. Clearly, the viscosity of the EPDM is too high compared to the viscosity of the 10/90 *i*-PP/HDPE blend, making it difficult for the EPDM to be properly dispersed and impart a significant impact strength enhancement.

CONCLUSIONS

Blending a small amount of *i*-PP with HDPE resulted in a material with reduced impact strength and tensile elongation at break. This points to the incompatibility of these two materials.
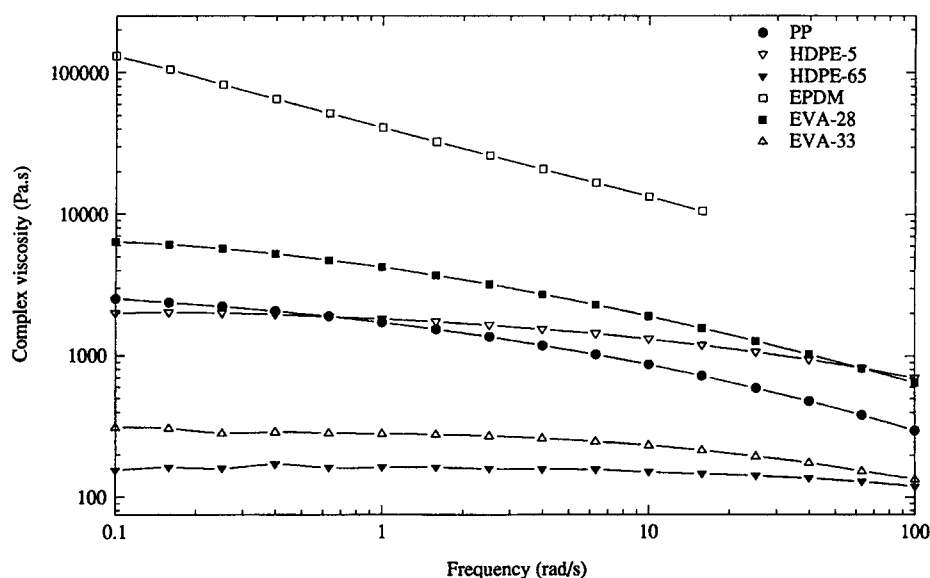
Figure 8   Flow behavior of *i*-PP, HDPE-5, HDPE-65, EPDM, EVA-28, and EVA-33.

The mechanical properties of blends of PP and HDPE in which the two homopolymers have closely matching melt-flow viscosities can be modified with EPDM or EVA. It was found that addition of 5% EPDM to a 10/90 i-PP/HDPE blend yielded a material with mechanical properties similar to that of the neat HDPE. EVA was also found to be useful in returning the mechanical properties back to the neat HDPE levels. However, in the case of impact strength, they were not as effective as was EPDM.

When the viscosities of the two polyolefin homopolymers are considerably different, these EPDM and EVAs are inefficient compatibilizers for the 10/90 i-PP/HDPE blend. Further work is continuing in this regard to study the effect of melt-viscosities of EP copolymers on compatibilization of PP/HDPE blends.

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