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Effects of Elastomers and Coupling Agent on Impact Performance of Wood Flour-Filled Polypropylene

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Abstract

The effects of elastomers, coupling agent, and their combinations on the tensile and impact performance of wood flour-tilled polypropylene were studied. Two different ethylene/propylene/diene (EPDM) terpolymers and one maleated styrene-ethylene/butylene-styrene (SEBS) triblock copolymer were used as impact modifiers. The coupling agent was a maleated polypropylene. Scanning electron microscopy was used to investigate the morphology of the composites and dynamic mechanical thermal analysis was also used to investigate the interactions of the component materials. The scanning electron microscopy study confirmed improved adhesion between wood particles and the polypropylene matrix when maleated polypropylene and maleated elastomers were added to the composite systems. The dynamic mechanical thermal analysis results of several polypropylene-elastomer blend: showed an increase in the amplitude of the tan δ peak when wood flour was added, suggesting that the wood flour is encapsulated by the elastomer. Notched and unnotched Izod impact tests, as well as instrumented drop weight impact (IDWl) tests, were used to investigate the impact performance. Tensile modulus of polypropylene was greatly increased by the addition of wood flour but, because of poor compatibility, a reduction in tensile strength was found. The addition of wood flour to polypropylene resulted in little change in notched Izod impact energy a large decrease in unnotched Izod impact energy, and a very large increase in IDWI energy (al-

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though initial damage occurred very early in the IDWI test). Maleated polypropylene increased the tensile strength of the composites and resulted in higher maximum loads but smaller deflections to failure during IDWl testing. The addition of elastomers reduced tensile modulus and reduced tensile strength except for the blends containing maleated SEBS, which demonstrated some ability to act as a coupling agent. The use of elastomers increased notched and unnotched Izod impact energies by as much as 107 percent and 94 percent, respectively with the compatibilized elastomers having the greatest increases. Addition of maleated EPDM and maleated SEBS to the composite resulted in improvements in IDWI energy but a greater proportion of the energy absorbed occurred after the maximum load was reached.

Introduction

One of the most common cellulosic materials added to thermoplastics is wood flour. Wood flour offers the advantages of being an inexpensive, easily processed filler that is commercially available in a number of different grades. Composites made from thermoplastics and wood flour have increased stiffness and heat deflection temperature when compared to unfilled polymer and are lighter weight than mineral fillers. However, as with many other fillers, filling thermoplastics with wood flour results in a reduction in toughness (5, 15, 21, 31). Creation of stress concentrations at fiber ends, poor interracial adhesion, and decreased polymer mobility can result in embrittlement of the polymer matrix when the filler is added.

The toughness of filled polymers can be improved in several ways:

- increase the matrix toughness;
- optimize the interface (or interphase) between the filler and the matrix through the use of coupling agents, compatibilizer, and sizes; or
- optimize the filler-related properties such as filler content, particle size, and dispersion (31).

This investigation focused on the first two approaches.

The most commonly used and most effective impact modifiers for polypropylene are ethylene/propylene copolymers or ethylene/propylene/diene terpolymer (EPDM) (3, 12, 14). Elastomer domain size distributions influence impact performance and are affected by elastomer-polymer viscosity ratio, compatibility of the phases, and missing intensity (4). Generally the elastomer particles act as stress concentrators which initiate the local yielding of the matrix and avoid brittle catastrophiuc failure of the material (31). Uniform distribution and small domain sizes (<1 μm) have been showm to improve the impact properties of polypropylene (13).

The mechanism of toughening is more complicated in composite systems than in single phase systems because of stress concentrations, incompatibility issues, and heterogeneity (10, 17, 26, 28–31). At low levels of addition, elastomers can either exist as a separate phase in the polypropylene matrix or partially or completely encapsulate the filler (17, 26, 29, 30).

Unlike unfilled polypropylene, many different types of elastomers have been used with filled polymers (10, 17, 26, 28–30). For instance, Stamhuis used styrene/butadien/styene rubber, styrene-ethylene/butylene-styrene (SEBS), acrylonitrile/butadiene rubber, ethylene vinylacetate, and EPDM as impact modifiers in talc filled polypropylene composites (29, 30). Impact properties were improved with all additives but the best results were obtained when the additives partially encapsulated the fillers.

Long and Shanks also studied filled polypropylene systems and showed that maleated SEBS (SEBS-MA) and maleated ethylene/propylene copolymers act not only as a toughening agent but also as compatibilizers between filler particles (talc, $CaCO_3$, nylon- 12) and the polypropylene matrix (17). The maleated elastomers encapsulated the filler particles resulting in improved impact properties.

Although considerable work on compatibilization has been performed in recent years (5, 7, 9, 11, 18, 19, 27) much less work has been performed on the use of impact modifiers in thermoplastics containing wood-based fillers and reinforcements. DaIvåg et al. (5), Park and Balatinecz. (25) and Oksman (22) are some of the few researchers that have investigated the use of elastomeric additives in polyethylene and polypropylene filled with wood or pulp fibers.

Dalväg et al. investigated several elastomeric additives including ethylene/vinyl acetate, ethylene/propylene thermoplastic elastomer, acrylonitrile/butadiene, ionomer modified polyethylene, and polyisobutylene (5). Adding elastomer; lowered moduli, and for polypropylene composites, polyisobutylene was the most effective in increasing unnotched Charpy impact strength.

Park and Balatinecz investigated the use of high-impact polypropylene and EPDM in composites of polypropylene and thermomechanical pulp (25). High-impact polypropylene and, to a greater extent, EPDM increased the notched impact energy of the composites but both led to significant decreases in modulus. The fracture toughness as described by a strength ratio (2) increased to a maximum at 20

percent wood fiber and increased with addtiom of impact mixlifier.

Oksman used the SEBS-MA in a wood flour-polyethylene composite system and reported an improvement of impact properties and also a compatibiliziing effect between the wood filler and polyethylene (22). It is also possible that SEBS-MA may act as a compatibilizer and an impact modifier in wood flour-polypropylene composites.

Because of the limited work on impact modifiers and even less on impact modifier-coupling agent combinations in wood-thermoplastic composites, an exploratory study was proposed. The purpose of the study was to investigate the effects of elastomer-compatibilizer combinations on the morphology and impact performance of wood flour-filled polypropylene. Notched and unnotched Izod impact tests as well as instrumented drop weight impact tests (IDWI) were used to investigate the impact performance. Dynamic mechanical thermal analysis (DMTA) was used to investigate the interactions of the component materials.

Materials and methods

Materials

Matrix:

- polypropylene: Fortilene 9200 (Solvay Polymers, Deer Park, Tex.), density 900 kg/m^3, melt flow index 4 g/10 min. (230°C/2, 160 g).

Impact modifiers and compatibilizer:

- ethylene/propylene/diene terpolymer (EPDM), Royalene IM-7200 (Uniroyal Chemical, Middlebury, Conn.) density 870 kg/m^3, ethylene to propylene ratio of 75/25;
- maleated ethylene/propylene/diene terpolymer (EPDM-MA), Royaltuf 465 (Uniroyal Chemical, Middlebury, Conn.) total maleic anhydride/acid content of 1 percent, ethylene to propylene ratio of 55/45.
- maleated styrene-ethylene/butylene-styene triblock copolymer (SEBS-MA), Kraton FG 1901X (Shell Chemicals, Houston, Tex.), styrene content 28 percent by weight, functionality 2 percent by weight as bound maleic anhydride, density 910 kg/m^3;
- maleated polypropylene (MAPP), Unite MP880 (Aristech Chemical Corp., Pittsburgh, Pa.) average molecular weight of 90,000.

Filler:

- wood flour, number 4020, ponderosa pine, particle size >40 mesh (420 µm) (American Wood Fibers, Inc., Schofield, Wis.).

Sample preparation

The polypropylene, wood flour, and additives were preblended in a Marion mixer and then compounded in a Davis-Standard (Pawcutuck, Conn.) 32-mm corotating twin-screw blender. The blends were dried at 105°C and standard ASTM specimens were injection-molded using a Cincinnati Milacron (Batavia, Ohio) 33-ton reciprocating screw injection molder.

The samples for the DMTA were mechanically blended in a Brabender mixer at 100 rpm at 180°C to 190°C. The polypropylene was first introduced in the mixing cavity, followed by the elastomer and the wood flour in compositions as listed in Table 1. The mixing continued for about 5 minutes until a constant torque was reached. Each batch of blend was at most 30 g. After blending, the materials were pressed in a laboratory press to form 2-mm-thick plates. The press temperature was 200°C and the pressure was about 10 MPa.

TABLE 1. Composition of the injection-molded wood flour-polypropylene composites.

Sample no.	Polvpropylene	Wood flour	MAPP	EPDM	EPDM-MA	SEBS-MA
	(% by weight)					
0	100	--	--	--	--	--
1	60	--	--	--	--	--
2	58	40	2	--	--	--
3	50	40	--	10	--	--
4	48	40	2	10	--	--
5	50	40	--	--	10	--
6	48	40	2	--	10	. -
7	50	40	--	--	--	10
8	48	40	2	--	--	10

Testing and characterization

The fracture surfaces of Izod impact specimens were coated with gold and examined using an Jeol JSM-5200 scanning electron microscope (SEM) at an acceleration voltage of 15 kv.

Tensile testing of the specimens was performed according to ASTM D 638 on a MTS 810 test machine (MTS Systems, Minneapolis, Minn.). At least 10 test specimens of every composition were tested. Izod impact testing was performed according to ASTM D 256 (Izod impact) on a Baldwin-Southwark Izod impact tester. IDWI tests were performed according to ASTM D 3763 on a Dynatup GRC 8250 instrumented impact tester (GRC Instruments, Munroeville, Pa.) at a speed of 2 m/sec.

Dynamic mechanical thermal properties, polymer damping peaks (tan δ), and storage modulus *(E')* were measured using a Rheometrics Scientific Mk III, dynamic mechanical thermal analyzer. Typical specimen size was 2 by 8 by 12 mm. Specimens were run at 1 Hz using a dual cantilever testing mode over a temperature interval of – 100°C to 120°C and a heating rate of 3°C/min.

Results and discussion

Morphology

Figure 1 is a SEM micrograph of the fracture surface of a wood flour-elastomer-polypropylene composite. The wood particle is embedded in the polypropylene matrix and the elastomer particles exist as a separate phase in the matrix. The elastomer have a domain size of approximately 0.1 to 1 µm. Little plastic yielding is found in the polypropylene matrix indicating brittle fracture. The interphase region between the wood particle and the polymer matrix shows that there are voids around the wood flour particle which indicates poor adhesion. Further details of the SEM analysis of fracture surfaces and composite morphology are presented elsewhere (23) but schematic representations of the morphologies found for the different blends are shown in Figure 2. In Figure 2A, the unmodified polypropylene filled with wood flour shows poor adhesion between the wood flour and polypropylene surfaces and there are voids around the wood flour particle. In Figure 2B, MAPP enhances interracial adhesion between the wood flour and polypropylene. In Figure 2C, the composite with EPDM elastomer, there is poor adhesion between the wood flour particle and the polypropylene matrix. In Figure 2D, MAPP is added with the EPDM elastomer, improving the interracial adhesion between the wood flour particle and the polypropylene matrix, but the EPDIM remains as a separate phase in the polypropylene matrix. Figure 2E, the composite containing EPDM-MA, shows good adhesion with wood flour particles, and the elastomer is expected to at least partially encapsulate the wood flour particles. A similar morphology is found when MAPP is added. Figure 2F shows the microstructure when SEBS-MA is added. Good adhesion between the surfaces is expected and the SEBS-MA forms a strong interphase between the wood flour and polypropylene. When MAPP is added the adhesion is even stronger.

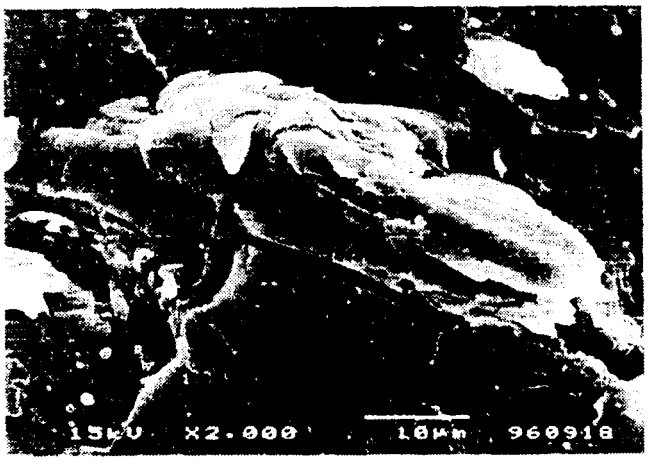

FIGURE 1.—SEM micrograph of fractured specimen shows wood flour-polypropylene composite with EPDM as an impact modifier.

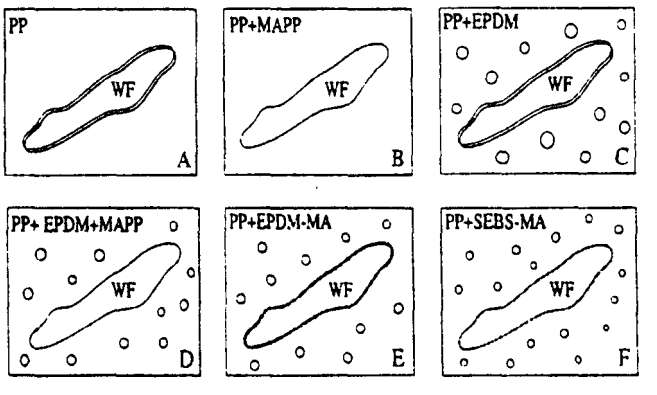

FIGURE 2.—Schematic representations of modified and wood flour-filled polypropylene. (A) and (C) show no adhesion between wood flour and polypropylene. (B) shows inter-facial adhesion and (D) to (F) show expected formation of interphase around the wood flour particle.

Dynamic mechanical thermal properties

Dynamic mechanical measurements can give information about the interaction bewteen different components in the composites. The position of the primary peaks in the damping curve (tan δ) can provide information about the molecular interaction between wood and polymers at the molecular level. The tan δ peak position can also provide insight into the impact behavior of materials (e.g., lower glass Transition temperature (T_g) can indicate improved low temperature toughness). Dynamic mechanical properties have also been used to study the elastomeric encapsulation of the filler. The transition peak amplitude and storage modulus of the elastomer have been shown to indicate possible encapsulation of the filler. Kolarik et al. have shown that peak amplitude is increased with increased EPDM encapsulation of $CaCO_3$ filler in polypropylene (16). The addition of filler usually decreases the tan δ amplitude because the relative damping peak height is affected by the concentration of the measured materials (20). This study analyzed polypropylene/EPDM, polypropylene/EPDIM-MA, and polypropylene/SEBS-MA with and without wood flour and MAPP. The DMTA data are presented in Figures 3 to 5.

Figure 3 shows the damping (tan δ) and storage modulus *(E')* for polypropylene/EPDM with and without wood flour and MAPP as a function of temperature. In the systems studied, two primary transi - tions can been seen, one for EPDM located around –30°C and one for polypropylene around 10°C. The tan δ peak position for the elastomer is not changed when wood flour and MAPP are added but the polvpropylene tan δ peak position is shifted about 4°C upward, which may indicate enhanced interaction with wood due to MAPP addition. Felix et al. (8) had similar findings when MAPP was used in the polypropylene/CF composite systems, the tan δ peak of polypropylene was shifted between 2°C and 5°C upwards when CF was treated with MAPP Figure 3 shows that both EPDM and polypropylene damping peak amplitudes are decreased with wood flour addition, which is expected because fewer molecules are involved in the transition. The wood flour addition has no effect on dynamic modulus below the elastomer transition but increases the modulus above the main transition of polypropylene compared to unfilled polypropylene/EPDM. The addition of fillers increases the modulus above the glass transition because of larger differences between filler and matrix modulus in the rubbery state.

Figure 4 shows the tan δ and the *E'* for the polypropylene/EPDM-MA with and without wood flour and MAPP. The elastomer tan δ peak is located at –38°C. It shifted about 5°C downwards and was broadened when wood flour and MAPP was added.

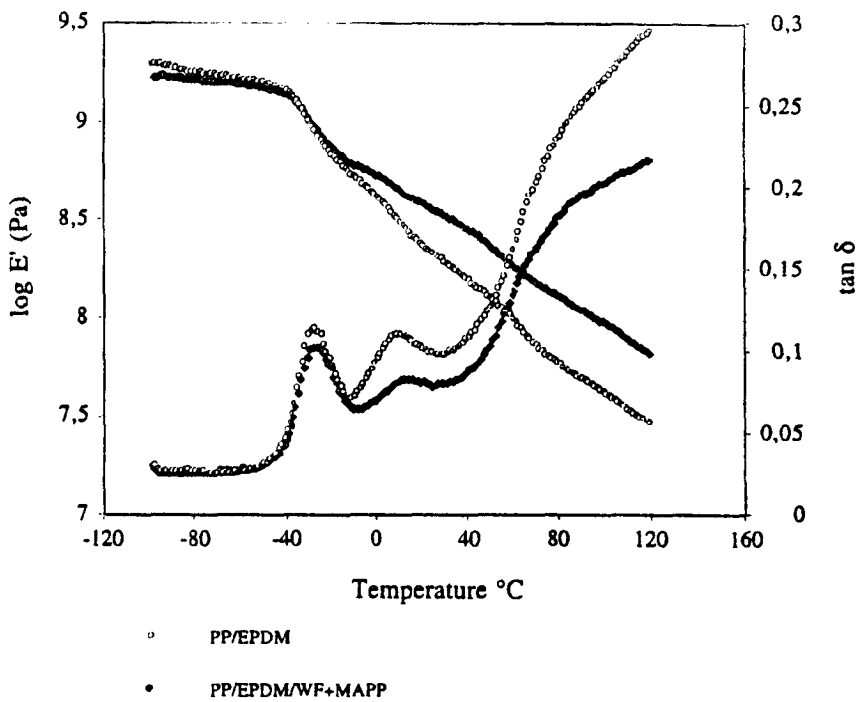

FIGURE 3.—DMTA curves of the polypropylene/EPDM and same with wood flour and MAPP. The tan δ peaks and *E'* are presented as a function of temperature.

The peak shift downwards indicates that the EPDM-MA molecular motion have become more mobile and that the free volume near filler surfaces have increased. The large drop in the *E'* above the tan δ peak temperature is probably the result of elastomeric encapsulation of wood flour particles. Kolarik et al. had similar findings in the polypropylene/$CaCO^3$/EPDM composites (16). The drop in *E'* increased with increased encapsulation of the rigid filler particles. If the elastomer completely encapsulates the filler, the filler can effectively act as an extender for the elastomer. This results in a increased damping

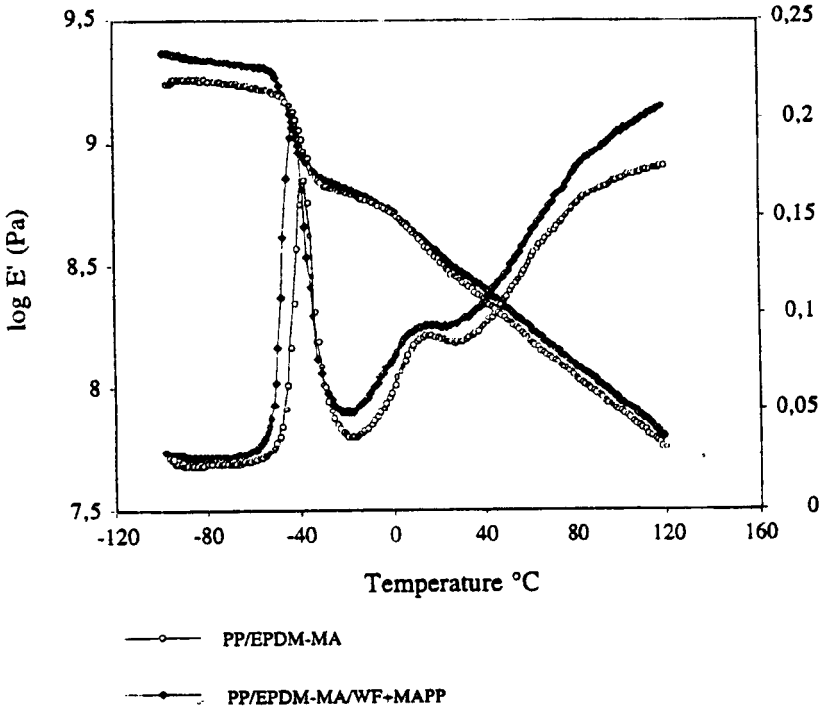

FIGURE 4.—DMTA curves of the polypropylene/EPDM-MA and same with wood flour and MAPP. The tan δ peaks and *E'* are presented as a function of temperature.

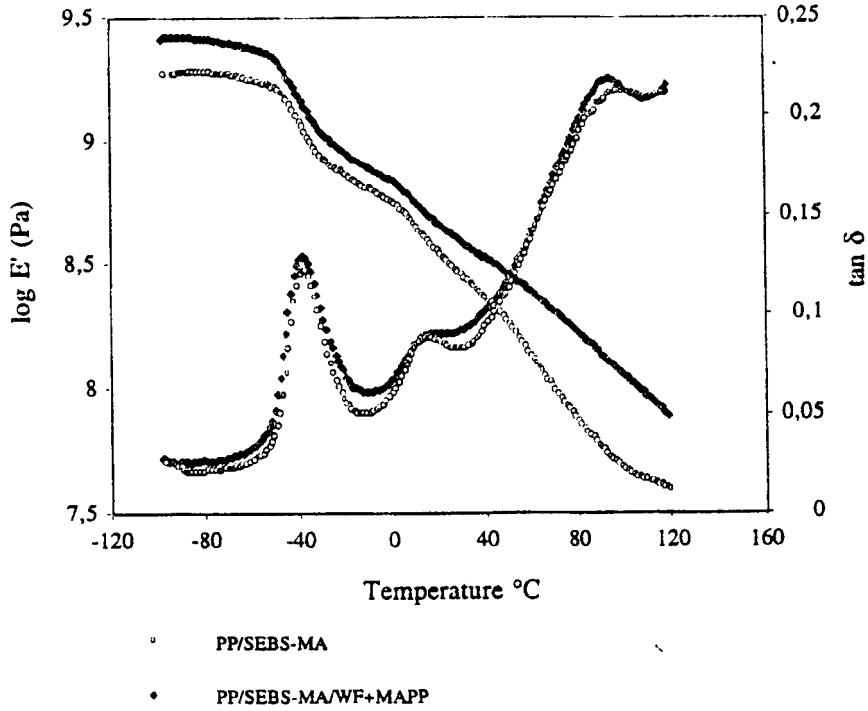

FIGURE 5.—DMTA curves of the polypropylene/SEBS-MA and same with wood flour and MAPP The tan δ peaks and *E'* are presented as a function of temperature.

peak and reduced E' relative to the unencapsulated filler morphology. The differences of the polypropylene tan δ positions in the polypropylene/EPDM and polypropylene EPDM-MA systems may depend on the interactions between ethlene/propylene and polypropylene, especially in the polypropylene/EPDM where the polypropylene and ethylene/propylene tan δ peaks are shifted toward each other.

Figure 5 shows the tan δ and *E'* of polypropylene/SEBS-MA and polypropylene/SEBS-iMA/wood flour+MAPP composites. In this system three transitions can be seen:

- maleated ethylene/butylene (EB-MA) at about –40°C;
- polypropylene at about 14°C; and
- PS at about 100°C.

The EB-MA peak is broadened which may be a result of the interracial effects but the position is not changed. A previous DMTA indicated that the EB-MA molecules in SEBS-MA interact with wood—the EB-MA peak was shifted about 7°C higher when 40 wt% wood flour was added (24). The tan δ peak of polypropylene is shifted about 6°C higher when wood flour and MAPP are added indicating interaction with wood due to MAPP addition. The PS tan δ is shifted 6°C lower when wood flour and MAPP were added to the system. *E'* is increased when wood flour and MAPP is added to the polypropylene/SEBS-MA system over the full temperature range. This increase, however, is not as great at the region between the EB-MA and polypropylene transitions. The larger *E'* drop in the rubbery state may indicate that the wood flour particles are partially encapsulated by the SEBS-MA but the effect is not as apparent as it was in the EPDM-MA system. This might be a result of the rigid styrene particles which have a reinforcing effect on the soft butadiene phase.

Mechanical properties

Although the focus was on improvement of impact performance, tensile properties were also performed in order to give some indication of the balance of properties achieved with the various blends. Table 2 and Figures 6 to 11 summarize the mechanical properties of the unfilled polypropylene as well as the different blends.

The addition of wood flour to polypropylene resulted in a loss of tensile strength (Fig. 6). This is not surprising given the poor compatibility and large particle size of the wood flour. The addition of MAPP helped to offset some of the reduction in tensile strengths because of improved matrix-wood flour stress transfer, but these improvements were limited by the low aspect ratio of the wood flour. The addition of EPDM further reduced the tensile strengths as a result of a lowering of the yield stress of the polymer. Although the EPDM-MA and SEBS-MA elastomers were present as separate domains in the polypropy-

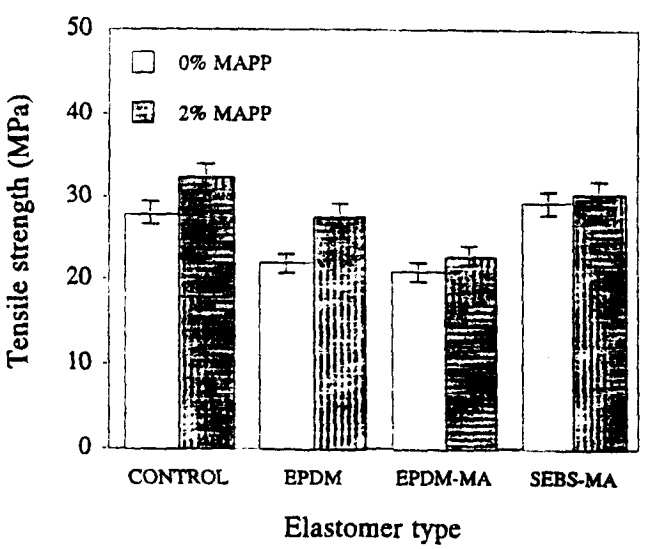

FIGURE 6. —Tensile strength of the wood flour-polypropylene composites with different impact modifiers and MAPP as compatibilizer.

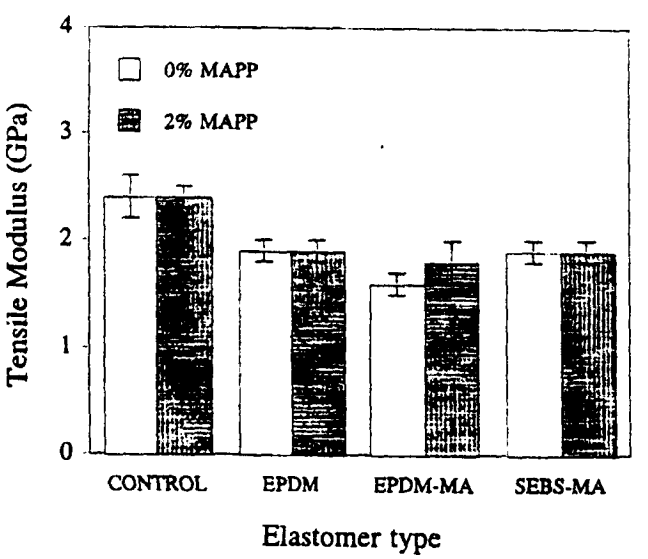

FIGURE 7. —Stiffness of the composites, pure polypropylene compared with wood flour-polypropylene composites with different additives.

lene matrix, the DMTA and SEM results suggest partial encapsulation of the wood flour particles as well. Therefore, these blends have the opportunity to act as a stress-transferring interphase. The different results of the two types of elastomers are probably a result of the EPDM-MA forming a softer or weaker interphase than the SEBS-MA.

The modulus of the polypropylene was greatly increased with addition of the stiffer wood flour (Fig. 7) whereas the MAPP had no effect on the modulus. Not surprisingly, the addition of the more flexible elastomers lowered the moduli, though the composites were still considerably stiffer than the unfilled polypropylene.

AS usual with the addition of a filler, adding 40 percent wood flour to polypropylene resulted in large decreases in elongation at break (Fig. 8). The MAPP generally had a negative effect on the elongation as a result of the greater adhesion between the wood flour and polypropylene restricting polymer mobility The elastomers increased the yielding of the polypropylene which resulted in greater elongations. The greater elongations with the EPDM-MA and SEBS-MA blends compared to EPDM blends are probably the result of the partial encapsulation by the elastomers being more effective at reducing the stress conentrations created by the wood flour particles.

Three different impact tests were performed. Some discussion is required on why these tests were chosen. The notched Izod impact test is a measure of the energy required to propagate a crack through a specimen of given dimensions and notch geometry. It is by far the most commonly used impact test in the United States and is usually used for material screening. The unnotched Izod impact test is somewhat less used and results in a value that includes both crack initiation and propagation energies of a given specimen geometry. Recently however, the Izod impact test has come under criticism because its loading geometry does not represent real conditions the material might see in actual applications.

One alternative approach to Izod impact testing is the instrumented drop weight impact (IDWI) test. The IDWI test involves a biaxial loading of a circular plate by a hemispherical impactor. This weighted impactor is fitted with instrumention that tracks the load over the entire impact event. However, some limitations of this test are the difficulty in dealing with the noise produced by the impact on the specimen and the fact that the complexity of the loading make interpretation difficult (1).

Table 2 includes a brief summary of the impact data and Figures 9 and 10 show the impact data graphically. The effect of wood flour addition to polypropylene underlines the differences between the impact tests. Addition of wood flour results in no change in the notched Izod impact energy, a very large decrease in unnotched Izod impact energy (a loss of 89%), and a very large increase in total energy absorbed during the IDWI testing (a 321% increase). The reasons for this discrepancy lie in the fact that each test is measuring something different. If a stress concentrator is already present, such as a notch in the notched Izod impact test, little change is seen with the addition of wood flour. However, in the absence of the notch, the addition of wood flour acts as stress concentrators and greatly reduces the crack initiation energy (reduction in the unnotched Izod impact energy). The increase in the IDWI energy is more difficult to explain because of the complexity of failure (biaxial bending, crack initiation, radial and tangential crack propagation, etc.) but is at least partially a result of the greatly increased modulus.

The addition of MAPP decreases notched impact energies presumably due to reduced polymer mobility. Surprisingly, MAPP did not consistently increase the unnotched impact energies. It was expected that improved adhesion would make crack initiation more difficult, as has been the case in previous work (6). MAPP decreased the total IDWI energy.

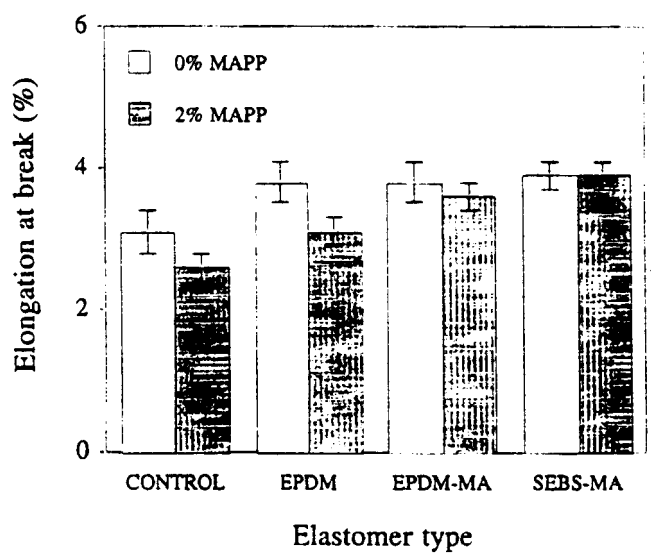

FIGURE 8. —Elongation at break of the wood flour-polypropylene composites with different impact modifiers and MAPP as compatibilizer.

TABLE 2. —Mechanical properties of wood flour-polypropylene composites.[a]

Composite no.	Tensile properties			Izod impact properties		
	Strength	Modulus	Elongation at break	Notched	Unnotched	IDWI[d]
	(MPa)	(GPa)	(%)	------ (J/m) ------		(J)
Unfilled polypropylene	37.2[b]	1.4[b,c]	590[b]	27[b]	800[b]	1.4 (±0.5)
Filled polypropylene blends						
1 - -	27.9 (±0.3)	2.4 (±0.2)	3.1 (±0.3)	26.1 (±1.1)	85.8 (±9.4)	5.9 (±0.5)
2 MAPP	32.4 (±0.2)	2.4 (±0.1)	2.6 (±0.2)	23.5 (±1.3)	86.1 (±9.4)	4.8 (±0.8)
3 EPDM	22.0 (±0.3)	1.9 (±0.1)	3.8 (±0.3)	38.2 (±1.2)	97.3 (±9.6)	5.6 (±0.5)
4 EPDM+MAPP	27.7 (±0.2)	1.9 (±0.1)	3.1 (±0.2)	34.4 (±1.4)	105.3 (±10.0)	5.0 (±0.8)
5 EPDM-MA	21.0 (±0.3)	1.6 (±0.1)	3.8 (±0.3)	47.7 (±2.2)	144.6 (±7.1)	6.6 (±0.9)
6 EPDM-MA+MAPP	22.9 (±0.6)	1.8 (±0.2)	3.6 (±0.2)	47.9 (±2.1)	146.0 (±16.9)	6.8 (±0.5)
7 SEBS-MA	29.3 (±0.5)	1.9 (±0.1)	3.9 (±0.2)	51.2 (±2.6)	153.6 (±16.4)	7.9 (±0.8)
8 SEBS-MA+MAPP	30.5 (±0.5)	1.9 (±0.1)	4.2 (±0.2)	54.1 (±2.2)	167.4 (±16.7)	8.5 (±0.7)

[a] Standard deviations are in parentheses.
[b] Manufacturer-supplied data.
[c] Secant modulus at 1% strain.
[d] Total energy absorbed.

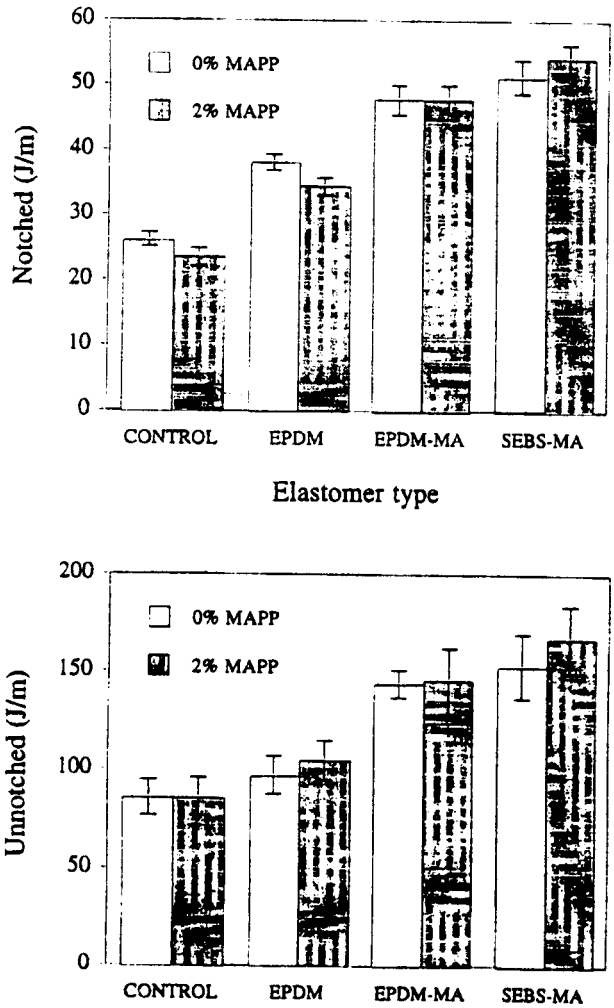

FIGURE 9. —Impact strength of (top) notched and (bottom) unnotched samples of different composites.

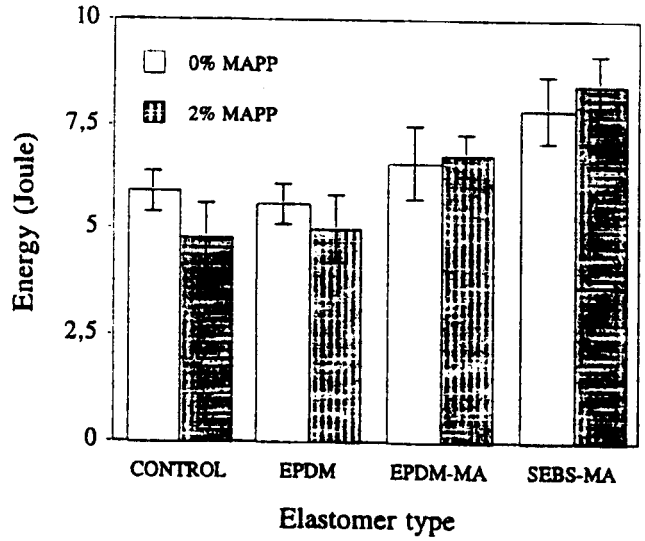

FIGURE 10. —Total IDWI energies of different composites.

The addition of clastomer inproved impact performance in nearly all cases, with the SEBS-MA blends having the best performance. Improved toughness because of localized yielding of the matrix material and partial encapsulation of the wood flour somewhat offset the effects of wood flour addition.

It is useful to take a closer look at the IDWI tests. Figure 11 shows typical curves for both the unfilled and wood flour-filled polypropylene. Table 3 summarizes the detailed results and statistics of the IDWI tests. Unfortunately, significant noise made features early in the impact event impossible to determine, such as dynamic modulus and incipient damage point. All samples failed in a brittle manner and very little yielding was observed. Examination of fractured samples showed cracks propagating radially from the point of contact followed by tangential cracking.

Figure 11 shows representative load versus deflection curves to give a general idea of curve shape. The curves for the unfilled and wood flour-filled polypropylene are quite different. The curve for unfilled polypropylene is characterized by a relatively linear

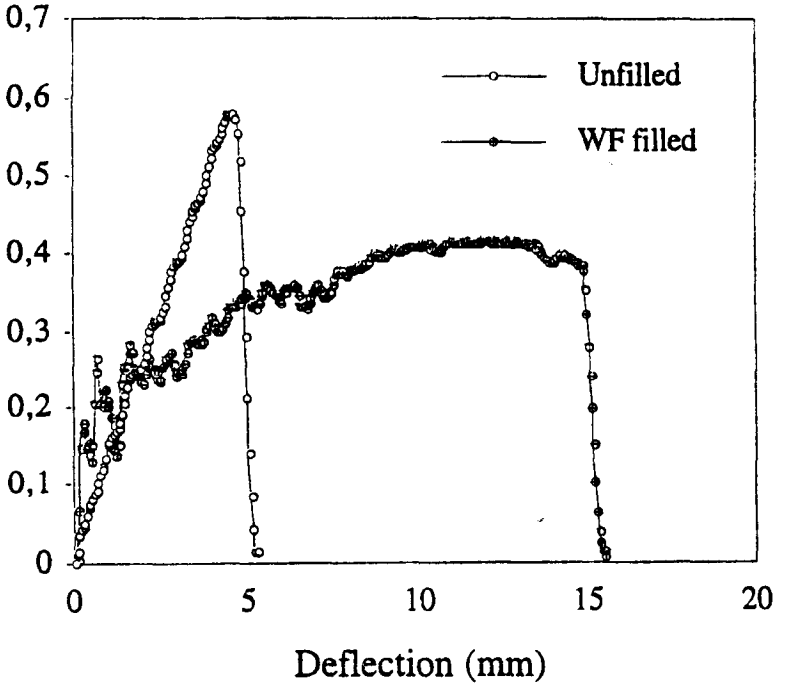

FIGURE 11 .—Typical IDWI test curves for unfilled and wood flour filled polypropylene.

TABLE 3.—IDWI tests of wood flour-polypropylene.[a]

Composite no.	Properties at maximum load			Properties at final failure		Ratios	
	Load	Deflection (DM)	Energy (EM)	Deflection (DF)	Energy (EF)	DF/DM	EF/EM
	(kN)	(mm)	(J)	(mm)	(J)		
Unfilled polypropylene	0.56 (±0.01)	4.3 (±0.8)	1.3 (±0.4)	4.6 (±0.8)	1.4 (±0.5)	1.1 (±0.1)	1.1 (±0.1)
Filler polypropylene blends							
1 - -	0.48 (±0.02)	12.5 (±0.9)	4.3 (±0.4)	16.1(±1.3)	5.9 (±0.5)	1.3 (±0.1)	1.4 (±0.2)
2 MAPP	0.53 (±0.03)	11.9 (±1.4)	4.3 (±0.7)	13.0 (±1.9)	4.8 (±0.8)	1.1 (±0.1)	1.1 (±0.1)
3 EPDM	0.42 (±0.02)	11.6 (±1.0)	3.7 (±0.4)	16.9 (±1.5)	5.6 (±0.5)	1.5 (±0.2)	1.6 (±0.2)
4 EPDM+MAPP	0.47 (±0.05)	12.2 (±1.3)	4.2 (±0.5)	14.3 (±2.0)	5.0 (±0.8)	1.2 (±0.1)	1.2 (±0.1)
5 EPDM-MA	0.45 (±0.03)	12.7 (±0.9)	4.4 (±0.4)	18.6 (±1.9)	6.6 (±0.9)	1.5 (±0.2)	1.5 (±0.2)
6 EPDM-MA+MAPP	0.48 (±0.02)	12.4 (±0.8)	4.5 (±0.3)	18.1 (±1.5)	6.8 (±0.5)	1.5 (±0.2)	1.5 (±0.2)
7 SEBS-MA	0.49 (±0.04)	13.7 (±0.6)	5.1 (±0.3)	20.8 (±2.3)	7.9 (±0.8)	1.5 (±0.2)	1.6 (±0.2)
8 SEBS-MA+MAPP	0.53 (±0.04)	13.3 (±0.7)	5.3 (±0.4)	20.6 (±1.4)	8.5 (±0.7)	1.6 (±0.2)	1.6 (±0.1)

[a] Standard deviations are in parentheses.

Table 4. — Summary of the effects of additives on the wood-flour polypropylene composites. Comparisons were made using the Students t-tests (5% significance level).[a]

Sample no.	σ_{max}	E	ε	Izod notched	Izod unnotched	IDWI
2 MAPP	+	O	–	–	O	–
3 EPDM	–	–	+	+	O	O
4 EPDM+MAPP	O	–	O	+	+	–
5 EPDM-MA	–	–	+	+	+	+
6 EPDM-MA+MAPP	–	–	+	+	+	+
7 SEBS-MA	+	–	+	+	+	+
8 SEBS-MA+MAPP	+	–	+	+	+	+

[a] + = positive; – = negative; O = little or no effect.

increase in load, high maximum loads, and small deflections at failure. The triangular appearance of the curve suggests a rapid loading followed by catastrophic failure because of unstable crack propagation. The curve for the wood flour-filled polypropylene is characterized by larger deflections and lower-maximum loads than the curve for unfilled polypropylene. Considerable noise can be seen, especially early in the impact event. These features suggest damage development beginning early and lasting through the impact test. General curve shapes were similar for all wood flour-filled blends, but the magnitude and position of curve features changed.

The addition of MAPP resulted in increases in maximum loads analogous to the tensile test. None of the blends had higher maximum loads than the unfilled polymers. The higher maximum loads resuited in greater energies to maximum load. However, MAPP had no effect on deflection at maximum load. Despite higher maximum loads, total energies were reduced with the addition of MAPP as a result of fracture shortly after maximum load was reached. MAPP has little effect on moduli and we can surmise that the MAPP allows better stress transfer resulting in higher loadings, but restricts polymer mobility and limits deflection before failure occurs.

Effects of elastomer addition are complex. Surprisingly, the addition of EPDM resulted in relatively poor IDWI performance relative to wood flour-filled polypropylene without any additives. However, the addition of the compatibilized elastomers, especially SEBS-MA, resulted in increased IDWI performance. In general both properties at maximum load and total properties were increased with the compatibilizer elastomers.

Conclusions

In wood flour-elastomer-polyproplene composites, several different morphologies are possible by controlling the compatibilt of the phases. The dynamic mechanical properties of composites with different elastomeric additives indicated that maleatd elastomers have higher affinity to wood flour, and encapsulated the wood particles. The damping peak intensities of maleated elastomers were increased when wood was incorporated in the systems. Results also indicated interaction with wood flour when AL4PP \vas added in the composite systems. In In wood flour-polypropylene composites with added elastomers, the tan δ peak position of the polvpropylene was shifted about 5°C upwards with added EPDM and SEBS-IMA, while it was only shifted about 1°C with added EPDM-MA.

Evaluation of the toughness of these composites is a complex problem. Selection of the appropriate tests and careful interpretation of results is critical. Because of the different test and specimen geometries, notched and unnotched Izod impact and IDWI tests can lead to different findings and care needs to be taken when interpreting results.

The addition of wood flour does not greatly alter crack propagation energies but can seriously reduce crack initiation energies. There was considerable difference in how unfilled and wood flour-filled polypropylene failed under biaxial loading of a plate at impact speeds. The unfilled polymer was rapidly loaded and failed catastrophically whereas wood flour filled polypropylene accumulated damage over the impact event.

The addition of IMAPP results in improved adhesion between polypropylene and wood flour but restricts polymer mobility and affects mechanical properties accordingly. The low aspect ratio of the wood flour limits the effectiveness of the MAPP. Addition of elastomers to wood flour-filled polypropylene results in increases in impact energies, with the compatibilized elastomers yielding the best impact performance. However, much of this impact energy is absorbed after maximum load is reached in the IDWI test.

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