Bonding of air-formed wood fibre/polypropylene fibre composites

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The effectiveness of a maleated polypropylene (MAPP) as a coupling agent in wood fibre/polypropylene fibre composites made by non-woven web technology has been evaluated. The composite panels were made with 70 or 85% wood fibre, with the MAPP being incorporated in the panels at a level of 1 or 3% by spraying an emulsified form on the wood fibres. Both levels of MAPP significantly increased bending and tensile strength and moduli and dynamic modulus. At the 70% wood fibre level, impact energy was increased significantly in panels with 3% MAPP. At the 85% wood fibre level, both 1 % and 3% MAPP significantly increased impact energy. The MAPP also led to small improvements in water resistance for composites containing 85% wood fibre. The effectiveness of MAPP is believed to be the result of efficient incorporation at the wood/polypropylene interface, thus providing effective coupling of the polar wood component to the non-polar polymer matrix.

Key words: polypropylene fibre; wood fibre; composite; coupling agent; maleated polypropylene; mechanical properties; physical properties; non-woven webs

Promising technology is evolving for using waste or low-grade wood blended with polyoletin plastics to make an array of high-performance reinforced composite products. This technology provides a strategy for producing advanced materials that take advantage of the enhanced properties of both wood and plastic. Benefits associated with these composite products include light weight and improved acoustic. impact and heat reformability properties.

A wide variety of wood and synthetic fibres can he assembled into a random web or mat using air-forming or non-woven web technology. The fibres are initially held together by mechanical interlocking. The web can then be fused or thermoformed into panels or into a variety of shapes. A thermosetting resin can also he incorporated in the web to provide additional bonding of the fibres.

Non-woven web composites provide options for balancing performance properties and costs. depending upon the application under consideration. However, poor attraction and low interfacial bonding between the hydrophilic wood and hydrophobic polyoletin limit the reinforcement imparted to the plastic matrix by the wood component. This reinforcement could be enhanced if the polar nature of the cellulosic surface were modified so that the wood surface characteristics were more compatible with the non-polar nature of the polymer matrix. One approach to developing greater compatibility is to use a coupling agent that possesses a dual functionality, enabling it to interact or react with both components[1-3].

The increased processing flexibility inherent in non-woven web technology has the potential to give rise to a host of new natural or synthetic fibre products[4]. These products can he produced in various thicknesses - from a material only a few millimetres thick to structural panels up to several centimetres thick. A great variety of applications are possible because of the many alternative configurations of the products. Potential products include:

1) storage bins for crops or other commodities;
2) temporary housing structures;
3) furniture components, including both flat and curved surfaces;
4) automobile and truck components;
5) panelling for interior wall sections, partitions and door systems;
6) floor. wall and roof systems for light-frame construction; and
7) packaging applications, including containers, cartons and pallets.

The purpose of the research reported here was to determine if a maleated polypropylene (MAPP)

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coupling agent could improve the properties of wood fibre/polypropylene fibre composites made by non-woven web technology.

Experimental design and analysis

The experimental design was completely random and consisted of six treatment combinations (Table 1). The six treatments constitute percentages in a mixture that must add up to 100%. with wood fibre constituting either 70 or 85%, MAPP 0, 1 or 3%, and the remainder polypropylene fibre. For analysing the results of the experiment, the treatment combinations could be considered individually or as a two by three factorial test (two levels of wood fibre and three of MAPP). For convenience in interpreting the results, the latter approach will be used in this paper.

Each treatment combination was replicated on 10 panels. Depending upon the property involved, one, two or eight measurements per panel were obtained by cutting one or more specimens per panel. Because of the pattern for cutting the specimens, some specimens were cut from the centre of the panel, where the panel was most dense, and other specimens were cut from the edges, where the panel was least dense. Therefore, the average value of the measurements for each panel was used as the experimental value assigned the panel. This is important to note because the measurements derived from specimens from one location on a panel were often very different from those of specimens from another location. We tested whether the effect of wood fibre and MAPP levels would be different if we took into account the location of the specimen on the panels. The results of this showed only two occasions where the panel location interacted with an independent variable in the design. Even in these two cases, it was decided that the mean value from the different locations on the panel represented the most accurate value for the panel.

An analysis of variance (ANOVA) was peformed to look for treatment effects. In all but one case, there was a significant interaction between wood fibre level and MAPP level; that is, the effect of MAPP level depended upon the amount of wood fibre in the mixture. Therefore, the effect of MAPP to wood fibre level was analysed by an ANOVA test at each wood fibre level, followed by a Tukey multiple comparison of the means when the ANOVA showed significance.

Table 1. Treatment combinations for tests of wood fibre/polypropylene fibre composites

Content (%)		
Wood fibre	Polypropylene fibre	MAPP
85	12	3
	14	1
	15	0
70	27	3
	29	1
	30	0

Materials and methods

Materials

Western hemlock *(Tsuga heterophylla)* wood fibres. obtained from Canfor Ltd* (Vancouver, BC, Canada). were produced from 100% pulp-grade chips, steamed for 2 min at 7.59 MPa, disc refined and flash dried at 160°C in a tube dryer. The fibres were then hammermilled using a 12.7 mm screen. The polypropylene fibres. obtained from Hercules Inc (Norcross, GA, USA), were 2.2 denier, 37 mm long and crimped. They had a density of 0.910 g cm^{-3} and a melting point of 162°C. The MAPP coupling agent was an anionic emulsion of Epolene E-43, available from Eastman Chemical Products Inc (Kingsport, TN, USA).

Processing

The hemlock fibres had an initial moisture content of 5%. They were sprayed with 40% solids content MAPP anionic emulsion. to achieve a MAPP level of 1 or 3% (dry weight basis). The hemlock fibres used for the control boards were not sprayed with MAPP.

The wood and polypropylene fibres were air mixed. transferred via an air stream to a moving support bed. and subsequently formed into a continuous, low density, 305 mm wide web of intertwined fibres, ranging in length from 12.2 to 18.3 m, depending upon the density of the formed web. Each roll of the web was trimmed to 305 mm square sheets. Six to eight sheets were selected according to their weight and stacked to maintain the same machine direction orientation and the same weight for each stack.

A manually controlled. steam-heated press was used to press the panels at 213°C for 6 min at a maximum pressure of 2.9.5 MPa. The panels were then cooled in the press for an additional 6 min until they reached a final temperature of 38°C. All panels were trimmed to 254 mm square, with a density of 1.0 g cm^{-3} and thickness of 3.2 mm.

Testing

Ten individual panels were used to test each treatment combination. resulting in a total of 60 panels. For each combination, three intact panels were tested for impact energy. The remaining seven panels were cut into various numbers of specimens, which were tested for other mechanical and dimensional stability properties, as shown in Table 2.

Tests for mechanical properties were conducted on conditioned (65% relative humidity, 20°C) Specimens at room temperature (about 23°C), with minimal exposure to ambient humidity. Maximum cantilever beam strength and secant modulus at 9° were determined on cantilever beam specimens in conformance with ASTM D747[5] using a Tinius Olsen tester with a loading rate of about 60° min^{-1}. Tensile strength and modulus of elasticity were tested in conformance with ASTM D1037[6] using an Instron testing machine. Dynamic modulus was determined with wave speed measUrements using a Metriguard 239A tester according to published Metriguard procedures[7]. A

*The use of trade or firm names in this publtcation is for reader information and does not rmply endorsement by the US Department of Agriculture of any product or service.

Table 2 Experimental design[a]

Type of test	Specimen size (mm)	Number of specimens cut from panel	Total number of specimens per treatment combination
Cantilever beam bending strength and modulus	127 X 254	4	28
Tensile strength and modulus	51 X 254	2	14
Dynamic modulus	25 X 254	2	14
Impact energy	254 X 254	3[b]	3
Dimensional stability	51 X 51		
24 h water-soak		2	14
2 h water-boil		3	21

[a]Ten panels were used to test each treatment combination: three intact panels were used for the impact energy test and the remaining seven panels were cut into various numbers of specimens for the other tests
[b]Intact panels used for tests on impact energy

stress wave was introduced into the specimens so as to propagate along their length. Speed of sound transmission was determined from measurement of transit time of the wave over a gauge length of 178 mm. Dynamic modulus of elasticity (MOE) was then computed from speed of sound values using the following equation:

$$\text{Dynamic E} = (\text{wave speed})^2 \times \text{density/acceleration by gravity}$$

where acceleration caused by gravity = 9.8 m s^{-2}. A more detailed explanation of stress wave behaviour and its relationship to static mechanical properties can be found in the literature*.

Nondestructive stress wave testing was conducted to determine if this technique would be usable for composites containing relatively high proportions of thermoplastic components. Impact energy was measured in conformance with TAPPI standard T803 om-88[9] with a General Electric impact tester.

The 24 h water-soak test was conducted at ambient temperature. The water-soak and water-boil tests were performed in conformance with ASTM D1037[6] and CAN3-0188.0-M78[10] standards, respectively.

Results

The results are presented in Figs 1 to 10 as bar charts; the lines above the bars indicate statistical significance. In all the figures, bars connected by a solid line indicate that the results are not significantly different at the 95% confidence level.

Mechanical properties

At the 70% wood fibre level. the incorporation of 1 or 3% MAPP resulted in an average statistically significant increase in cantilever beam strength and secant modulus of 50 and 40%, respectively. At the 85% wood fibre level, MAPP increased maximum cantilever beam bending strength from 42 to 58% (Fig. 1). For secant modulus, the increases were somewhat smaller; from 29 to 42% (Fig. 2). For either property, additional benefits obtained from increasing MAPP content from 1 to 3% were small. Nevertheless, all improvements were statistically significant.

At the 70% wood fibre level, 1% MAPP caused an increase in peak tensile strength of 78% compared with that of the control material; with 3% MAPP, the tensile strength was 56% higher than that of the controls (Fig. 3). At the 85% wood fibre level, tensile strength at the 1 and 3% MAPP levels was respectively 37 and 54% higher than that of the controls.

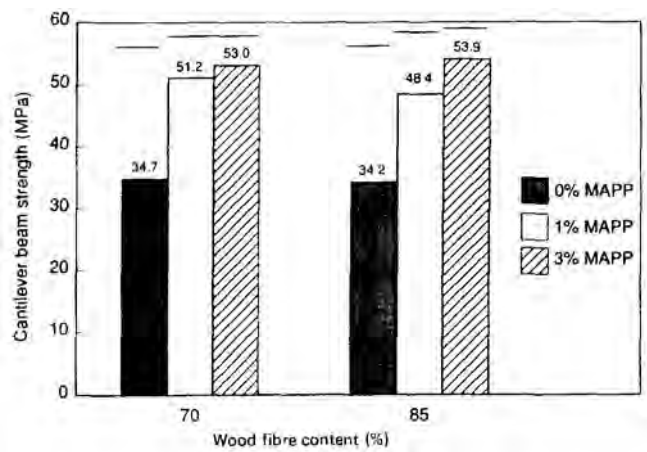

Fig 1. Maximum cantilever beam bending strength of non-woven web composites as a function of wood fibre content and MAPP level

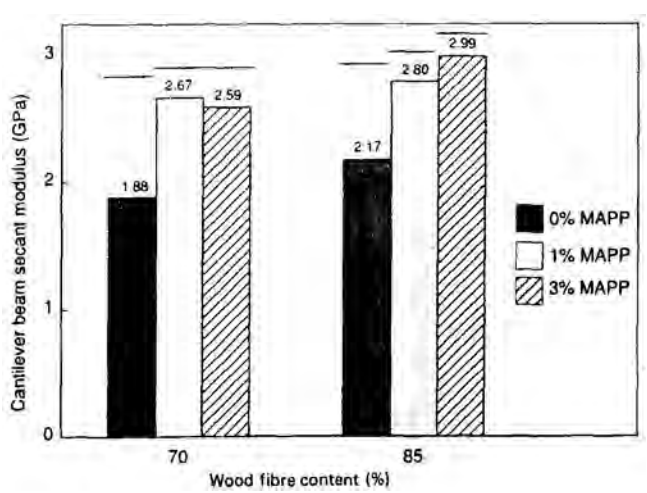

Fig. 2 Cantilever beam secant (9°) modulus of non-woven web composites as a function of wood fibre content and MAPP level

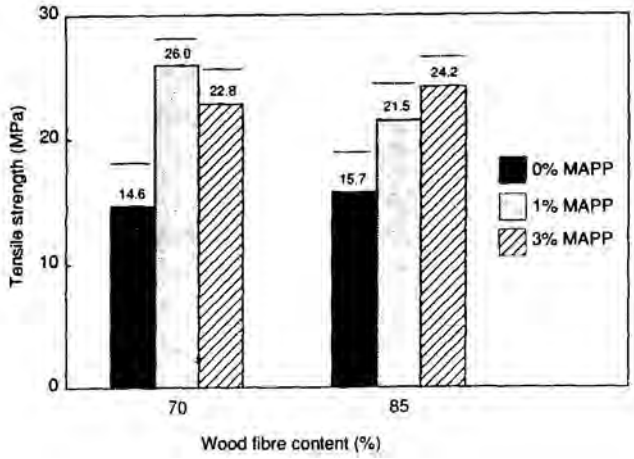

Fig. 3 Tensile strength of non-woven web composites as a function of wood fibre content and MAPP level

Compared with tensile strength (Fig. 3), similar trends were observed for tensile modulus (Fig. 4). The modulus of the 70% wood fibre system was increased by 48% by adding 1% MAPP and by 26% by adding 3% MAPP. At 85% wood fibre level, the tensile modulus was increased by 14% with 1% MAPP and by 22% with 3% MAPP.

The dynamic modulus of the 70% wood fibre system was increased by 40% by incorporating 1% MAPP and by 21% by 3% MAPP (Fig. 5). At the 85% wood fibre level, the dynamic modulus was increased by 7 and 15% when using 1 and 3% MAPP, respectively. However, these differences were not statistically significant.

At the 70% wood fibre level, 1% MAPP did not significantly influence impact energy; however, 3% MAPP increased impact energy by 45% (Fig. 6). At the 85% wood fibre level, impact energy of panels with 1 or 3% MAPP was increased by about 53 and 72%, respectively. These values are statistically different from control values, but they are not statistically different from each other.

Dimensional stability

A 24 h water-soak test and 2 h water-boil test were used to measure thickness swell and water absorption properties of the panels. Although thickness swell after the 2 h water-boil test was approximately twice that after the 24 h water-soak test, the effects of MAPP were similar for both tests (Figs 7 and 9). At the 70% wood fibre level for both the 24 h water-soak and 2 h water-boil tests, the addition of 1% MAPP did not produce statistically significant results compared with the tests on the control panels without MAPP. At the 3% MAPP level, thickness swell properties for the 24 h water-soak and 2 h water-boil tests increased by 20 and 23%, respectively. compared with the average thickness swell properties of the controls and the panels with 1% MAPP.

At the 85% wood fibre level for both the 34 h water-soak and 2 h water-boil tests, the addition of either 1 or

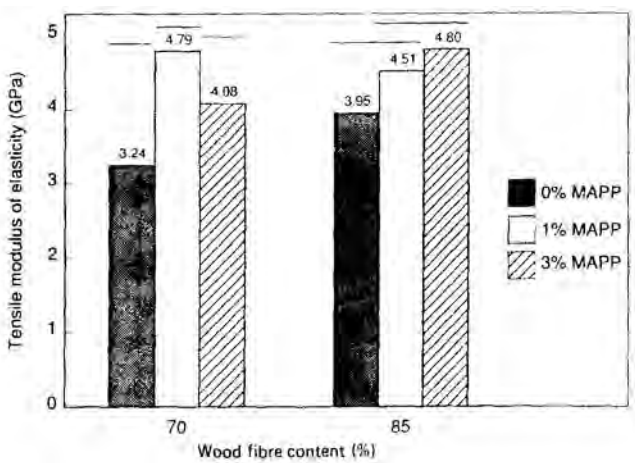

Fig. 4 Tensile modulus of non-woven web composites as a function of wood fibre content and MAPP level

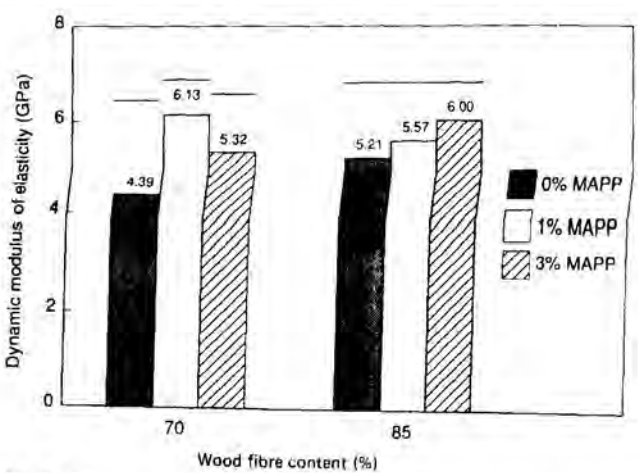

Fig. 5 Dynamic modulus of non-woven web composites as a function of wood fibre content and MAPP level

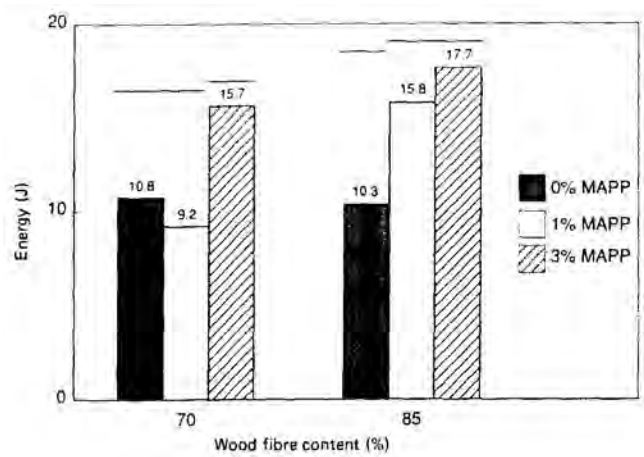

Fig. 6 Impact energy of non-woven web composites as a function of wood fibre content and MAPP level

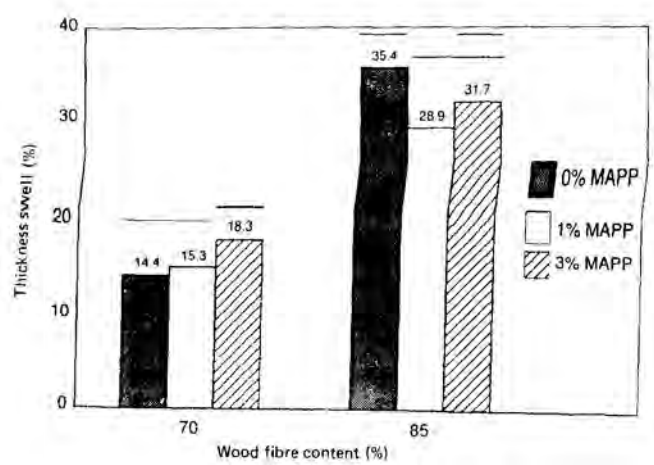

Fig. 7 Thickness swell of non-woven web composites in 24 h water-soak test as a function of wood fibre content and MAPP level

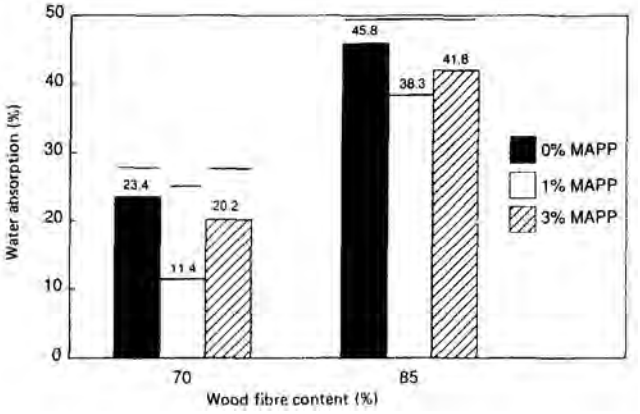

Fig. 8 Water absorption of non-woven web composites in 24 h water-soak test as a function of wood fibre content and MAPP level

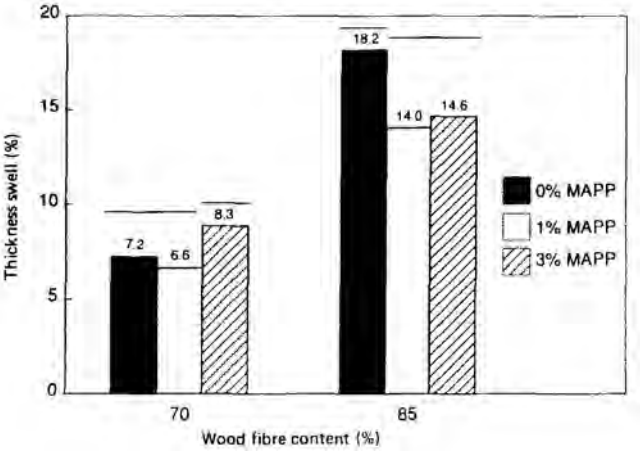

Fig. 9 Thickness swell of non-woven web composites in 2 h water-boil test as a function of wood fibre content and MAPP level

3% MAPP reduced thickness swell properties compared with that of the controls. Because the thickness swell values for both tests for the panels with MAPP were not significantly different. these values were averaged for the purpose of comparison. With the 24 h water-soak test. the average thickness swell was reduced by 21% for the MAPP-containing panels compared with that of the controls. Similarly, a 14% reduction in average thickness swell was obtained in the 2 h water-boil test.

For the 24 h water-soak test, water absorption values at the 70% wood fibre level were statistically different for all MAPP levels (Fig. 8). Water absorption decreased 51% at 1% MAPP and 14% at 3% MAPP, compared with the controls. No statistical differences were noted at the 85% wood fibre level for panels with MAPP compared with the controls.

For the 2 h water-boil test, both the 1 and 3% MAPP levels produced statistically significant reductions in water absorption values - 39 and 27%, respectively - for the 70% wood fibre level (Fig. 10). At the 85% wood fibre level, MAPP did not significantly influence water absorption.

Discussion

The increase in most mechanical and dimensional stability properties of non-woven web composite panels after incorporation of MAPP indicates that this agent does indeed provide some degree of coupling between the wood and polypropylene fibres. Differences were

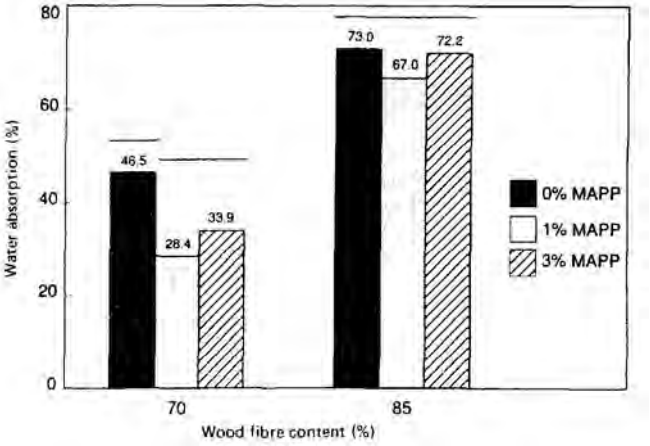

Fig. 10 Water absorption of non-woven web composites in 2 h water-boil test as a function of wood fibre content and MAPP level

observed between modulus of elasticity values obtained from the nondestructive stress wave test and those from the cantilever bending test[11]. We believe that these differences can be attributed to the time-dependent behaviour of the materials being tested in this study. During the static cantilever bending tests conducted on the wood fibre/polypropylene fibre composites. significant relaxation and rearrangement between the constituents may have occurred. thus increasing the deflections observed and lowering the values obtained for cantilever beam bending stiffness. 'lime-dependent properties are not a consideration during dynamic testing[X].

The TAPPI standard impact energy test used for the non-woven web system is probably the best test for conditions that automotive panels are likely to be subjected to. This test emphasizes the initiation step of impact fracture and hence the influence of stress concentrations at existing defects. The positive influence of MAPP on impact fracture may reflect improved bonding and wetting between wood and polymer, a consequent reduction in number and size of fracture-initiating defects, and finally, an increase in energy-absorbing ability caused by increased bonding between the wood and polymer components of the composite[12].

Depending upon the end-use of the product, dimensional stability in water, especially in the thickness direction. can be a great problem in composites made from a high percentage of wood fibres. The composites undergo not only normal (reversible) swelling but also swelling caused by the release of residual compressive stresses imparted to the product during pressing[13]. One noteworthy observation from the water-soak and water-boil experiments is that doubling the amount of polypropylene (that is, decreasing the amount of wood fibre from 85 to 70%) approximately halved both the thickness swell and water absorption values. These results suggest that the polypropylene is encapsulating the wood fibres, thus limiting water uptake by these fibres.

Concluding remarks

The influence of small quantities of a maleated polypropylene (MAPP) on the properties of

thermoformable composites prepared by using non-woven web technology with wood and polypropylene fibres was examined.

At both 70 and 85% wood fibre levels, the addition of as little as 1% MAPP significantly increased bending and tensile strength and moduli, and dynamic modulus. No consistent improvements in these properties were noted with an increase in MAPP content from 1 to 3%.

Impact energy at the 70% wood fibre level was increased significantly at the 3% MAPP level, but not at the 1% level. At the 85% wood fibre level, both MAPP levels significantly increased the capability of the panels to absorb impact energy.

Thickness swell properties after a 24 h water-soak or 2 h water-boil test were improved by 1 or 3% MAPP only at the 85% wood fibre level. With 70% wood fibre, no definitive trends at the 1 or 3% MAPP level were observed in either test.

The presence of MAPP at either the 1 or 3% level decreased water absorption properties at the 70% wood fibre level in both the 24 h water-soak and the 2 h water-boil tests. No definitive trends were noted at the 85% wood fibre level at either MAPP level for either of these tests.

The effectiveness of MAPP is believed to be a result of efficient incorporation of the material at the wood/polypropylene interface, thus providing some degree of effective coupling of the polar wood components to the non-polar polyolefin matrix.

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