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Flat-Pressed Wood Plastic Composite as an Alternative to Conventional Wood-Based Panels

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ABSTRACT

This study evaluated physical and mechanical properties of the wood plastic composite panels made using dry-blended rubberwood fiber-polypropylene (PP) powder formulations using a conventional flat-press process under laboratory conditions. Three levels of the rubberwood fibers (*Hevea brasiliensis*), 40%, 50%, and 60% based on the composition by weight, were mixed with the PP powder without and with 3% (based on weight) maleic anhydride grafted PP (MAPP) as a coupling agent. Water resistance of the panels was negatively influenced by the increasing wood fiber content. Maximum value of the modulus of rupture of the panels was reached at 50% fiber content and then decreased as the fiber content reached 60%. The modulus of elasticity the panels increased with the increase in fiber content from 40 to 60%. Internal bond strength and screw withdrawal resistance declined with the increase in fiber content from 40 to 60%. Formulations with MAPP were found to have higher strength and better water resistance.

INTRODUCTION

Wood plastic composites (WPCs) are a relatively new class of materials and one of the fastest growing sectors in the wood composites industry. WPC consists of a mixture of wood, thermoplastics and some additives. Typically, the wood content of WPCs is in the range between 50% and 80% (by weight) [Clemons 2002]. The predominant technologies to produce WPCs are extrusion to obtain endless profiles and injection moulding leading to 3-dimensional forms, although commercially less important. Another possibility which has only little been explored is to produce WPCs on a flat-press. The advantage of this technology is that only a relatively low pressure level is required, compared to extrusion and injection moulding. As a consequence, the naturally given wood structure is maintained, resulting in a considerably reduced material density. The productivity of the pressing technology is much higher than that of extrusion and injection moulding. Flat-pressed WPCs made using a dry-blending method have a clear cost advantage.

Hot press molding is a new, simple method for producing panels with high fiber content, high dimension, different density, and lower cost in comparison with other methods and its products are closely comparable to commercial medium density fiberboard (MDF) and particleboard. Moreover, an important drawback of MDF and particleboard is the dispersion of formaldehyde gases that can be environmentally dangerous. WPC panels may be used for applications that require high moisture resistance, and that shall be easy to maintain. The use of conventional wood-based composites, such as particleboard and MDF, is quite limited for exterior and moist applications, due to the strong tendency of such materials to absorb water. By contrast, WPCs show a considerably reduced affinity towards water, compared to conventional wood-based composites such as particleboard and fiberboard, what is caused by their relatively high thermoplastic content.

Currently, interior fitment and furniture manufacturers using wood based panels such as particle board and MDF do not commonly know the flat-pressed WPC panels. However, WPC panels can be a competitor to overlaid wood based panels in office furniture manufacture. In a previous study, it was reported that WPC panels can be overlaid with wood veneer sheeet using urea-formaldehyde resin [Jarusombuti and Ayrilmis 2009]. Overlaid panels can be also used in the construction of cabinets, paneling, kitchen worktops, and work surfaces in offices, educational establishments, laboratories, and other industrial product applications.

Physical and mechanical properties of the flat-pressed WPC panels made using a dry-blending method have not been widely studied. For this aim, physical and mechanical properties of the WPC panels made from various mixtures of the wood fiber and PP powder were investigated, using a method currently used in the wood based panel industry. In addition, effect of the compatibilizer on the above mentioned properties of the WPC panels was evaluated. Rubberwood (*Havea brasiliensis*) fibers were used in the WPC panel manufacture. It is main raw material for wood composite panel production such as fiberboard and particleboard in Asia. Projected rubberwood resources for composite panel industry is approximately 1.13 and 1.93 million m^3 for the years 2007 and 2017, respectively [Hiziroglu et al. 2004]. Majority of MDF and particleboard produced in Thailand is used as substrate for thin overlay in cabinet and molded door skin production. Table 1 shows the raw material formulations used for the WPC panels. The values chosen for the wood fiber/plastic content are within a range most commonly employed in the manufacture of wood plastic composites [Clemons 2002].

EXPERIMENTAL INVESTIGATION

Materials

Rubberwood fibers (*Hevea brasiliensis*) having average 1.5 mm length, were obtained from a commercial MDF plant in Thailand. The wood fibers were produced using a thermo-mechanical refining process without any chemical and resin. The moisture content of the fibers, as determined by oven-dry weight, was found to be a 2–3% prior to treatment. Rubberwood is composed fibers (58%), vessel elements (8.5%), axial parenchyma (11.5%), and rays (22%) and are distributed in different patterns and proportions as in other typical hardwood species. The fibers are non-septate, and belong to the medium group with a length of 0.8-1.8 mm. The width of the fibers ranges from 19-27 µm [Mathew 2004].

The polypropylene (PP) (T_m = 160°C, ρ = 0.9 g/cm^3, MFI/230°C/2.16 kg = 6.5 g/10 min) and Maleic anhydride-grafted PP (MAPP-OPTIM-415; the reactive modifier maleic anhydride (MAH) content = 1 wt.%) were used as the polymeric materials. The PP granules then processed by a rotary grinder without adding additional water. Finally, the PP powder passing through a U.S. 40-mesh screen and was retained by a U.S. 80-mesh screen. The PP powder was then dried in a laboratory oven at 102°C for 24 hours to moisture content of 0-1% based on the oven-dry PP weight.

Table 1. Compositions of the Evaluated WPC Panel Formulations

WPC panel type	Panel composition (by % weight)		
	Wood fiber	Polypropylene	Maleic anhydride-grafted polypropylene (MAPP)
A	40	60	-
B	50	50	-
C	60	40	-
D	40	57	3
E	50	47	3
F	60	37	3

Flat-pressed WPC panel manufacture

Flat-pressed WPC panels were manufactured using standardized procedures that simulated industrial production at the laboratory. The mixture was weighed and then formed into a mat on an aluminum caul plate, using a forming box. After mixing wood fibers and the PP powder and placing the mixture into a rotary drum blender the mixture was weighed and then formed into a mat on an aluminum caul plate, using a forming box. Wax paper was used to avoid direct contact of PP powder with the metal platens during heating and pressing. To reduce the mat height and to densify the mat, the mat was cold pressed. This procedure allowed for easy insertion of the mats into the hot-press. The mats were then subjected to hot-pressing, using a manually controlled electrical-heated press. The maximum press pressure, pressing temperature, and total press cycle were 3.5 N/mm^2, 170ºC, and 6 min, respectively. Temperature was set to ensure that it is slightly above the melting point of the plastic component. At the end of the press cycle, the board was removed from the press for cooling (Fig. 1). The nominal panel size was 250 mm x 250 mm x 10 mm after the cooling process. A total of 12 experimental panels, two for each type of panel, were manufactured (Fig. 1). The density values of the WPC panels were 0.79 to 0.80 g/cm^3.

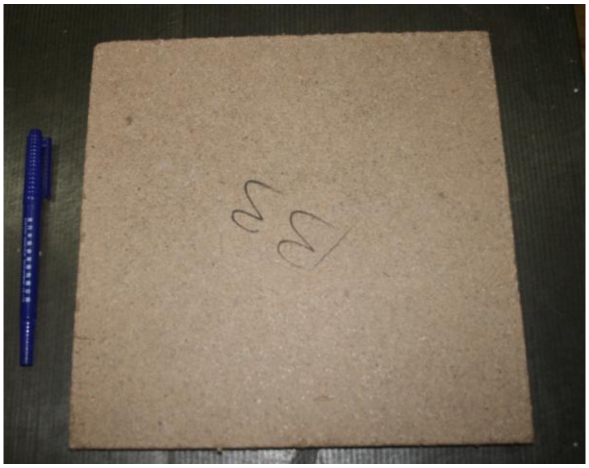


Fig. 1. Flat-Pressed WPC Panel Made From Dry-Blended Rubber Wood Fibers and PP Powder

Determination of water resistance

Water resistance of the panels, thickness swelling (TS) and water absorption (WA), was evaluated according to EN 317 (1993). Twenty samples, 50 mm x 50 mm x 10 mm, from each type of panel type were used for the TS and WA properties. Prior to tests, samples were conditioned in a climatized room at 20°C and 65% relative humidity. The samples were immediately weighed. The sample thickness was determined by taking a measurement at a specific location, the diagonal crosspoint, on the sample. After 24 h of submersion, samples were drip-dried for 10 min, wiped clean of any surface water, and weighed. Density of the samples was evaluated according to the test method and requirement of EN 323 (1993).

Determination of mechanical properties

Flexural properties (modulus of rupture (MOR) and modulus of elasticity (MOE)) of the samples conditioned to equilibrium at a temperature of at 20°C and 65% relative humidity were conducted according to EN 310 (1993). A total of 20 samples with dimensions of 250 mm x 50 mm x 10 mm, 10 parallel and 10 perpendicular to the panel surface, were tested for each panel type to determine MOR and MOE. The flexural samples were tested on a Instron testing system Model-22 5500-R equipped with a load cell with a capacity of 5 ton. Load-deflection data for the calculation of the sample's MOE were recorded at the 10% and 40% values of failure load (P_{max}). The crosshead speed was adjusted so that failure would occur within an average of 60 ± 10 s.

Internal bond (IB) tests were conducted on samples cut from the experimental WPC panels according to EN 319 (1993). Twenty samples in 50 mm x 50 mm x 10 mm from each type of panel were used to determine the IB strength. The load was continuously applied to the samples throughout the tests at a uniform rate of motion of the movable crosshead of the testing machine of 1.2 mm/min until failure occurs. For screw withdrawal resistance (SWR) perpendicular to the plane of the board, twenty samples with dimensions of 75 mm x 75 mm x 10 mm from each type of panel were tested according to EN 320 (1993). The force required to withdraw each screw was recorded as Newton.

RESULTS AND DISCUSSION

Water resistance

Table 2 shows the TS and WA values of the panel types at various fiber content levels after 24 h immersion. Water resistance of the WPC panels decreased with the increasing of the wood fiber content. As shown, the panels with 40% fiber content had TS and WA values with 3.23% and 5.33%, whereas the panels with 60% fiber content had TA and WA values with 6.64% and 8.57%, respectively. In other words, as fiber content increased from 40 to 60%, the TS values of WPC panels due to the hydrophilic property of natural fibers increased. The WA values of the samples showed the similar tendency to the results the TS. The WA values of the composites were higher than the TS values. Statistical analysis found some significant differences among panel types for the TS and WA values. Significant differences are shown by letters in Table 2. Wood based panel standards were used here for comparison of the TS and the WA values since there was no established minimum property for the WPC. Table 2 also shows that the samples containing the MAPP had significantly lower TS and WA than those made without the MAPP. 24-h TS values of all panel types met particleboard Type 7 (9%) and MDF Type HLS (10%) maximum requirements of EN 312 (2003) and EN 622-5 (1997), respectively. The TS and WA values of the samples were also less than those of particleboard, oriented strandboard, and medium density fiberboard because the matrix polymers are hydrophobic [Akbulut et al. 2002; Ayrilmis 2000]. In a previous study, average TS and WA values of MDF panels after 24-h of submersion were found as 6.7% and 15.9%, respectively [Ayrilmis 2000].

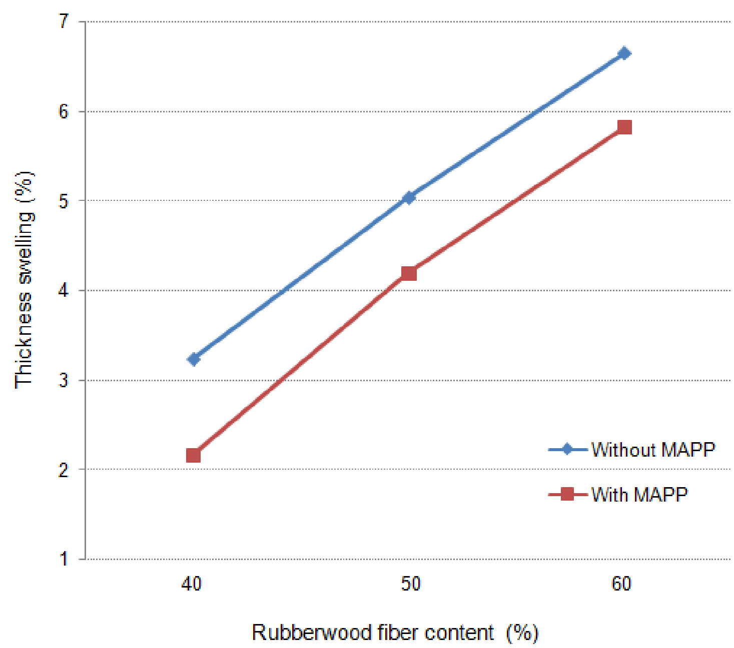
Table 2. Physical Properties of the Flat-Pressed WPC Panels

WPC panel type	Physical properties		
	Density (g/cm^3)	Thickness swelling (24h) (%)	Water absorption (24 h) (%)
A	0.81 (0.05)	3.23 (0.35) A[1]	5.33 A (0.43)
B	0.80 (0.06)	5.03 (0.46) B	7.14 B (0.50)
C	0.83 (0.07)	6.64 (0.61) C	8.57 C (0.57)
D	0.82 (0.04)	2.16 (0.29) D	4.51 D (0.24)
E	0.81 (0.05)	4.19 (0.38) E	6.24 E (0.45)
F	0.80 (0.03)	5.82 (0.55) F	7.85 F (0.49)
Quality requirements for MDF	> 0.60[2]	Max. 10[3]	-

[1] Groups with same letters in column indicate that there is no statistical difference ($p < 0.01$) between the samples according Duncan's multiply range test. Values in parentheses are standard deviations.
[2] Quality requirement for dry-process fiberboards according to EN 316 (1999).
[3] Quality requirements for load bearing MDF panels (Type HLS) for use in humid conditions (short periods of loading) and nominal thickness > 9mm to 12 mm) according to EN 622-5 (2005).

The water resistance of the panels improved with the increasing polymer content (Fig. 2). This was attributed to the hydrophobic character of PP because of its being devoid of functional polar groups such as hydroxyls in the molecular and thus chemically inactive. Wood is a hydrophilic porous composite of cellulose, lignin and hemicellulose polymers that are rich in functional groups such as hydroxyls readily interact with water molecules by hydrogen bonding [Clemons 2002]. For this reason, the WPC composites have potential to take up water under humid conditions due to the presence of numerous hydroxyl [Adhikary et al. 2008]. Wood also has a critical surface energy in the 40–60 mJ/m^2 range [Gupta et al. 2007]. On the other hand PP has very low surface energy (20-25 mJ/m^2), is hydrophobicoid of functional groups [Inagaki 1996]. This large difference between PP and wood is what causes PP to be water repellent or hydrophobic. The lower TS and WA of the WPC panels having higher plastic powder can also be explanied by the fact that it fills micropores in wood. The PP may also crystallize on the wood fibers and thereby wrapping the wood fibers better and leaving less exposed the wood on the WPC surface. With the increasing wood fiber content, the TS and WA tend to increase as a larger share of the particle surface is insufficiently bonded and protected by the plastic component, and the greater connectivity between particles allows for easier moisture intrusion.

MAPP compatibilizer has been extensively used in wood fiber and polymer composites and improve the filler/fiber bonding and in turn to enhance the water resistance [Clemons 2002]. Addition of the MAPP into the WPC panels significantly improved the water resistance. The strong interfacial bonding between the filler and the polymer matrix caused by the compatibilizing agents (the MAPP chemically bonds with the OH groups in the lignocellulosic filler) limits the WA of the composites. The coupling agents improve the quality of adhesion between plastics and fibers to reduce the gaps in the interfacial region and to block the hydrophilic groups [Youngquist 1999]. The anhydride groups in the MAPP enter into an esterification reaction with the surface hydroxyl groups of wood fibers and covalently bond to the hydroxyl groups [Adhikary et al. 2008]. With the decreasing hydroxyl groups on the fiber surface, hydrogen-bonding sites for water molecules decreased on the WPC surface and this resulted in a lower TS and WA value.



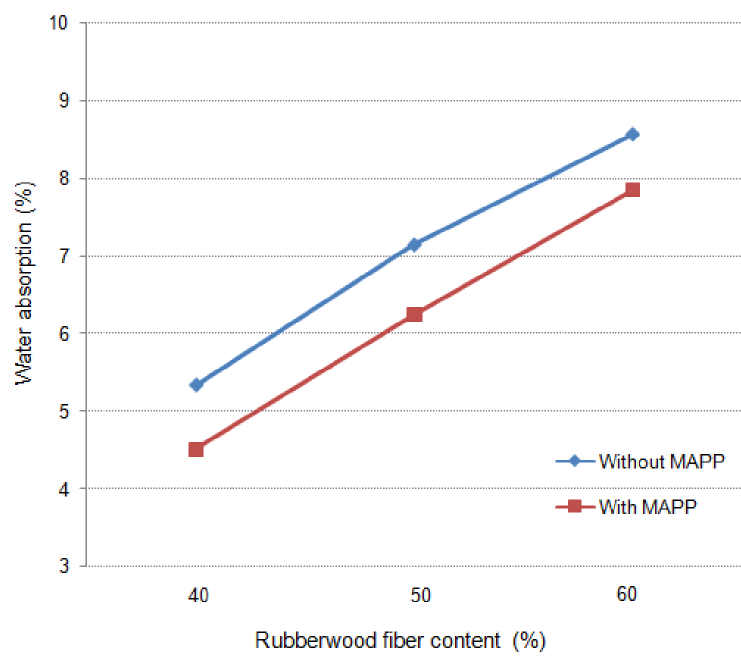


Fig. 2. **Effects of Wood Fiber Content (% by weight) and Coupling Agent (MAPP) on the Thickness Swelling and Water Absorption of the WPC panels**

Mechanical properties

The MOR of the panels significantly increased with the increase in the wood fiber content from 40 to 50% and then decreased as the fiber content reached 60% but this decrease was not significant (Table 3). The average MOR value of the panels containing 40 wt. % wood fiber (panel type: A) were 23.6 N/mm^2 as compared to the panels containing 50 wt. % wood fiber (panel type: B) which were 26.5 N/mm^2. The modulus of elasticity the panels increased with the increasing fiber content from 40 to 60%. The moduli of natural fibers are higher than that of PP [Chaharmahali et al. 2008]. Hence, when fiber content of the panels increased from 40 to 60%, the moduli of the WPC panels increased. Similar results were also reported in previous studies [Caulfield et al. 2005; Chaharmahali et al. 2008; Youngquist 1999]. Addition of the MAPP into the WPCs significantly improved flexural properties as compared to the WPCs without MAPP at the same wood fiber content (Table 3). These results are consistent with previous studies [Youngquist 1999; Adhikary et al. 2008; Nourbakhsh and Ashori 2009]. The MOR and MOE values of all panel types met particleboard Type 5 (18 N/mm^2 and 2550 N/mm^2) and MDF (22 N/mm^2 and 2500 N/mm^2) minimum requirements of EN 312 (2003) and EN 622-5 (1999), respectively. The MOR and MOE values of the samples were also higher than those of commercial particleboard (20.5 N/mm^2 and 2400 N/mm^2) and MDF (24 N/mm^2 and 2400 N/mm^2) reported [Youngquist 1999].

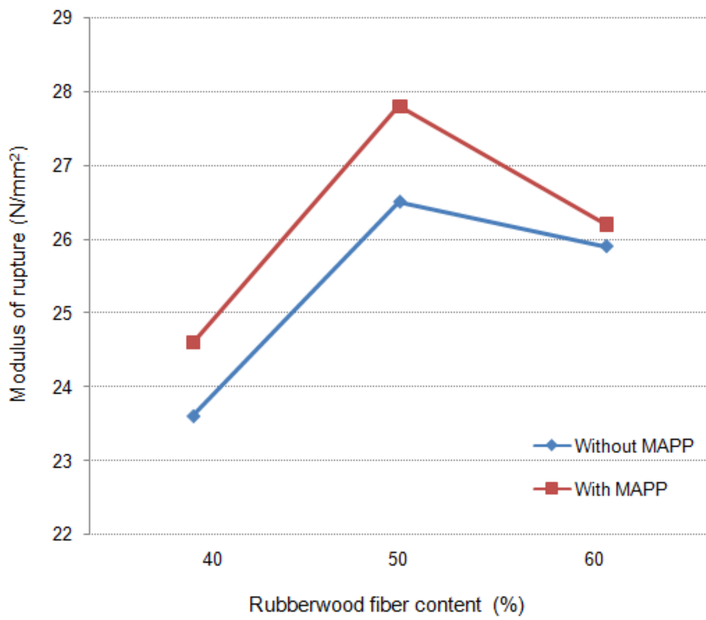
Table 3. Mechanical Properties of the Flat-Pressed WPC Panels

WPC panel type	Mechanical properties			
	Modulus of rupture (N/mm^2)	Modulus of elasticity (N/mm^2)	Internal bond (N/mm^2)	Screw withdrawal resistance (N)
A	23.6 (0.88) A[1]	2590.5 (125) A	0.92 (0.15) A	1301.4 (51) A
B	26.5 (1.05) B	2743.7 (132) B	0.76 (0.14) B	1198.8 (36) B
C	25.9 (0.91) B	2924.6 (164) C	0.61 (0.10) C	1098.6 (42)C
D	24.6 (0.85) C	2684.5 (146) D	0.96 (0.18) A	1332.5 (58) A
E	27.8 (1.16) D	2834.3 (152) E	0.84 (0.15) D	1224.1 (55) B
F	26.2 (0.94) B	2978.4 (161) C	0.69 (0.12) E	1121.3 (46) C
Quality requirements for MDF	Min. 22[2]	Min. 2500[2]	Min. 0.60[2]	1100[3]

[1] Groups with same letters in column indicate that there is no statistical difference ($p < 0.01$) between the samples according Duncan's multiply range test. Values in parentheses are standard deviations.
[2] Quality requirements for general-purpose MDF panels for use in dry conditions and nominal thickness > 9mm to 12 mm) according to EN 622-5 (2005).
[3] Medium density fiberboard (MDF) Grade 130, ANSI A208.2–2002, Medium density fiberboard (MDF) for interior applications.

It is generally accepted that longer fibers obtain an increased network system by themselves and result in increased bending properties of composites. Strength loss is due to the relatively larger surface area of the fine materials [Maloney 1977]. Therefore, the MOR of the panels improved as wood fiber content increases from 40 to 50%. On the other hand, with increasing fiber content from 50 to 60%, the MOR values of the WPC panels decreased (Fig. 3). It appears that the amount of plastics in the panels decreases as fiber content increases from 50 to 60% and the utilized plastics in these composite panels act as an adhesive for binding wood fibers together.

Wood is a lignocellulosic material made up of three major constituents (cellulose: 42–44%, hemicelluloses: 27–28%, and lignin: 24–28%) with some minor constituents (extractives: 3–4%) [Walker 2004]. The major portion of the wood is crystalline cellulose. The aligned fibril structure of the cellulose along with strong hydrogen bond has high stiffness thus addition of the wood fiber can increase the stiffness of the thermoplastic based composites. Lignin as an amorphous polymer does not greatly contribute to the mechanical properties of the wood fiber but plays an important role in binding the cellulose fibrils that allows efficient stress transfer to the cellulose molecules. Hence, the wood fiber increases the stiffness of the PP without excessively increasing the density [Adhikary et al. 2008].



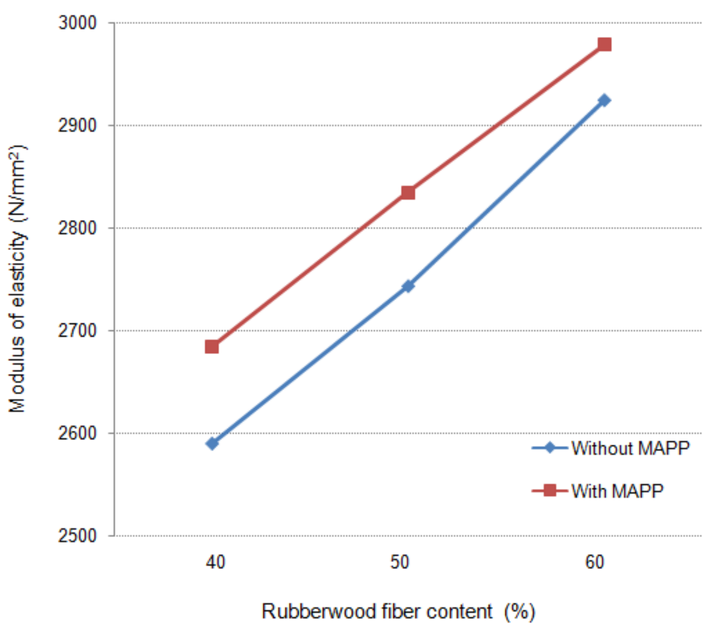


Fig. 3. Effects of Wood Fiber Content (% by Weight) and Coupling Agent (MAPP) on the Modulus Rupture and Modulus of Elasticity of the WPC Panels

The average IB values of each type of WPC formulation are presented in Table 3. The IB values of the WPC samples were significantly affected by the increasing portion of wood fibers in the panel (Fig. 4). The average IB strength decreased by 33.7% when comparing the 40% and 60% wood filler content results. For example, the average IB value of the panels containing 40 wt. % wood fiber (panel type: A) were 0.92 N/mm^2 as compared to the panels containing 60 wt. % wood fiber (panel type: C) which were 0.61 N/mm^2. This fact is due to decreasing the amount of binding between plastics and wood fibers, since the fiber content increases and so the amount of plastic, as the adhesive, decreases. The WPC samples with MAPP had higher IB strength than those of the samples without MAPP. This was attributed to polar interactions between MAPP and hydroxyl groups on the fiber surface. As mentioned before, the use of MAPP improves interaction and adhesion between the fibers and matrix.

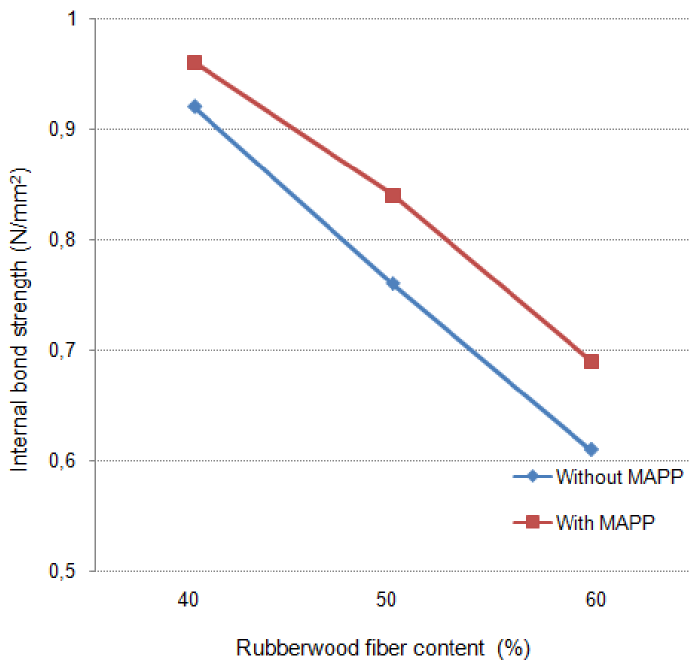


Fig. 4. Effects of Wood Fiber Content (% by weight) and Coupling Agent (MAPP) on the Internal Bond Strength of the WPC Panels

It can be observed that the surface SWR in all cases significantly decreased with the increase in fiber content (Table 3). The average SWR strength decreased by 15.6% when comparing the 40% and 60% wood filler content results. The WPC panels with wood fiber to polymer ratio of 60:40 had a SWR value of 1098.6 N while the SWR of the panels with wood fiber to polymer ratio of 40:60 was 1301.4 N. These findings show that for higher fiber loading the fastener withdrawal strengths are decreased. The SWR values of wood based panels such as particleboard, MDF, and oriented strandboard, range from 700 to 1100 N [Ayrilmis 2000; Akbulut et al. 2002]. As shown in Table 3, the flat-pressed WPC panels showed better SWR than those of the wood based panels. The higher capacity of the screws in the WPCs compared with those of the wood based panels is probably due to the ability of the thermoplastic to conform around the thread of the screw, allowing continuous load transfer along the thread [Falk et al. 2001]. Furthermore, the panels with MAPP have slightly higher SWR than those without MAPP. This finding is also consistent with previous findings [Razi et al. 1999] and also with Adhikary et al.'s (2008) measurements of other properties.

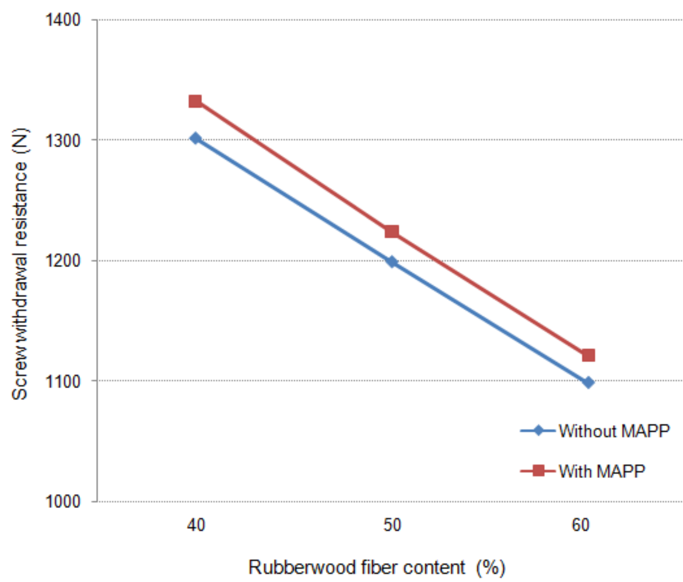


Fig. 5. Effects of Wood Fiber Content (% by weight) and Coupling Agent (MAPP) on the Screw Withdrawal Resistance of the WPC Panels

CONCLUSIONS

The following general conclusions can be drawn from the study provided in the paper:

- The physical and mechanical properties of the flat-pressed WPC panels were significatly affected by the rubberwood fiber/polymer ratio.
- With the increasing polymer content, the water resistance of the panels improved.
- The modulus of elasticity the panels increased with the increase in the wood fiber content from 40 to 60%. The material stiffness properties were significantly increased with the addition of wood fiber content to thermoplastic from 40 to 60%.
- The WPC panels with higher wood fiber content exhibit lower fastener strength and internal bond strength.
- WPC formulations with MAPP were found to have higher strength and better water resistance.
- The comparison of the physical and mechanical properties of the produced panels with those of MDF and particleboard revealed that the flat-pressed WPC panels can be evaluated as an alternative to conventional wood based panels in construction and furniture industries. A 50/50 formulation of the rubberwood fiber and PP appears to a practical choice for applications requiring a higher water resistance such as roof siding and fastener strength for furniture manufacture.

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