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WOOD-PLASTIC COMPOSITES FROM LESSER-KNOWN TROPICAL TIMBER SPECIES: AN ALTERNATIVE MATERIAL IN WOOD-BASED INDUSTRY

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INTRODUCTION

Wood-plastic composites (WPCs) are defined as composite materials containing wood (in many forms) and thermoplastic materials. WPCs are renewable and biodegradable (Tabarsa et al. 2011). WPCs have been developed and widely used for the last 40 years in both structural and non-structural applications. Some of the applications include component and product prototyping, outdoor decking (Schwarzkopf & Burnard 2016), and as material in construction and automotive industries (Eder & Carus 2013). WPCs have become one of the preferred building materials because of the low density, low manufacturing cost, renewability, and highly recyclable (Zhang et al. 2012) as well as having good stability and mechanical properties (Adhikary et al. 2008).

Among the main advantages of using WPCs are their low maintenance, thermally stable than plastic, good dimensional stability, low water absorption, resistant to rot (for WPCs containing biocide), can be easily fabricated into engineered profiles, lower physical and mechanical variability than wood, do not warp and splinter, and possibility to be used as tailored products (Suttie 2007). Thus, it makes many researchers and inventors more eager to work and adapt WPCs into a wide range of applications (Valles-Rosales et al. 2016).

In the manufacture of WPCs, polypropylene (PP), polyethylene (PE) and polyvinyl chloride (PVC) are the widely used thermoplastics (Panthapulakkal et al. 2006). Of these three, PP is more favorable to be used because of its density being the lowest among commodity plastics. It also has excellent chemical resistance, can be applied by many methods such as injection moulding and extrusion, and is a free-colour material with excellent mechanical properties (Maddah 2016). Nevertheless, the particle size, surface characteristics and the interfacial properties between the wood and plastic will influence the mechanical properties of WPCs (Shebani et al. 2009).

Production of WPCs using commercial tropical wood species such as *Gmelina arborea* and *Terminalia superba* is a common practice (Aina & Fuwape 2008), but the use of lesser-known species especially from plantation forest is unheard of. *Macaranga* sp. from the Euphorbiaceae family is one of the lesser-known species that has potential as an alternative source for wood-based industries if its properties can be improved (Ang et al. 2014). Therefore, the objective of this study was to determine the physical and mechanical properties of WPCs board using *Macaranga* sp. wood and low-density polypropylene at different mixing ratios.

MATERIALS AND METHODS

Macaranga sp. tree

Macaranga sp. wood was obtained from the Forest Research Institute Malaysia campus. The logs of approximately 2 m length are air-dried for several days to reduce the moisture content before being converted into wood chips.

Polypropylene

The polymer used was a low-density polypropylene and the compositions of plastic and fibre contents are given in Table 1. This polymer was supplied by Polypropylene Malaysia Sdn. Bhd. in pellet form.

Table 1 The composition of plastic and fibre content

Plastic content (%)	Fibre content (%)
100	0
90	10
80	20
70	30
60	40

Preparation of wood particles

Macaranga sp. logs were manually cleaned from dirt and impurities. A drum chipper machine (Pallmann PZ 8) was used to disintegrate the *Macaranga* sp. into chips. The chips were further refined with a knife ring flaker machine (Pallmann PHT 120/430) and a disc mill (FFC 45A) to obtain particles less than 0.5 mm size. The particles were then dried in an oven at 70^{o}C to achieve a moisture content of 6 to 8%.

Mixing process

The mixing process of *Macaranga* sp. particles and low-density polypropylene (LDPP) polymer was done in a blender with 3000g capacity at 180^{o}C. Four different mixtures were prepared, namely 90:10, 80:20, 70:30 and 60:40 (LDPP:wood). The mixture's size was reduced to less than 0.5 mm using a crusher. Table 2 shows the production parameter of the WPCs.

Table 2 Production parameters of WPCs

Parameter	Value
Press temperature (^{o}C)	180
Pressing time (min)	9–10
Press pressure (kg/cm^2)	10
Hardener (%)	0
Thickness (mm)	3
Target density (kg/m^3)	1000

WPCs board making

The wood-plastic mixtures were manually arranged in a mould to form a mat with dimensions of 250 mm (length) × 250 mm (width) × 3 mm (thickness). The mat was then pre-pressed in a cold press at 35 kg/cm^2 pressure and subsequently pressed in a hot press machine (Taihei) at 180°C for 9–10 min to obtain the targeted thickness. Three replicates were prepared for each WPCs composition (Table 1). All samples were kept in a conditioning chamber at 65% relative humidity and at temperature of 20°C for approximately three days prior to testing.

Physical properties

Two tests, namely thickness swelling (TS) and water absorption (WA), were performed for the produced WPCs based on ASTM D7031-18 (2018) method. The WPC panels were cut into 76.2 mm × 25.4 mm dimensions for TS and WA. The thickness (mm), weight (g) and length (mm) of the samples were measured prior to the test. Then the test blocks were soaked in water at room temperature for 24 hours, and the final measurements were subsequently taken. Ten (10) replicates were tested for each test including 10 replicates as control samples (100% plastic). The TS and WA were calculated based on the following equations:

$$\text{TS (\%)} = [(T_f - T_o)/T_o] \times 100, \tag{1}$$

where, T_f was the thickness (mm) of WPC after soaking in water, and T_o was the original thickness (mm) of WPC.

$$\text{Water absorption (\%)} = [(W_t - W_c)/W_c] \times 100 \tag{2}$$

where, W_t was the weight gain (g) in WPC due to water pickup after 24 h and W_c was the initial weight (g) of WPC.

Mechanical tests

a) Static bending test

Static bending test was carried out using test samples measuring 25 mm (length) × 130 mm (width) based on ASTM D790-17 (2017) method at room temperature. Modulus of rupture (MOR) was the ultimate breaking strength when each sample was loaded as a simple beam while the modulus of elasticity (MOE) was related to the stiffness of the beam.

b) Tensile test

Tensile test was performed in accordance with ASTM D638-10 (2010). The test was conducted at a constant strain rate of 10 mm/min at ambient condition. Tensile stress was applied until the failure of the sample and the stress-strain curve was obtained. Five replicates were tested for each composite composition.

c) Izod impact test

Izod impact strength was measured with a Gotech impact pendulum tester (MODEL GT-7045-MD) according to ASTM D256-18 (2018) on acutely notched samples (notch depth = 0.2 mm) at ambient condition. Samples for the test were each having dimensions of 64 mm (length) × 13 mm (width) × 3 mm (thickness). Each sample was clamped into a pendulum impact test fixture with the notched side facing the striking edge of the pendulum. The pendulum was released and allowed to strike the sample. The impact energy was expressed in J/m^2. Impact strength was calculated by dividing impact energy in Joule by the cross-sectional area of the notched part of the sample. Five replicates for each composition were tested.

d) Termites bioassays

Test samples each measuring 25 mm (length) × 25 mm (width) × 6 mm (thickness) were cut from each of the WPCs boards. The samples were subjected to termite bioassays according to the no-choice test procedure of Roszaini et al. (2019). Untreated rubberwood (*Hevea brasiliensis*) and board with 100% plastic samples were also used as control. Five replicates which include the control samples, were used for each test.

Subterranean termites, *Coptotermes curvignathus* Holmgren (Isoptera: Rhinotermitidae), were collected from active field colonies in FRIM campus using a trapping technique (Kirton et al. 1998). Screw-top bottles of 8 cm in diameter by 13 cm in height were filled with 200 g of sterilised sand and 30 ml distilled water. The bottles were left overnight to equilibrate to laboratory conditions before test initiation. One sample was placed on the surface of the damp sand and 400 termites (360 workers and 40 soldiers) were added to each bottle. Then, the bottles were stored in an incubator maintained at 22±2°C and 65±5% relative humidity for 28 days. Within this period, if observations made indicated that all the termites were dead, the bottle would be taken out and the number of days until 100% mortality would be recorded. At the end of the fourth week, the samples were removed, cleaned, dried overnight and reweighed. The remaining living termites were weighed and recorded for each of the bottles. As detailed in the standard, the condition of the test blocks was rated visually using a 0–10 scale, where 10 is rated as sound and 0 represents a total failure.

e) Statistical analysis

Mechanical properties and termite bioassay data were analyzed for significant differences between the means using the one-way analysis of variance (ANOVA) procedure in SigmaStat (SPSS 1997). Tukey's multiple comparisons test (95% confidence) was employed to determine the differences between untreated samples and the various treatments.

RESULTS AND DISCUSSION

Physical properties

Figure 1 shows that water absorption increases in proportion to the amount of wood particles. Mixtures of WPCs began to show increased water absorption starting from mixing ratio 100:0 (0.33%), followed by 90:10 (0.51%), 80:20 (0.53%), 70:30 (1.57%) and 60:40 (1.87%), all which were less than the value (20–75%) specified in ASTM D7031 (2011) for water absorption. This study also found that WPCs produced from *Macaranga* sp. can reduce the absorption rate of water even though the addition of wood particle exceeds 30%. The study revealed that when plastic content in the WPCs was reduced, the protection of wood content decreased (less encapsulated) where the number of free hydroxyl groups (OH) groups in the cellulose (wood particles) increased. When these OH groups were exposed to water, formation of hydrogen bonds will occur resulting in increased water absorption. Thus, wood particles will easily absorb water due to the lack of barriers (Mishra & Verma 2006). This finding was similar to the study by Izekor and Mordi (2014) on the properties of wood composites. The ANOVA (at 0.05 probability level) results showed that water absorption was significantly affected by the amount of wood when tested in the 24 hours water immersion test.

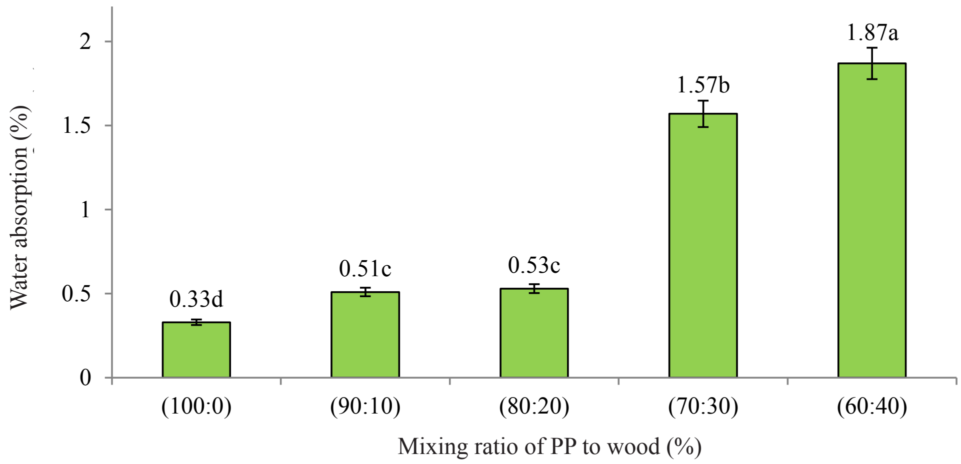

Figure 1 Water absorption of experimental boards after 24 hours immersion in water. Mean values (values above bars) followed by the same letter are not significantly different at 0.05 level of probability.

WPCs containing different plastic-wood fibres mixture ratios showed low thickness swelling percentage. After the 24 hours water immersion tests (Figure 2), the plastic-wood fibres mixing ratio 100:0 showed 0% thickness swelling, while 90:10 (0%), 80:20 (0.65%), 70:30 (0.81%) and 60:40 (0.91%). The percentage of thickness swelling from the panel produced increased as the portion of PP in the mixing ratio decreased. The lower plastic content in the panels will cause higher water content to be absorbed, proportional to the thickness swelling (Ratanawilai et al. 2017, Aina et al. 2013). They found that when WPCs were exposed to water, the swelling increased with the increasing amount of wood flour and these led to the increasing amount of cracks on the surface. The dimensional stability of WPCs was better when there was more amount of plastic than the wood itself. ANOVA (at 0.05 probability level) results showed that thickness swelling was affected by the amount of wood in WPC when tested with 24 hours of water immersion.

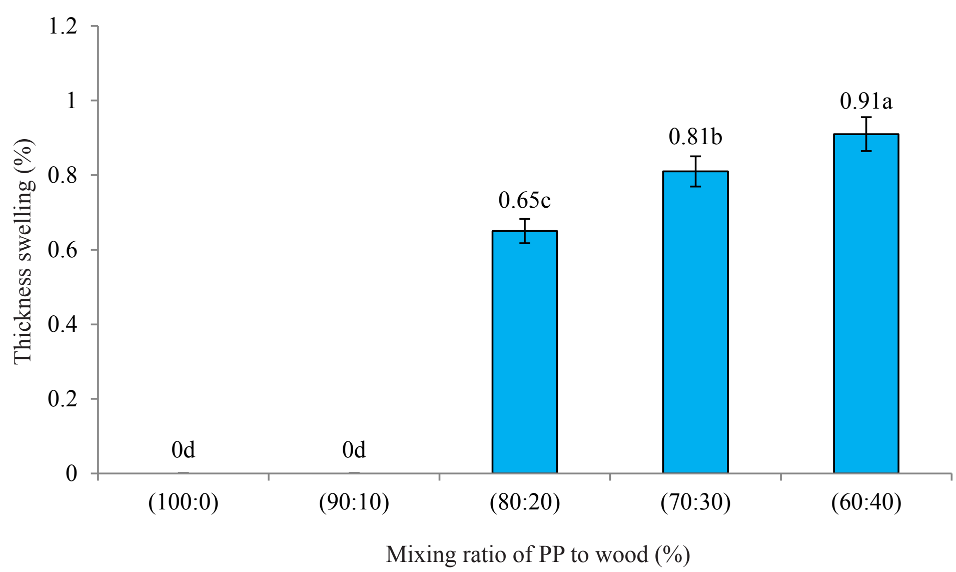

Figure 2 Thickness swelling of experimental boards after 24 hours immersion in water. Mean values (values above bars) followed by the same letter are not significantly different at 0.05 level of probability.

Mechanical properties

a) Static bending test

Figures 3 and 4 illustrate the MOR and MOE values of the tested wood plastic composites. The highest values of MOR (87 MPa) and MOE (2157 MPa) were measured from WPCs board with 100% PP and board with a mixture of 70% PP and 30% wood, respectively. The lowest MOR (32 MPa) and MOE (1597 MPa) values were determined from WPCs with a mixture of 60% PP and 40% wood. The results showed that the wood content in the mixture significantly decreased the MOE and MOR values of the WPCs. However, MOR values of all the WPCs were still higher than the minimum requirements in BS EN312 (2005) particleboard for general uses (11.5 MPa) and interior fitments including furniture (13.0 MPa). For MOE, only 60:40 mixture (1597MPa) did not meet the minimum requirements of BS EN312 (2005) particleboard for interior fitments (1600 MPa). Other WPCs had higher MOE values than the minimum requirements of BS EN312 (2005) particleboard for general uses. Hossain et al. (2014) found that by increasing the amount of wood particle content, uniform mixture and distribution of wood particles were difficult to obtain. The loss of bending strength in WPCs was probably due to moisture penetration into the boards which degraded the wood-polymer interface (Chung et al. 2017).

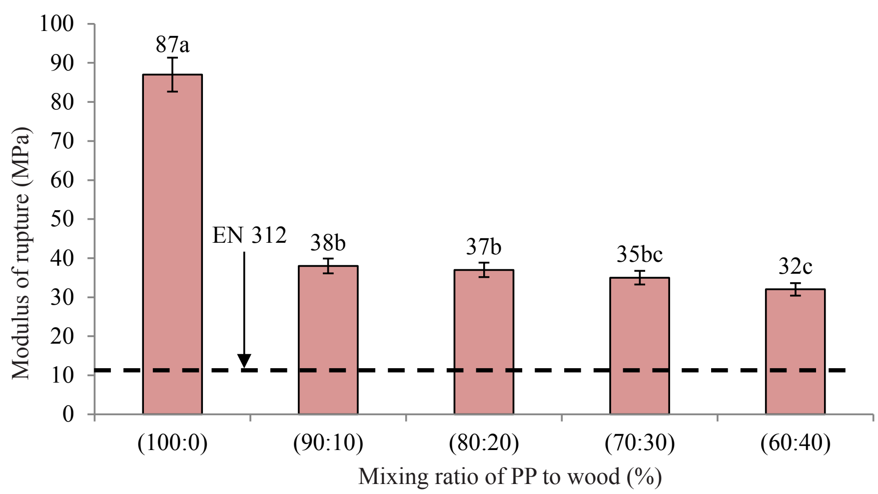

Figure 3 Modulus of rupture (MOR) of tested boards. Mean values (values above bars) followed by the same letter are not significantly different at 0.05 level of probability.

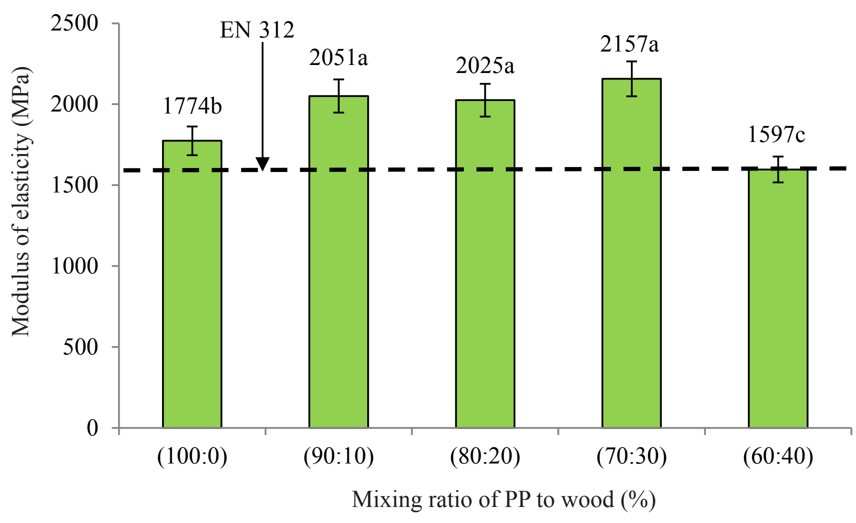

Figure 4 Modulus of elasticity (MOE) of tested boards. Mean values (values above bars) followed by the same letter are not significantly different at 0.05 level of probability.

b) Tensile test

Figure 5 depicts the tensile strength of WPCs made from different ratios of polypropylene and wood particles. Results showed that the polypropylene (100% plastic) exhibited the highest value (26 MPa) compared to other samples. The tensile strength of the composites decreased when wood particles were added due to the increment in area for a given mass, which generates a greater amount of interface between the wood particles and the polymeric matrix (Ichazo et al. 2001). Sun et al. (2006) reported that filler composition and the interfacial adhesion between particles and matrix will influence the tensile strength of some of the tested composites. The results of ANOVA showed that the PP and wood particles mixing ratio had a significant effect ($p \leq 0.05$) on the tensile strength of WPCs boards. Gulitah and Liew (2018) reported that the wood fibres were not fully bonded with the plastic matrix during the mixing process resulting in lower tensile strength. Wood fibre is hydrophilic while plastic is hydrophobic, which are not compatible when mixed.

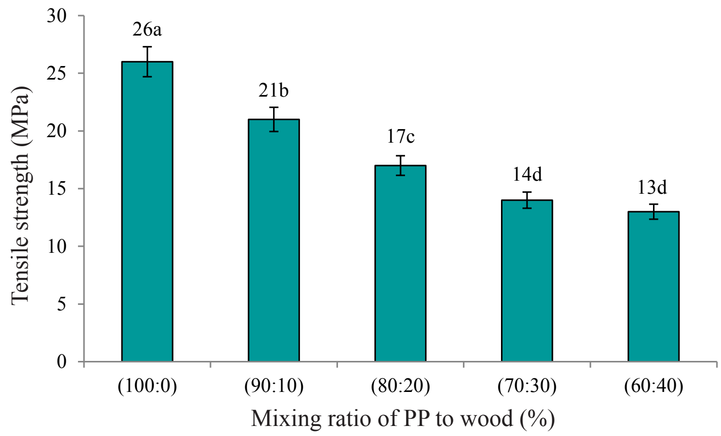

Figure 5 Tensile strength of tested boards. Mean values (values above bars) followed by the same letter are not significantly different at 0.05 level of probability.

c) Izod impact test

Figure 6 shows the Izod impact strength curve of WPCs. Composites with high wood fiber content showed low impact strength compared to 100%. The impact strength decreased to almost half (from 17,789 kJ/m^2 to 8,798 kJ/m^2) when 10% wood particles were added to WPCs. Albano et al. (2002) and Ndiaye et al. (2012) reported that the scattering/distribution of wood particles is a major factor influencing the impact strength of WPCs. Apart from that, the impact strength was also influenced by the size of the wood particles (Mareri et al. 1998). Large particles represent flaws and weak points that could easily initiate cracks and reducing the stress required to fracture the composite.

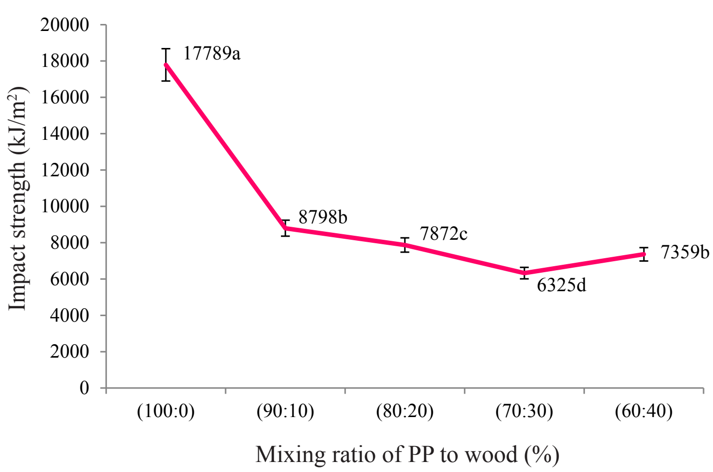

Figure 6 The effect of mixing ratio on impact strength of tested boards. Mean values (values above lines) followed by the same letter are not significantly different at 0.05 level of probability.

Termite bioassay

Figure 7 shows the mean percentages of weight loss and termite survival of different mixing ratio of WPCs boards. WPCs boards with high plastic contents (90%) had the lowest weight loss (0.12%) compared to WPCs boards with more wood contents and control (*H. brasiliensis*) samples. ANOVA results showed that there was no significant difference in weight loss percentage between WPCs from different plastic-wood fibres mixing ratios. The manufactured WPCs in this study showed high termites resistant, with less than 0.27% weight loss percentage. Kennedy et al. (1994) reported that timber or wood products could still be considered as having good termites resistant if the weight loss is less than 3% because it is considered as cosmetic damage. The lack of moisture (low wood contents) in WPCs will normally result in lower weight loss and higher mortality of the termites (Ibach et al. 2018). After 28 days of exposure to *C. curvignathus* in laboratory conditions, all WPCs samples showed visual ratings between 8.6 to 10.0. No severe termite attack can be seen visually on the tested samples except for *H. brasiliensis* samples (Figure 8). Tajvidi et al. (2008) reported that WPCs have higher resistance against biological deterioration agents and could be an alternative material to solid wood in building structure and industrial applications.

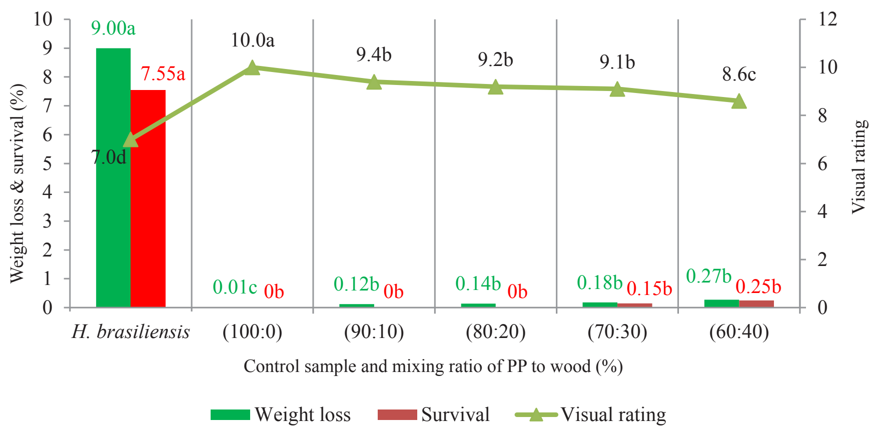

Figure 7 Average weight loss, termite's survival percentage and visual rating of WPCs with different mixing ratios against *C. curvignathus*. Mean values (values above respective bars and line) followed by the same letter are not significantly different at 0.05 level of probability in their respective groups.

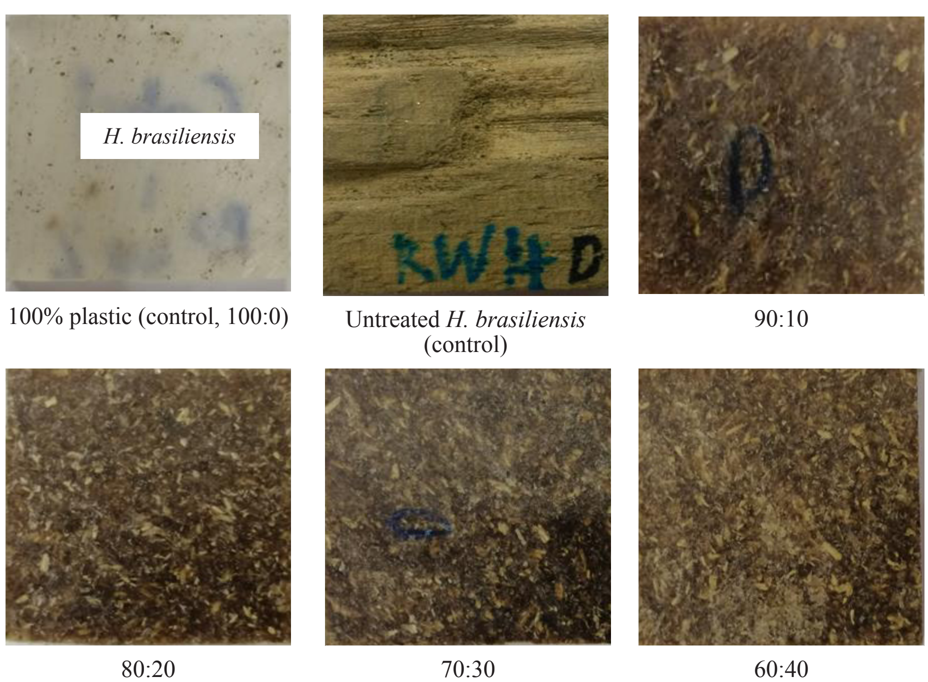

Figure 8 Visual rating of different mixing ratios of WPCs samples against *C. curvignathus*

CONCLUSION

The effects of different mixing ratios (polypropylene:wood fibres) on the mechanical properties of WPCs boards were tested. From this study, we can reasonably infer that the differences in the physical properties of WPCs were caused by the different mixing ratios of polypropylene and wood fibres. The higher polypropylene contents in the mixing ratio, resulted in the higher stability (less thickness swelling and water absorption) of the WPCs boards. Mechanical properties (MOE and MOR static bending) of WPCs produced from *Macaranga* sp. exceed the BS EN312 (2005) particleboards minimum requirements for general uses and interior fitments including furniture, except for mean MOE value of 60:40 mixing ratio. The results showed that there were no significant differences in the weight loss percentages between WPCs from different mixing ratios of polypropylene to wood fibres. Future works should include further variations of polypropylene and wood fibres mixing ratios in the production of WPCs boards in order to verify these preliminary results and to have better understanding on the behaviour of termite feeding resistance.

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This article evaluated the physical and mechanical properties, as well as the resistance against termites (*Coptotermes curvignathus*) of wood-plastic composites (WPCs) manufactured using *Macaranga* sp. Plastic-wood fibres mixing ratios of 100:0 (control), 90:10, 80:20, 70:30 and 60:40 were used. Static bending, tensile and Izod impact strength of WPCs were evaluated. Additionally, physical properties of WPCs and its resistance against termites were also tested. Results showed that the mechanical properties of WPCs were affected by the different mixing ratios of polypropylene (plastic) and wood fibres. WPCs with higher wood contents (60:40) showed higher water absorption and thickness swelling but have lower mechanical properties compared to other mixing ratios. There were no significant differences in termite resistance when compared with WPCs made from different plastic-wood fibres mixing ratios.

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