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REGULAR ARTICLE

Effects of Natural Fiber Waste, Content, and Coupling Agent on the Physical and Mechanical Properties of Wood Species–Plastic Composites as Green Materials

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Abstract

The use of recycled or waste materials is environmentally beneficial. This study focuses on recycled plastic and wood waste which are produced as wood–plastic composites (WPCs). The effect of loading, wood species, and maleic anhydride-grafted polypropylene (MAPP) on the physical and mechanical properties of WPCs is evaluated. Extrusion and compression were employed to produce the composite samples. Three types of wood waste are evaluated, namely rubberwood flour (RWF), coir fiber, and palm fiber at wood loadings of 30, 40, and 50 wt%. The results indicate that loading and wood species significantly affected the hardness, tensile strength, and flexural properties of the WPCs. Moreover, the addition of MAPP had a significant effect on the physical and mechanical properties of WPCs resulting in improved compatibility of wood and polymer matrix and crystallization properties. The highest impact strength (3.88 kJ/m^2), tensile strength (25.73 MPa), flexural strength (37.55 MPa), and crystallinity (42.52%) were accomplished at 40 wt% RWF with MAPP. However, the water absorption, hardness, tensile modulus, and flexural modulus of the WPCs increased as the wood loading increased. Moreover, WPCs based on 30 wt% RWF with MAPP had the lowest water absorption (5.59%) after being immersed for 8 weeks. Therefore, this study provides a use for low-cost recycled plastic and wood waste as filler materials for WPCs that can be used in structures and building applications because of their high performance, benefitting both the economy and the environment.

Keywords Rubberwood flour · Palm fiber · Coir fiber · Wood waste · Wood–plastic composites · Mechanical properties

1 Introduction

Wood–plastic composites (WPCs) are innovative materials and demand for them is increasing. In the United States, demand for WPCs and plastic lumber products is forecast to increase by 6.9% per year, after reaching about $5.9 billion in 2020 [1]. It is estimated that the use of natural fiber-reinforced composites will increase from 12% in 2010 to 18% and 25% by 2020 and 2030, respectively [2]. WPCs have been utilized in numerous items as a substitute for wood (for example in fencing, flooring, and decking), and WPCs are particularly beneficial in damp work environments, or any place where wood filaments routinely get wet.

In North America and Europe, WPCs are utilized essentially to make wall linings, flooring, roofing materials, fences, windows, doors, and embellishments utilized in jetties, landscape architecture, panels, and footbridges. European WPCs are advertised as being empty and solid sections as well as finishing accessories for construction purposes. Furthermore, Poland produces a few tens of tons of wood–polymer composite materials. The combination of locally created products incorporates floor panels, handrails, boxes, balustrade systems, flowerpots, and outside siding panels [3].

WPCs have good physical and mechanical properties, including resistance to cracking and deformation, lightweight, no surface fungal, high water resistance, and flame retardant. Moreover, WPCs are structural materials that can be sawed, planed, and nailed. Compared with ordinary wood, WPCs have twice the service life and can normally

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be used for 15–20 years. Raw material costs are low and the wood does not require maintenance or painting, which helps consumers save money. Thus, the economic benefits are significant and wood materials can be recycled.

WPCs are composites manufactured from thermoplastics matrix, wood flour fillers, and additives through extrusion, injection molding, or compression molding processes [4].

A number of researchers have used various combinations of wood and matrices, such as rubberwood, hemp, sisal, jute, kenaf, and flax [5–9] to make WPCs. Besides, rubberwood waste material is utilized to manufacture furniture and in lumber production, with waste dumped in landfill or burned but it has also been used to manufacture experimental WPC panels [8]. Although the coconut coir is widely available and makes up the majority of coconut fruits, only a small portion of it is actually employed in manufacturing. By removing the cellulose from the coconut coir and then transforming it into useful goods, one may raise the added value of the material [10]. Two main forms of fibrous materials left in palm oil mills are oil palm empty fruit bunches and oil palm fibers. Oil palm fibers are tough and have been shown to have reinforcing potential in polymer matrices [11]. Therefore, the utilization of wood waste as reinforcement in polymer composite could create value from waste materials and reduce WPC production costs, making it a good candidate for this study.

As with any composite material, the properties of WPCs depend on the properties of its components. Thermoplastic polymers are hydrophobic while natural wood is a hydrophilic porous composite of cellulose, hemicellulose, and lignin. These components contain hydroxyl groups, and the result is weak compatibility between plastic and wood. To ensure the compatibility of wood fiber with polymers, additives that provide an adequate bond between the polymer surface and the wood fiber must be used [12]. Maleic anhydride-grafted polypropylene (MAPP) is a typical compatibilizer used to increase plant fiber and PP compatibility. MAPP's acid anhydride group has increased activity and is able to interact with hydroxyl groups on plant fibers surfaces [13]. In general, the inclusion of a maleated coupling agent improves the dimensional stability, mechanical characteristics, and impact strength of composites [14]. This is because MAPP has a significant influence on the resulting microstructure, especially the crystallization of the polymer matrix [15]. One interesting matrix is polypropylene (PP) which is not soluble in water and therefore protects dissolvable filaments, enhances their toughness, and reduces the requirements for overhauling activities to a certain degree [12]. Furthermore, PP is advantageous because it has a low material weight, is cost-effective, has greater processability, is durable in severe environmental conditions, and is reusable [16].

Therefore, the use of recyclable material is beneficial in that it helps prevent adverse effects on the environment that can occur when some materials are discarded. In addition, many researchers have studied the use of waste materials to produce WPCs. These researchers, including Gupta et al. [17], investigated bio-composite film produced from coconut coir and groundnut shells which are agricultural waste. Ramakrishnan et al. [18] reported that the addition of banana fly ash and a hybrid natural fiber combination of sisal and pineapple results in good overall friction. Homkhiew et al. [19] concluded that latex sludge waste has the potential to be an excellent filler in plastic composites. Paul et al. [20] studied the incorporation of carbon black from waste tires into the production of new rubber goods. Gairola et al. [21] found that the intended composites have to employ 40% fewer components of plastic with an approximate decrease in mechanical performance due to the expected use of waste needles of pine and recycled in polymeric composites.

The introduction of different materials as fillers mixed with polymer matrix has led to the production of natural WPCs. The materials can be recycled and are environmentally friendly, which increases the value of wood waste. Additionally, WPCs made from various proportions are chosen to be suitable for use in various fields such as construction work and interior decoration. The purpose of this study is to examine the influence of wood loading, species of wood waste, and MAPP on the physical and mechanical characteristics of WPCs. Furthermore, the compatibility between wood and plastic matrix is studied by considering the morphology of the composite materials.

2 Materials and Methods

2.1 Materials

Recycled polypropylene (rPP) pellets were purchased from Southern Plastic Co., Ltd. (Songkhla, Thailand). This material has a melt flow index of 14.08 g/10 min at 230 °C. Characteristics of natural fiber waste of rubberwood flour, coir fiber, and palm fiber are presented in Fig. 1a–c, respectively. Rubberwood flour (RWF) was made from wood sawdust acquired from the local furniture industry (Songkhla, Thailand). Palm fiber was obtained from Thana Palm Product Co., Ltd. (Surat Thani, Thailand). Coir fiber was obtained from Coco Agriculture Co., Ltd. (Songkhla, Thailand). The compositions of these natural woods are shown in Table 1. These fibers were separated by filtering with an 80-mesh sieve. The wood fiber particle sizes were less than 180 μm. The wood fiber and rPP pellets were dried in an oven at 110 °C for 8 h prior to reducing their moisture content to less than 3%. The coupling agent used to increase the interfacial adhesion of WPCs was maleic anhydride-grafted

Fig. 1 Characteristics of natural fiber waste: **a** rubberwood flour **b** coir fiber, and **c** palm fiber

Table 1 Composition of wood fiber [6, 10, 22]

Wood fiber	Composition (%)			
	Hemicelluloses	Cellulose	Lignin	Other
RWF	29.0	39.0	28.0	4.0
Coir	24.5	38.4	31.8	5.3
Palm	39.9	37.1	18.6	4.4

Table 2 Wood–plastic composites formulation (percentage by weight)

Code	Wood fiber	Loading	rPP	MAPP
R1	RWF	30	67	3
R2		40	57	3
R3		50	47	3
C1	Coir	30	67	3
C2		40	57	3
C3		50	47	3
P1	Palm	30	67	3
P2		40	57	3
P3		50	47	3
PN1	Palm (control)	30	70	–
PN2		40	60	–
PN3		50	50	–

polypropylene (MAPP), which was provided by Sigma-Aldrich (Missouri, USA).

2.2 Processing of Composites

The WPC compositions consisting of rPP pellets, wood fiber, and MAPP are shown in Table 2. There are three levels of wood fiber: 30, 40, and 50 wt%, and MAPP is fixed at 3 wt%. Ratanawilai et al. [6] recommended a MAPP at 3 wt% leading to composite materials with moisture resistance. Moreover, Huang et al. [15] concluded that the addition of 3 wt% MAPP optimally contributed to the acceleration of crystal growth of the polymer matrix resulting in an improvement in composite properties. The raw materials were mixed using a twin-screw extruder (Model CTE-D25L40) from Chareon Tut Co., Ltd. (Samut Prakan, Thailand). The extruder's temperature zones were kept between 170 and 190 °C, with the screw rotation speed set to 60 revolutions/min. The extruded compound was cut to get the WPC pellets as shown in Fig. 2a–c which are rubberwood pellets, coir pellets, and palm pellets, respectively. The pellets were dried at 110 °C for 8 h before being placed in 190 °C hot compression molding machine at 2000 psi for 15 min. The substance was then cooled to room temperature under pressure. WPC samples were machined and tested for physical and mechanical properties in accordance with the American Society for Testing and Materials (ASTM) standards.

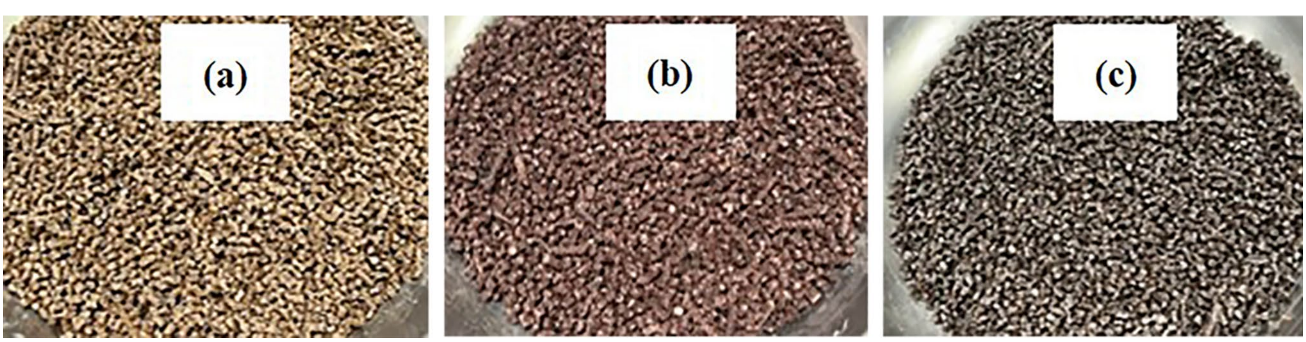


Fig. 2 WPC pellets: **a** rubberwood flour **b** coir fiber, and **c** palm fiber

2.3 Morphology and Visual Surface Observations

The fracture morphology of the WPCs was investigated using a scanning electron microscope (SEM) on a FEI Quanta 400 microscope (FEI Company, Oregon, USA) set to 20 kV. The fractured surfaces were coated with a thin layer of gold to avoid electrical charging during imaging. The SEM micrographs were imaged with a 200 × magnification. In addition, the changes on the WPC surfaces before and after water absorption for 8 weeks as a result of deterioration were discovered using optical microscopy (Zeiss Axioskop, Oberkochen, Germany). The optical microscopy images were taken at a magnification level of 100 ×.

2.4 Thermal Characterization

Differential scanning calorimetry (DSC) was used to assess the melting temperature (T_m) and the crystallization temperature (T_c) in the composites using a DSC-7 (Perkin Elmer, USA). The effects of wood species as reinforcing filler concentration in WPCs are commonly studied at heating temperatures ranging from 20 to 200 °C at a heating rate of 10°C/min. The percentage crystallinity of maxing (X_c) was determined according to Eq. (1):

$$\chi_c(\%) = \frac{\Delta h_f}{\Delta h_f^0} \times 100, \quad (1)$$

where, Δh_f is the enthalpy of fusion determined from DSC and, Δh_f^0 is the theoretical enthalpy of fusion of 100% crystalline plastic melting (165 J/g for PP).

2.5 Water Absorption Testing

Water absorption testing of the WPCs was performed in accordance with ASTM D570. Prior to testing, samples were dried in a 50 °C oven for 24 h, cooled in a desiccator, and weighed to the nearest 0.001 g. The samples were immersed in distilled water at room temperature for 24 h and 8 weeks, respectively. For each sample species, five replications were employed. Water absorption was calculated by Eq. (2):

$$\mathrm{WA}(\%) = \frac{\left(W_2 - W_1\right)}{W_1} \times 100, \quad (2)$$

where *WA(%)* is the percentage of water absorption, W_1 is the weight of the sample before immersion, and W_2 is the weight of the sample after immersion.

2.6 Hardness Testing

Hardness testing was determined using Shore D Durometer scales (Model GS-702G from Teclock Corporation, Nagano, Japan) in accordance with the ASTM D2240. The samples measured 25.4 mm in width, 25.4 mm in length, and 4.8 mm in thickness. Five replicates of each condition and location were measured at room temperature (25 °C).

2.7 Mechanical Characterizations

The tensile test was carried out in accordance with ASTM D638 at a crosshead speed of 5 mm/min. The flexural test was performed in accordance with ASTM D790 at a crosshead speed of 2 mm/min and a span length of 80 mm. Tensile and flexural tests were performed using the Narin Instrument Co., Ltd. Universal Testing Machine (Model NRI-TS500-20B). The Izod impact test was performed using an ASTM D256 pendulum impact tester (Zwick/Roell, model HIT5.5P; Germany) with a 1 J hammer. Five replications were measured for mechanical testing at room temperature.

2.8 Statistical Analysis

The results were statistically assessed using a two-way analysis of variance (ANOVA) to determine group homogeneity and the effect of loading and wood species on the physical and mechanical properties of the WPCs. Furthermore, statistical analysis with Tukey's multiple comparison test at the 95% confidence level using Minitab Statistical Software 21.3.1.0 was used to confirm the comparison of wood loading, species of wood, and MAPP on the physical and mechanical properties. In addition, the effect of MAPP was conducted only on the palm fiber-reinforced plastic composites. All statistical analyses were performed at a 5% significance level ($\alpha = 0.05$).

3 Results and Discussion

3.1 Water Absorption of WPCs

The effect of loading and species of wood on the short-term water absorption of WPCs is shown in Fig. 3. The immersion period was 24 h in distilled water at room temperature. The result showed that the amount of absorbed water of 50 wt% of RWF reinforced rPP matrix increased faster than 40 wt% and 30 wt% wood loading, respectively. This result was the same for coir fiber and palm fiber. The highest water absorption was found to be the 50 wt% wood loading of composites made from coir fiber-reinforced plastic composites, the value of which was 4.79%. This was followed by RWF and palm fiber, which had values of 3.76% and 1.30%, respectively.

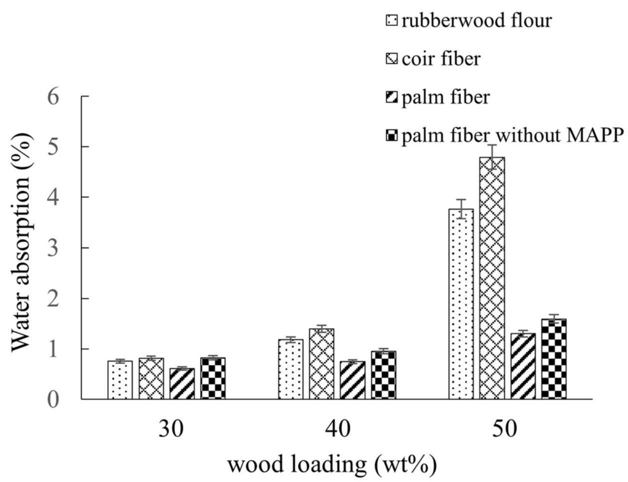


Fig. 3 The water absorption for 24 h of WPCs with various loading and species of wood

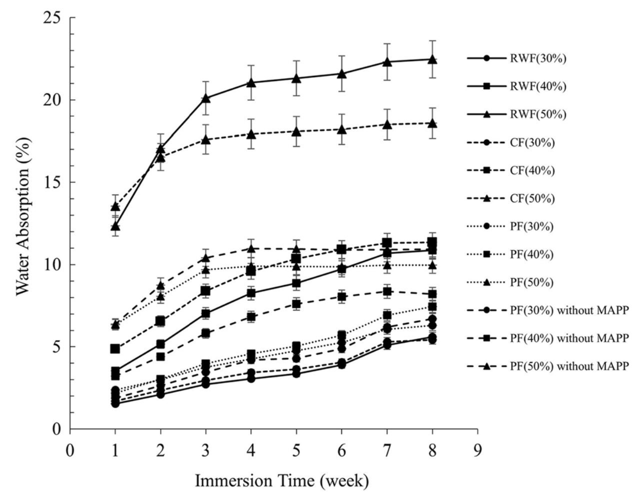


Fig. 4 The long-term water absorption behavior of WPCs

This is related to the result by Abu-Jdayil et al. [23] that the maximum water absorption of composites was found at 50 wt% wood loading. Consequently, the hydrophilic nature of wood flour is responsible for water absorption in the composites, so a higher content of wood flour results in a greater amount of absorbed water [24].

Moreover, the ANOVA results showed that loading significantly affected the water absorption (24 h) of WPCs (p-value < 0.05), as shown in Table 3. The wood species did not appear to affect water absorption. Therefore, the lowest water absorption of the composites was 30 wt% wood loading, which was found for this experiment and had values of palm fiber following RWF, and the coir fiber composites were 0.62%, 0.76%, and 0.82%, respectively. Palm fiber had the lowest water absorption. This result implies that the absorption depends on the cellulose content in the chemical composition. Palm fiber is 37.1% cellulose, which is the lowest compared to RWF and coir fiber.

In the long-term water absorption experiment, specimens of all conditions were dripped in distilled water which was ambient temperature for 8 weeks. The water absorption behavior is demonstrated in Fig. 4. The result indicates that water absorption increases continuously with a longer absorption time for all samples. In particular, it increased very rapidly in the beginning and remained stable in the final weeks. For example, the results of long-term water absorption were described for WPCs based on 40 wt% wood loading. It was found that coir fiber with MAPP had the highest water absorption, followed by RWF with MAPP and palm fiber with MAPP, respectively, with water absorption values of 11.35%, 10.86%, and 7.45%, respectively. Therefore, this experimental result is consistent with Khamtree et al. [8] and Salleh et al. [25] who concluded that several variables influence the water absorption of composites, including wood content, particle size, wood species, phase compatibility, and plastic matrix type.

The ANOVA results in Table 3 demonstrate that the effects of the wood loading on water absorption are statistically significant for WPCs, although wood species are not significant at a 5% level for water absorption at 8 weeks. In addition, Turkey's test in Table 4 was also conducted to the effect of the species of wood (RWF, coir fiber, and palm fiber) on the water absorption of WPCs. The result shows that composites reinforced with 40 wt% palm fiber loading (suffix e) had significantly lower water absorption than RWF (suffix d). Moreover, it can be observed that the addition of MAPP reduced the water absorption of WPCs. The effect of MAPP on water absorption was also verified

Table 3 Analysis of variance of the effect of loading and species factors on the properties of WPCs

Factor	p-value							
	%WA 24 h	%WA 8 weeks	Hardness	Impact strength	Tensile		Flexural	
					Strength	Modulus	Strength	Modulus
Loading	0.031*	0.020*	0.014*	0.064	0.001*	0.002*	0.028*	0.035*
Species	0.263	0.296	0.000*	0.057	0.000*	0.080	0.010*	0.008*

*p-value < 0.05 is considered significant

Table 4 Effects of type of wood, wood content, and MAPP on physical and mechanical properties of WPCs

Properties	Type of wood	Wood content (% by weight)		
		30	40	50
%WA (24 h)	RWF	0.76^{ad}	1.18^{bd}	3.76^{bd}
	Coir fiber	0.82^{ad}	1.40^{bde}	4.79^{abd}
	Palm fiber	0.62^{adg}	0.75^{aeg}	1.30^{bdg}
	Palm fiber without MAPP	0.82^{g}	0.96^{g}	1.60^{g}
%WA (8 weeks)	RWF	5.59^{ad}	10.86^{bd}	22.46^{abd}
	Coir fiber	5.68^{ad}	11.35^{ade}	18.58^{ad}
	Palm fiber	6.30^{adg}	7.45^{beg}	9.97^{cdg}
	Palm fiber without MAPP	6.69^{g}	8.20^{h}	10.93^{h}
Hardness (HD)	RWF	80.00^{ad}	80.20^{ad}	80.60^{ad}
	Coir fiber	74.60^{ae}	76.20^{be}	76.60^{be}
	Palm fiber	76.80^{aeg}	77.00^{abeg}	77.60^{beg}
	Palm fiber without MAPP	74.20^{h}	75.60^{g}	75.80^{h}
Impact strength (MPa)	RWF	1.52^{ad}	3.88^{bd}	2.84^{bd}
	Coir fiber	1.30^{ad}	1.98^{be}	1.61^{abde}
	Palm fiber	2.09^{aeg}	2.47^{adeg}	2.17^{adfg}
	Palm fiber without MAPP	1.32^{h}	1.92^{g}	1.62^{g}
Tensile strength (MPa)	RWF	24.59^{ad}	25.73^{ad}	20.79^{ad}
	Coir fiber	21.05^{ade}	24.71^{bd}	18.80^{ade}
	Palm fiber	24.29^{adfg}	25.25^{adg}	22.49^{bdfg}
	Palm fiber without MAPP	16.22^{h}	19.09^{h}	14.42^{h}
Flexural strength (MPa)	RWF	35.25^{ad}	37.55^{ad}	33.19^{ad}
	Coir fiber	35.43^{ad}	31.11^{ae}	27.10^{ad}
	Palm fiber	33.22^{adg}	35.37^{abdeg}	30.47^{acdg}
	Palm fiber without MAPP	29.71^{g}	27.51^{h}	25.34^{h}
Tensile modulus (MPa)	RWF	1039.15^{ad}	1169.95^{bd}	1238.50^{abd}
	Coir fiber	1057.67^{ad}	1075.24^{ae}	1154.33^{ad}
	Palm fiber	1019.29^{adg}	1035.58^{aeg}	1186.37^{bdg}
	Palm fiber without MAPP	941.68^{h}	1021.49^{g}	1178.25^{g}
Flexural modulus (MPa)	RWF	1078.35^{ad}	1302.03^{bd}	1650.06^{bd}
	Coir fiber	877.41^{bd}	1135.94^{be}	1569.57^{bd}
	Palm fiber	1017.64^{abdg}	1116.12^{adeg}	1174.06^{adg}
	Palm fiber without MAPP	607.82^{h}	700.59^{h}	705.92^{h}

Means within each property with same letter (suffixes a–c for effect of wood content) is not significantly different ($\alpha = 0.05$) by Turkey's test. Different letter (suffixes d–f for effect of species of wood) indicate significant difference ($\alpha = 0.05$)

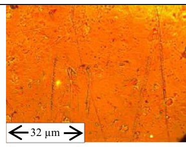
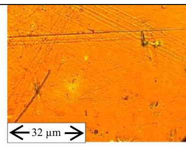
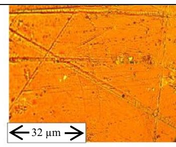
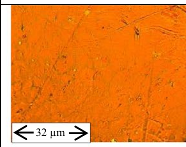
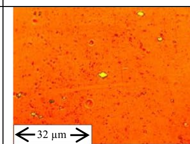
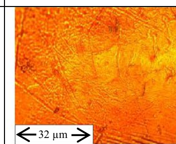
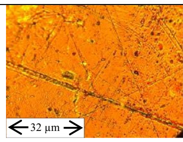
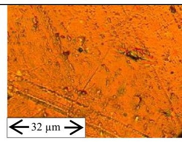
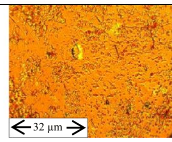
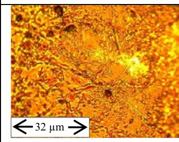
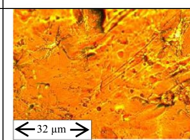
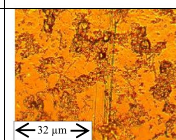
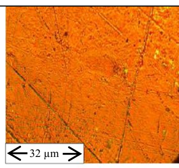
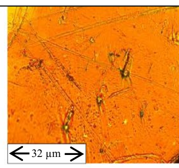
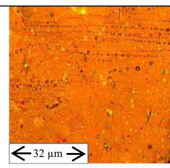
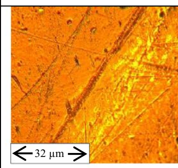
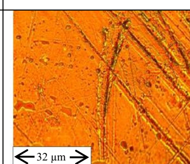
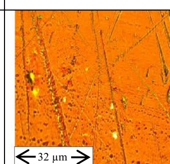
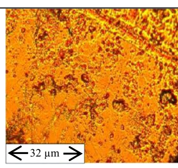
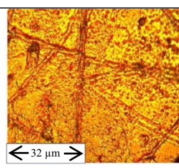
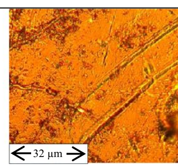
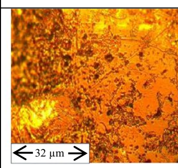
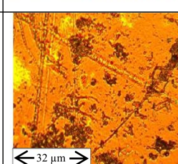
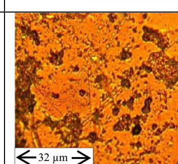
The same letter (suffixes g–h for effect of MAPP) is not significantly different ($\alpha = 0.05$)

by statistical analysis (*t*-test). The results indicate that the addition of MAPP had a significant (p-value < 0.05) effect on the water absorption (8 weeks) of 40 wt% and 50 wt% palm loading of WPCs. For example, at 40 wt% palm fiber loading, the composite with MAPP (suffix g) had significantly lower water absorption than the composite without MAPP (suffix h). This is because the maleated coupling agents are a highly efficient technique to improve the interfacial contact between fibers and polymer matrix, which leads to an increase in resistance to water absorption [26].

3.2 Visual Surface Characteristics

Optical microscope images were utilized to examine the degradation of the WPC surfaces with different species and the loading of wood. Microscope observations of the WPCs before and after water absorption for 8 weeks are shown in Table 5. The composites made from rPP as a matrix reinforced with RWF, coir fiber, and palm fiber in which these agglomerates appear to be dispersed

Table 5 Optical microscopy images before and after water absorption for 8 weeks of the WPC surfaces with different species and loading of wood

Code	R1	R2	R3	C1	C2	C3
Before						
After						
Code	P1	P2	P3	PN1	PN2	PN3
Before						
After						

throughout the plastic matrix, according to the micrographs, revealed cracked and corroded WPC surfaces.

In general, the appearance of cracks and defects when the material is employed indicates poor surface performance of WPCs [27, 28]. Water absorption reduced the interfacial adhesion between the rPP matrix and wood fibers. Roughness is observable on the surface of the composite samples before and after water absorption for 8 weeks. From the results, it can be concluded that the duration time of water absorption also affects the roughness on the surface of the composite. Moreover, cracks and voids on the WPCs surface increased with longer immersion time and greater wood content. When comparing different natural woods, RWF is shown to create the fewest observable fractures and voids on the surface, however coir fiber produced the greatest cracks in the WPC formulations.

Moreover, wood loading affected the roughness of the composite surfaces. WPC samples reinforced with RWF had a smoother surface when compared to coir and palm fibers. Likewise, the 30 wt% wood fiber exhibited fewer cracks and smoother surfaces than the 50 wt% wood fiber, and these findings are consistent with the mechanical property results. These results could be explained by the bonding resulting from the combining operations of WPC materials and plastic ratios and wood fiber concentrations. This result is in agreement with Durmaz [29] who concluded that the increased wood content resulted in surface roughness, allowing water molecules to easily permeate into the center of composite. As the proportion of wood fiber rises, wood fiber enclosed with the polymer may become unable to inhibit water absorption. In other words, the addition of MAPP at 3 wt% could improve interfacial interaction between the plastic matrix and wood fibers, reducing the number of cracks and voids on the surface observation [30].

3.3 Hardness Property of WPCs

Figure 5 illustrates the effect of loading and species of wood on the hardness property of WPCs. The result shows that the hardness value clearly increased with an increase in wood loading (RWF, palm fiber, and coir fiber) in the plastic matrix. Therefore, 50 wt% wood loading showed the highest hardness value. In addition, the hardness of composites made from RWF was higher than that of composites made from palm fiber and coir fiber, which had hardness values of 80.6 HD, 77.6 HD, and 76.6 HD, respectively. Normally, the hardness test is a measure of deformation resistance. The addition of fillers to the polymer matrix results in reduced matrix flexibility. Therefore, all the fillers employed are non-deformable solids, and the addition of more rigid particles leads to an increase in the material's rigidity and stiffness [31]. These results are consistent with ANOVA analysis (Table 3) which showed the loading and species of wood significantly (p-value < 0.05) affected the hardness of WPCs.

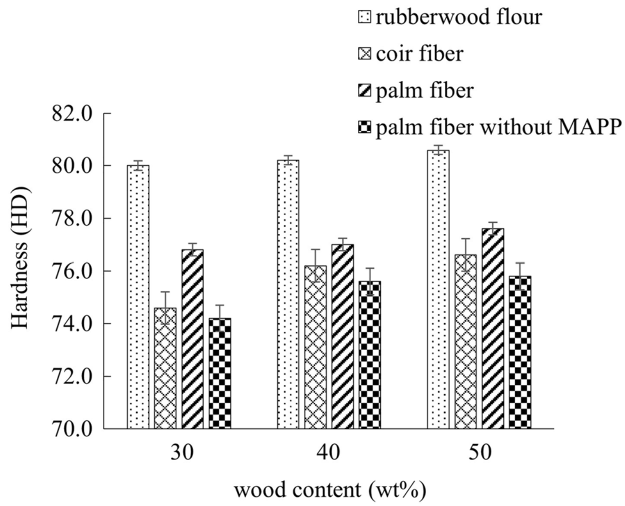


Fig. 5 The hardness of WPCs with various loadings and species of wood

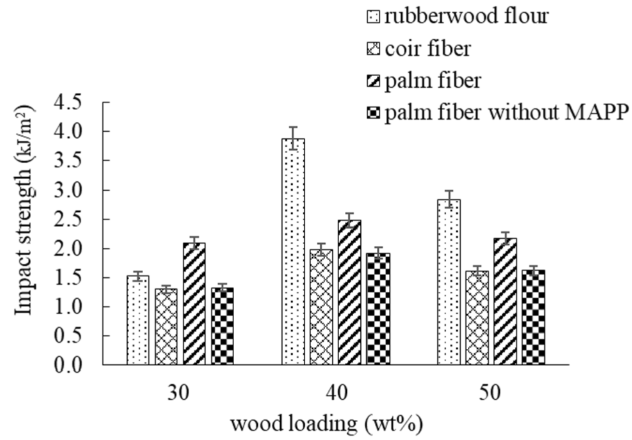


Fig. 6 Impact strength of WPCs with various loadings and species of wood

Moreover, Fig. 5 also illustrates the effects of MAPP addition on the hardness property of WPCs. The results show that the palm fiber-reinforced composites with MAPP had higher hardness values than those without MAPP, with values at 50 wt% increased approximately by 75.8 HD and 77.6 HD, respectively. Tukey's test in Table 4 indicates that WPCs based on 50 wt% palm fiber loading with MAPP (suffix g) have significantly higher hardness values than the composites without MAPP (suffix h). It can be concluded that the MAPP improved the hardness of WPCs. This result is in agreement with Homkhiew et al. [32] who reported that the addition of the coupling agent to the composites enhanced the hardness values of wood composites. This is because of the stronger interfacial adhesion between the filler and plastic matrix and better dispersion of the wood flour into the plastic matrix resulting in fewer voids.

3.4 Mechanical Properties of WPCs

Figure 6 shows the effect of loading and species of wood on the impact strength of WPCs. The impact strength increased when the wood loading was increased from 30 to 40 wt%. However, the impact strength decreased when the wood loading increased to 50 wt%. These results of RWF, coir fiber, and palm fiber of WPCs provided consistent results. This result is compatible with Lu et al. [33] who summarized that the impact strength of WPCs decreased as the wood fiber loading increased. However, by adding the fillers, the composites' interfacial strength and toughness were optimized by giving the composites better resistance to external pressures, which ultimately improved their impact strengths. Two-way analysis of variance (ANOVA) was performed (p-value < 0.05) to evaluate the effects of loading (30, 40, and 50 wt%) and species (RWF, coir fiber, palm fiber) on impact strength, as shown in Table 3. The results do not appear to indicate that loading and species affect impact strength. Moreover, the highest impact strength values of RWF, palm fiber, and coir fiber-reinforced plastic composites were 3.88 kJ/m^2, 1.98 kJ/m^2, and 2.47 kJ/m^2, respectively, which were observed for plastic composites reinforced with 40 wt% wood.

When comparing palm fiber with MAPP to palm fiber without MAPP at 30 wt%, 40 wt%, and 50 wt% wood loading, the palm fiber with MAPP was found to have greater impact strength than the palm fiber without MAPP, as shown in Fig. 6. Furthermore, statistical analysis (t-test) confirmed the effect of MAPP on impact strength, as shown in Table 4. The results indicate that the addition of MAPP had a significant effect on the impact strength of WPCs. For example, WPCs with 30 wt% palm fiber with MAPP (suffix g) gave a significantly higher impact strength than those without MAPP (suffix h). This result is in agreement with Effah et al. [34] who concluded that the use of compatibilizers enhanced the impact strength of the majority of the wood composites. When maleated coupling agents were applied to the composites, their mechanical performance increased.

The tensile and flexural strengths of WPCs at different loading and species of wood are shown in Fig. 7a, b, respectively. The results indicate that the tensile and flexural strengths of RWF and palm fiber plastic composites increased with increasing wood loading from 30 to 40 wt%, while these properties decreased when the wood loading was 50 wt%. This is similar to the findings of Durmaz [29] who concluded that flexural strength decreased with higher amounts of Scotch pine wood flour in the high-density polyethylene matrix. In addition, the highest tensile and flexural strengths of the composites was 40 wt% of wood loading for this study. When comparing the flexural strength of

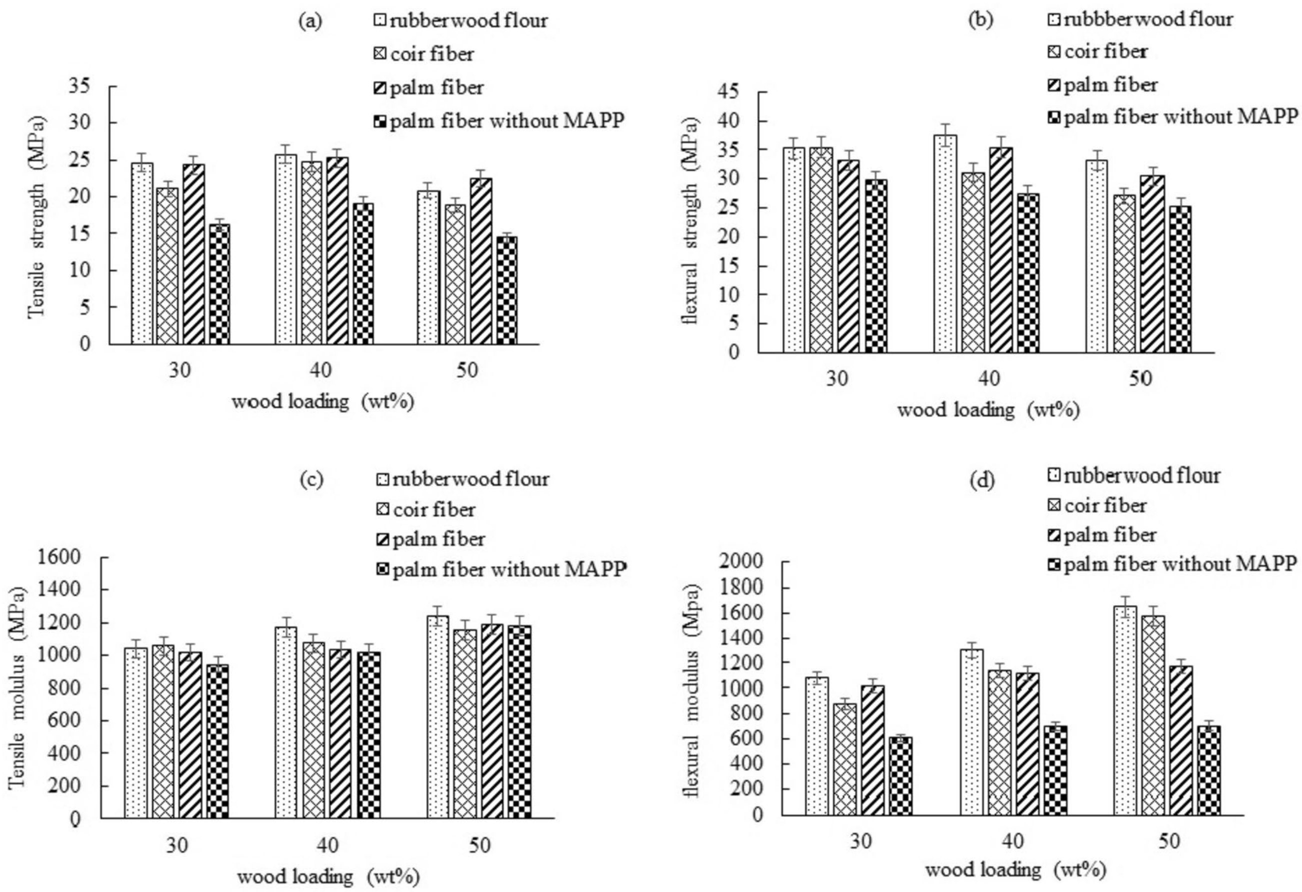


Fig. 7 The mechanical properties of WPCs with various loading and species of wood: **a** tensile strength, **b** flexural strength, **c** tensile modulus, and **d** flexural modulus

composites at 40 wt% wood loading, the results showed that RWF gave the highest flexural strength (37.55 MPa) of the composites, followed by palm fiber (35.37 MPa) and coir fiber (31.11 MPa), respectively. This is because the flexural strength of the composites varied depending on the type of fibers (Zhang et al. [24]). Likewise, the results showed that RWF had the highest tensile strength (25.73 MPa) of the composites, followed by palm fiber (25.25 MPa) and coir fiber (24.71 MPa), respectively.

As shown in Table 3, a two-way analysis of variance (ANOVA) was performed (p-value < 0.05) to evaluate the effects of loading and species on tensile and flexural strength. The result indicates that the loading had a statistically significant effect on tensile and flexural strength. This result is in agreement with Khamtree et al. [8] which reported that wood content significantly affected the tensile and flexural properties of WPCs.

Moreover, the tensile and flexural strengths of palm fiber composites with MAPP were significantly higher than WPCs without MAPP, as shown in Table 4. For example, at 40 wt% palm loading, the flexural strength of palm fiber with MAPP was 35.37 MPa (suffix g) and 27.51 MPa (suffix h) without MAPP. This result is statistically significant at p-value < 0.05. This result is in agreement with Singh et al. [14] which concluded that the mechanical properties of recycled HDPE-pine composites with the maleated coupling agent were higher than the properties of recycled HDPE/bagasse composites. Adding a coupling agent into the production process therefore improved the performance of the WPCs.

The tensile and flexural modulus of WPCs for different loading and species of wood are shown in Fig. 7c, d, respectively. The results indicate that the tensile and flexural modulus increased with higher wood loading for the same species of wood, which is in agreement with the findings of Khamtree et al. [35]. The RWF at 50 wt% loading exhibited the highest tensile modulus with a value of 1238.50 MPa. Likewise, RWF at 50 wt% loading obtained the maximum flexural modulus with a value of 1650.06 MPa. This is because natural fibers are more rigid than the plastic matrix. Therefore, the modulus of the composites increases with the amount of wood content in the WPCs as well [35]. This result is consistent with a two-way analysis of variance (ANOVA) which was performed (p-value < 0.05) as shown in Table 3, which indicates that the loading had a statistically significant effect on the tensile and flexural modulus. Moreover, when comparing the tensile and flexural modulus of palm fiber composites with MAPP and without MAPP, the results indicate that WPCs with MAPP gave a higher modulus than those without MAPP, which is in good agreement with Effah et al. [34] which concluded that the tensile modulus of compatibilized composite was high with the maleated coupling agent. Moreover, the statistical analysis (t-test) shown in Table 4 also confirms the effect of MAPP on the properties of composites. The result indicates that the properties of the modulus changed significantly (p-value < 0.05) when MAPP was added to the process. For example, the 50 wt% palm fiber composites with MAPP (suffix g) had a significantly higher flexural modulus than the 50 wt% palm fiber composites without MAPP (suffix h).

3.5 Morphology of WPCs

The mechanical properties of WPCs were substantiated by SEM micrographs depicting the interfacial adhesion between the palm fiber and the rPP matrix.in Fig. 8a–c. The

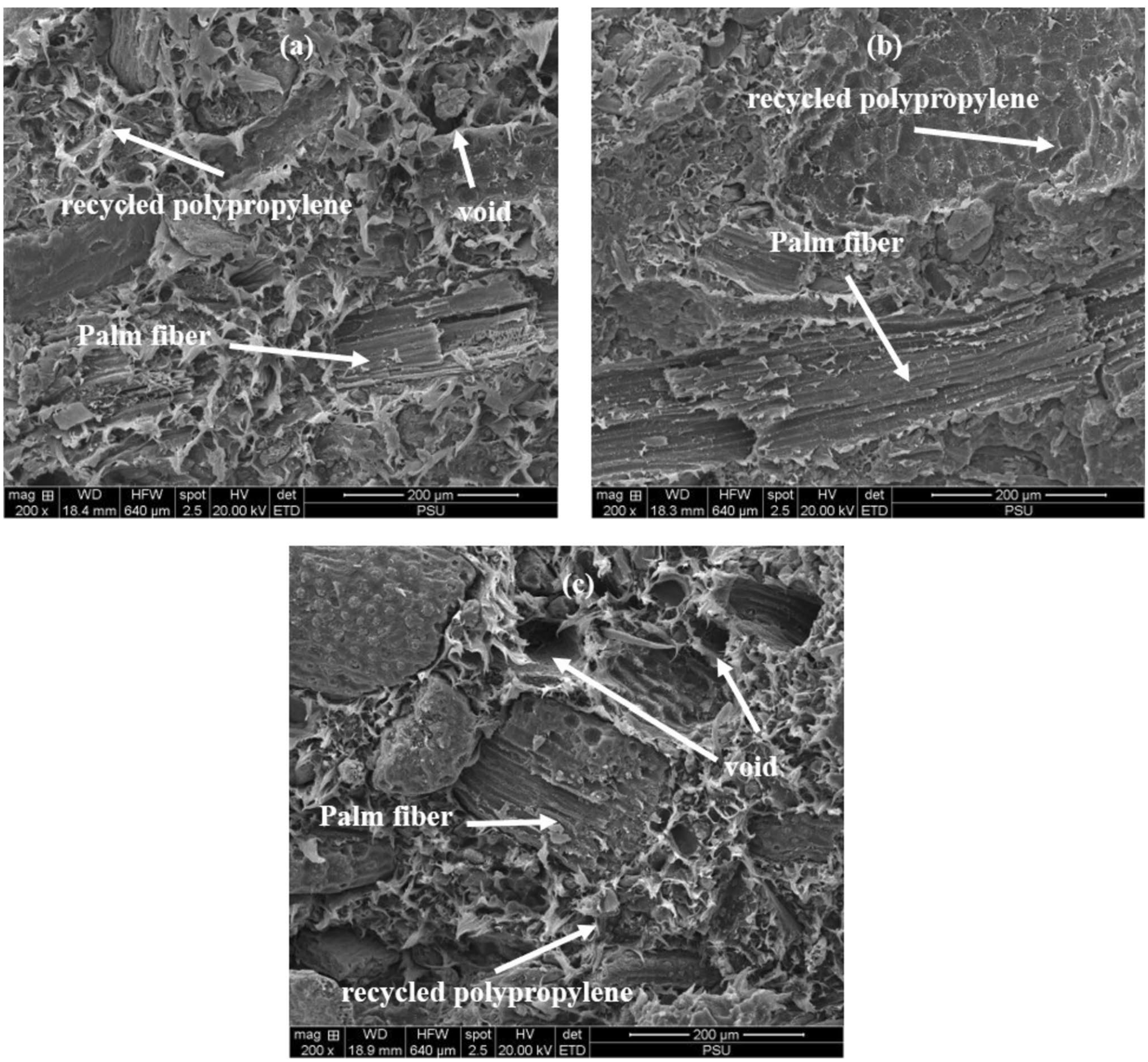


Fig. 8 SEM micrographs of the flexural fracture surfaces of palm fiber composites: **a** 30 wt% loading with MAPP, **b** 40 wt% loading with MAPP, **c** 40 wt% loading without MAPP

results show that WPCs with 30 wt% of palm fiber loading (Fig. 8a) exhibited higher voids than those with 40 wt% loading (Fig. 8b). Meanwhile, the surface of 40 wt% loading is compatible with a number of WPCs with 30 wt% loading and the dispersion of wood in the recycled polypropylene is good. This is due to the optimum viscosity of the polymer melt and efficient interfacial bonding between the fiber reinforcing and plastic matrix [35, 36] which is beneficial for transferring the stress from the matrix to fillers. Therefore, good dispersion leads to mechanical strength enhancement [37]. Likewise, the improved mechanical properties of WPCs depend on the proportion of wood filler they contain [38].

Therefore, 40 wt% of wood loading had the highest impact strength, tensile strength, and flexural strength among the various WPCs. In addition, the use of compatibilizers can improve adhesion between the two materials which may improve the mechanical properties of the composites. The morphological characterization of 40 wt% palm fiber loading with MAPP and without MAPP reinforced the plastic as supported by SEM images in Fig. 8b, c, respectively. The palm fiber-reinforced plastic matrix compatibilized with MAPP had fewer voids than the WPCs without MAPP. The WPCs with MAPP provided superior mechanical properties as well as less water absorption and, due to the use of MAPP as a compatibilizer, the maleic anhydride reacts with hydroxyl groups on the surface of the wood fiber [15]. Therefore, WPCs with MAPP as the compatibilizer showed better adhesion and the physical and mechanical properties were also improved.

3.6 Differential Scanning Calorimetry (DSC)

The DSC values of WPCs with reinforcing fillers at ratios of 40 wt% of RWF, coir fiber, and palm fiber are displayed in Table 6. All the samples were performed to observe the melting temperature (T_m), crystallization temperature (T_c), and percentage crystallinity of maxing, respectively. The T_m and T_c value results were determined in ranges from 163.17 to 165.33 °C and 117.33 to 119.83 °C, respectively. WPCs reinforced with palm fiber at 40 wt% have a melting temperature of about 165.33 °C, which is comparatively higher than that of RWF (163.17 °C) and coir fiber (164.57 °C), indicating that the type of wood results in a small amount of interference with the processing temperature. This is because the thermal stability of the WPCs markedly increased with increasing wood content [39]. Moreover, the highest melting temperature found that the inclusion of wood fiber increases the crystallization enthalpy and the crystallinity of the polymer [40]. Meanwhile, WPCs with 40 wt% coir fiber showed the highest crystallization temperature (118.17 °C) compared to RWF (118.00 °C) and palm fiber (117.33 °C), respectively. Additionally, the percentage crystallinity of WPCs with different wood types as reinforcing fillers is shown in Table 6. In theory, factors including composition, size distribution, interfacial interactions, and fiber type and content all impact the crystallization behavior of WPCs, resulting in improved mechanical properties [41, 42]. This experiment found that reinforcing RWF composites had greater crystallinity degrees than reinforcing palm fiber and coir fiber composites, in which WPCs reinforced with RWF gave the maximum value of approximately 42.52% followed by palm fiber (38.04%) and coir fiber (32.32%), respectively. Moreover, the addition of chemical fillers, namely MAPP as a coupling agent, has a good effect on thermal characteristics although this may reduce the toughness and ductility of WPCs [43]. For example, composites with MAPP as a coupling agent have a percent crystallinity of about 38.04%, which is comparatively higher than that of composites without a MAPP value of 30.01%. It can be observed that the incorporation of chemical filler, wood contents, and polymer matrix in WPC materials improved overall melting and crystallization properties. SEM photographs of the interface that result in improved compatibility between the polymeric matrix and fillers are shown in Fig. 8a, b.

Table 6 Thermal characteristics of WPCs with 40% wood content

Type of wood	T_m (°C)	T_c (°C)	Crystallinity (%)
RWF	163.17	118.00	42.52
Coir fiber	164.57	118.17	32.32
Palm fiber	165.33	117.33	38.04
Palm fiber without MAPP	164.57	119.83	30.01

T_m is the melting temperature; T_c is the crystallization temperature

4 Conclusions

The purpose of this study was to determine the effect of loading, wood species, and MAPP on the physical and mechanical characteristics of wood–plastic composites (WPCs). The ANOVA results reported that the wood loading on water absorption is statistically significant for WPC, although wood species is not found to be significant for water absorption. The water absorption of the WPCs increased with higher wood loading. WPCs based on 30 wt% RWF had the lowest water absorption. This is supported by optical microscope images showing that WPCs with 30 wt% RWF had a smoother surface and fewer cracks than other samples. Moreover, the ANOVA results concluded that loading and species significantly affected the hardness, tensile strength, and flexural properties of WPCs. Loading at 40 wt% RWF provided the highest strengths of impact, tensile, and flexural of WPCs whereas loading at 50 wt% RWF showed the maximum hardness and mechanical modulus of

WPCs. Furthermore, the physical and mechanical properties of WPCs with MAPP were superior to those without MAPP. Indeed, the effects of MAPP on long-term water absorption, hardness, tensile strength, and flexural strength of WPCs with palm fiber are statistically significant for WPCs. Accordingly, MAPP has a good effect on thermal characteristics. In addition, MAPP improved the adhesion between fibers and polymer matrix which led to an increase in resistance to water absorption and improved the mechanical properties of WPCs which is consistent with SEM micrographs showing fewer voids than the WPCs without MAPP. Hence, the findings of the present study are valuable to enhance the characteristics of WPCs used in construction as well as the added value of wood waste and recycled plastic.

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Data Availability The data analyzed during this study are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The authors declare no conflict of interest.

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