Effects of Gmelina Bark Content and Particle Size on the Characteristics of a Recycled Polypropylene Composite

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Bark plastic composite is a composite wood board consisting of a plastic matrix and bark in the form of powder or fibers as a filler. This research aimed to determine the influence of ratio and particle size on the characteristics of the composite made of Gmelina bark mixed with recycled polypropylene. Bark plastic composites were made with variations in powder: plastic ratio, namely 40:60% (P60), 30:70% (P70), 20:80% (P80), and 0:100% (P100), as well as variations in filler particle size, namely 40 to 60 mesh (M40), 60 to 80 mesh (M60), and 80 to 100 mesh (M80). Maleic anhydride (MAH) as a compatibilizer was added at 5% of the matrix's weight. The reference testing standards were JIS A 5908:2003 and SNI 03-2105-2006. In the physical property testing, including density, moisture content, water absorption, and thickness swelling, all boards with different treatments met the standards. In the modulus of elasticity (MOE) testing, none of the boards with different treatments met the standards, while in the internal bond testing, all boards with different treatments met the standards. As for the modulus of rupture (MOR) testing, hardness, and screw-holding power, some samples met both standards. The M40P80 treatment produced the best bark plastic composite.

DOI: 10.15376.biores.19.4.7393-7407

Keywords: Gmelina bark; Composition; Bark plastic composite; Recycled polypropylene; Particle size

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INTRODUCTION

Wood is one of the main materials used for construction and furniture, and its demand continues to increase. In Indonesia, the government implements solutions such as planting trees that belong to fast-growing wood species such as Gmelina (*Gmelina arborea* Roxb.), pine (*Pine* sp.), Agathis (*Agathis* sp.), sengon (*Falcataria moluccana*), and others. Gmelina or white teak (*Gmelina arborea* Roxb.) is a tree that falls under the category of fast-growing wood species. According to data from the Central Statistics Agency (2019, 2020), the production of Gmelina round wood increased from 52.4 thousand m^3 to 65.6 thousand m^3 between 2018 and 2019. Each piece of Gmelina round wood contains wood bark in the range of 9.31 and 12.05% (Saragih 2017). Therefore, with a large production volume, the amount of wood bark waste is also substantial. In addition to the increasing demand for wood, the amount of waste is also increasing. According to data from the National Waste Management Information System of the Ministry of Environment and Forestry of Indonesia, the amount of waste generated in Indonesia reached 29.8 million tons throughout 2021. Of this amount, 17.54% was plastic waste (Puspita 2022). Jambeck *et al*. (2015) noted that Indonesia is the world's second-largest contributor of plastic waste

to the ocean, after China, with an annual contribution of 3 million tons. Polypropylene (PP) plastic is one of the most produced types of plastic. Polypropylene plastic has low density (0.91 to 0.94 gr/cm^3) while maintaining strong mechanical properties, and it is chemically inert and cost-effective (Maddah 2016). To optimize bark usage and reduce plastic waste, one alternative is to create bark plastic composite (BPC). A bark plastic composite is a composite wood board consisting of a mixture of plastic as the matrix and bark powder as a filler (Sutrisno *et al*. 2021). Bark plastic composite materials must be combined using high pressure and temperature to achieve good results. Various types of wood can be used as filler, including the bark and sawdust waste. Similarly, various types and forms of plastic can be used as a matrix, whether in pellet form or as waste, as long as they are thermoplastic (Sutrisno *et al*. 2021; Waluyo *et al*. 2021).

Several important factors influence the physical and mechanical properties of bark plastic composite, including the particle size of the filler and the ratio between matrix and filler (Waluyo *et al*. 2021). Adding filler to the matrix can improve the mechanical properties of BPC, such as impact strength and bending strength. Different particle sizes of the filler also result in different mechanical values. Smaller particle sizes have been found to create better mechanical properties (Poyoh *et al*. 2013). In a study by Poyoh *et al*. (2013), the bending strength of wood plastic composite (WPC) made from 70% polyester resin matrix and coconut stem sawdust filler with particle sizes of 250 and 180 mesh was 72.3 MPa and 57.4 MPa respectively. Similarly, in a study by Rahman *et al*. (2018), WPC with a polyester matrix and sengon wood (*Falcataria moluccana*) powder filler with a 20 mesh particle size had higher flexural strength than filler with a 10 mesh size. The smaller particles increase flexural properties because the area of bond between particles and matrix is larger (Rahman *et al.* 2018). Apart from the particle size of the filler, the ratio of matrix and filler greatly affects the mechanical properties of WPC. Rahman *et al.* (2018) reported that WPC with filler composition of 30 to 37.5% showed increasing bending strength values of 28.8 to 34.7 MPa, but a significant decrease to 24.7 MPa occurred at a 40% filler percentage. Utilizing Gmelina bark waste and recycled polypropylene plastic to create this BPC can be an alternative solution to waste issues. However, to obtain bark plastic composite with appropriate physical and mechanical characteristics according to standards and purposes, further research is needed in the production process. Therefore, this research aims to determine the influence of composition and particle size on the physical and mechanical characteristics of the composite, made from recycled polypropylene plastic and Gmelina bark, and its suitability to standards. Additionally, it aims to identify the treatment that yields the best bark plastic composite.

EXPERIMENTAL

Materials

The materials used in this study were *Gmelina arborea* Roxb. bark powder, maleic anhydride (MAH), aluminum foil, and recycled polypropylene (RPP) pellets obtained from CV. Metal Rizki Manufacturing, Indonesia.

Methods

Production of samples

The Gmelina bark was ground into powder using a grinder machine (Disk mill FFC-45) until was turned into fine particles. The powder was then sieved to obtain Gmelina bark

powder with particle sizes of 40 to 60 mesh, 60 to 80 mesh, and 80 to 100 mesh. Recycled polypropylene plastic pellets were mixed with maleic anhydride (MAH) at a level of 5% of the total matrix weight. The mixture of plastic pellets and bark powder is blended inside a plastic container, following the specified composition in Table 1, until it was evenly distributed and reached a target density of 1.0 g/cm^3. The plastic and bark powder mixture was placed in a pan and heated on a stove. Stirring was performed every 4 to 6 min. The stirring continued until the mixture reached an average temperature of about 200 to 250 °C (Ross 2021). Subsequently, the mixture was pressed using a cold press for 4 min with a pressure of 30 kg/cm^2. After the bark plastic composite has been pressed, it is left to cool under pressure until it reaches room temperature to prevent dimensional changes such as bending.

Table 1. Experimental Design

Composition of Filler: Matrix	Treatment		
	Filler particle size (mesh)		
	40-60 (M40)	60-80 (M60)	80-100 (M80)
40%:60% (P60)	M40P60	M60P60	M80P60
30%:70% (P70)	M40P70	M60P70	M80P70
20%:80% (P80)	M40P80	M60P80	M80P80
0%:100% (P100)	Control		

Physical Properties

Density and moisture content

Three specimens measuring 25 × 25 × 10 mm^3 were used for density and moisture testing using the gravimetric method based on JIS A 5908:2003 and SNI 03-2105-2006 standards. Density was determined by weighing (m) and volume measuring (v) specimens in air-dry conditions. The moisture content is determined by weighing the specimen in air-dry conditions (m_1, g) and then dried in an oven at a temperature of 103 ± 2 °C until its weight was constant (m_2, g). The density and moisture content (MC) values were calculated by Eqs. 1 and 2.

$$\text{Density (g/cm}^3) = m / v \quad (1)$$

$$MC\ (\%) = [(m_1 - m_2) / m_2] \times 100 \quad (2)$$

Water absorption and thickness swelling

Three specimens measuring 25 × 25 × 10 mm^3 were used to determine the water absorption and thickness swelling following the JIS A 5908:2003 and SNI 03-2105-2006 standards. The specimen volume (v_1, mm^3) and weight (m_1, g) were measured in air-dry conditions. The specimens were soaked in the water at room temperature for 24 h. Furthermore, the volume of the specimen (v_2, mm^3) and weight (m_2, g) after soaking in water for 24 h were obtained. The water absorption (WA) and thickness swelling (TS) values were calculated using Eqs. 3 and 4,

$$WA\ (\%) = [(m_2 - m_1) / m_1] \times 100 \quad (3)$$

$$Ts\ (\%) = [(t_2 - t_1) / t_1] \times 100\% \quad (4)$$

Mechanical Properties

Modulus of rupture and modulus of elasticity

Three specimens measuring 160 × 20 × 4 mm^3 were used for testing MOR and MOE according to JIS A 5908:2003 and SNI 03-2105-2006 standards using Universal Testing Machine (UTM) (AGS-X 50 kN, Shimadzu, Japan). The MOE and MOR values were calculated by Eqs. 5 and 6,

$$MOR\ (kg/cm^2) = 3 \cdot P \cdot L^2 / b \cdot h^2 \quad (5)$$

$$MOE\ (kg/cm^2) = \Delta P \cdot L^3 / 4 \cdot \Delta y \cdot b \cdot h^3 \quad (6)$$

where P is maximal load (kg), L is span distance (cm), b is length of sample (cm), h is thickness of sample (cm), ΔP is change of the load, and Δy is change of the deflection.

Internal bond

Internal bond (IB) testing was conducted using samples measuring 50 mm × 50 mm. The samples' length and width were measured, and they were bonded with two iron blocks on both sides using Kleiberit adhesive from Germany. This adhesive had a bonding strength of 0.7 to 1 N/mm^2 and a viscosity of 12,000 ± 2,000 mPa·s at 20 °C (Kleiberit, n.d). The samples were left to dry for 24 h. They were then tested using a Universal Testing Machine (UTM) (AGS-X 50 kN, Shimadzu, Japan) by applying vertical tension at a speed of 2 mm/min, and the maximum load was recorded. This testing complied with JIS A 5908:2003 and SNI 03-2105-2006 standards.

Hardness

Hardness testing used samples measuring 50 mm × 50 mm. The samples were subjected to compression using a half-sphere steel ball with a diameter of 11.3 mm until the ball's depth reached half its diameter. The testing was performed using a Universal Testing Machine (UTM) (AGS-X 50 kN, Shimadzu, Japan), and the maximum compression force was recorded. This testing followed the ASTM D134-94 standard.

Screw withdrawal

Screw withdrawal testing was performed on samples measuring 50 mm × 100 mm. Screws with a diameter of 3.5 mm and a length of 16 mm were inserted into the samples to a depth of 8 mm. The screw withdrawal test was conducted using a Universal Testing Machine (UTM) (AGS-X 50 kN, Shimadzu, Japan) at a pull speed of 2 mm/minute. The pull-out strength was indicated by the maximum load. This testing complied with JIS A 5908:2003 and SNI 03-2105-2006 standards.

Composite Morphology

Composite morphology was studied through a microscope using scanning electron microscopy (SEM) (JEOL JSM-6360 LA, Japan).

Data Analysis

The data obtained were analyzed using analysis of variance (ANOVA) with Duncan's advanced test at the 5% real level using IBM SPSS software.

RESULTS AND DISCUSSION

Physical Properties

Density

Density is the ratio of weight to the volume of a board. It influences the mechanical strength of the board, such as MOE, MOR, IB, and screw withdrawal. Higher-density boards tend to have better mechanical properties but lower dimensional stability, and *vice versa* (Ross 2021). The obtained average density values ranged between 0.92 and 1.00 g/cm³ (Fig. 1). All the produced bark plastic composites met the target density of 1 g/cm³. The ANOVA results indicated that composition and particle size did not significantly affect the density values. These composites fell into the high-density board category (above 0.8 g/cm³), suggesting a compact structure with strong particle bonding (Lopez *et al.* 2021).

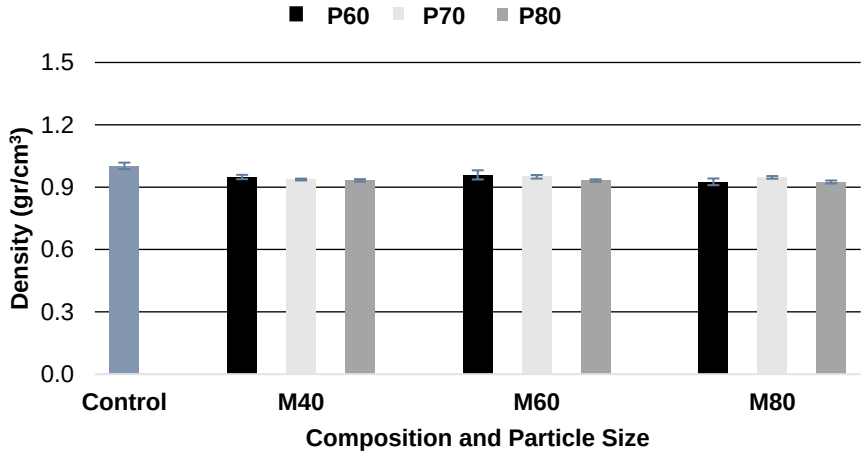

Fig. 1. Density of BPC

Moisture content

Moisture content (MC) refers to the amount of water in wood, particularly in cell walls and intercellular spaces. Particle board properties are highly influenced by moisture content (Muhamad *et al.* 2019; Ross 2021). The obtained average moisture content values ranged between 0.13 and 0.25% (Fig. 2).

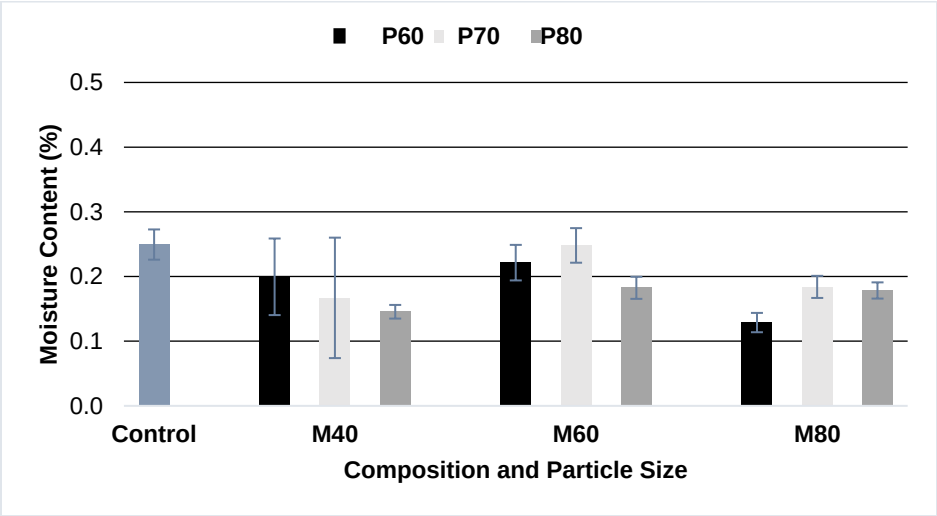

Fig. 2. Moisture content of BPC

All composite treatments met the standard requirements of being below 13% moisture content, which is defined for structural particle boards. Both composition and particle size did not significantly affect the moisture content values. The heating process during production affected moisture content due to the melting of PP plastic, typically done between 160 and 220 °C (Maddah 2016; Ross 2021).

Water absorption

Water absorption (WA) measures the amount of water that can be absorbed by wood products due to hydrogen bonding between water molecules and -OH groups in cellulosic components (Rahmad *et al.* 2018). The obtained average water absorption values ranged between 0.26 and 1.13% (Fig. 3). While JIS A 5908:2003 and SNI 03-2105-2006 don't specify absorption standards, referring to the Indian standard IS 3087:1985, all boards met the standard of being below 20%. Composition significantly affected water absorption values, with boards having more filler showing higher water absorption (Bootkul *et al* 2017). Pores in the wood powder form hydrogen bonds with water. Excessive volume fractions of fillers can create voids that prevent proper wetting by the matrix (Rahman *et al.* 2018; Adhikary *et al*. 2008). The low absorption capacity is also caused by the high density of the board, making it difficult for water or water vapor to fill the void (Arifin and Syahyuniar 2017).

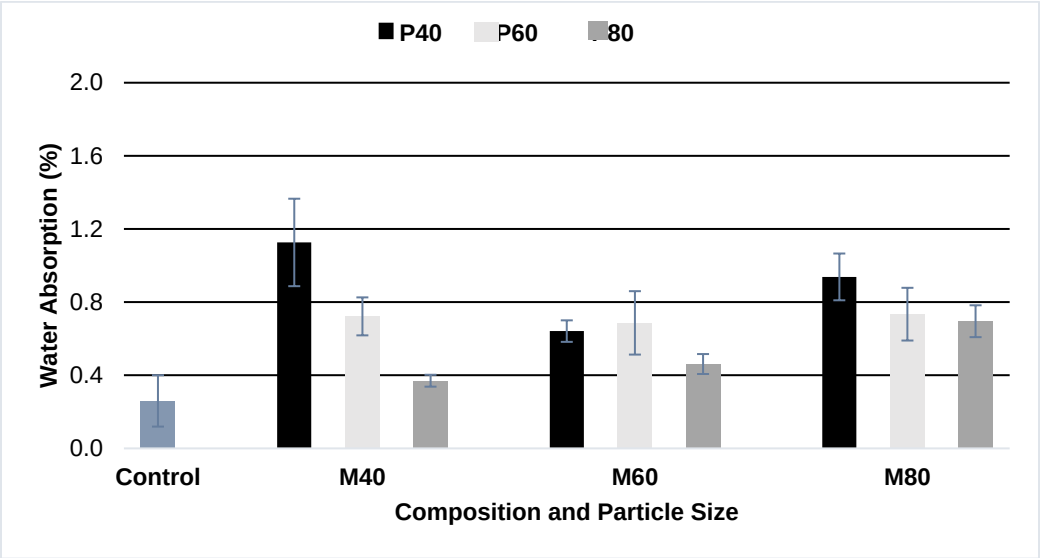

Fig. 3. Water absorption of BPC

Thickness swelling

Swelling can occur because of the additional water content in the composite. Thickness swelling (TS) is determined by measuring the volume of the composite test sample before and after soaking for 24 h. Thickness swelling indicates the dimensional stability of particle boards when exposed to water. Lower swelling thickness values imply higher dimensional stability (Muhamad 2019; Ross 2021). The average swelling thickness values ranged between 0.14 and 0.47% (Fig. 4).

All composite treatments met the maximum 20% thickness swelling requirement for structural particle boards. Both composition and particle size did not significantly affect swelling thickness. There was a positive correlation between water absorption and swelling

thickness. Higher water absorption leads to greater swelling thickness (Adhikary *et al.* 2008).

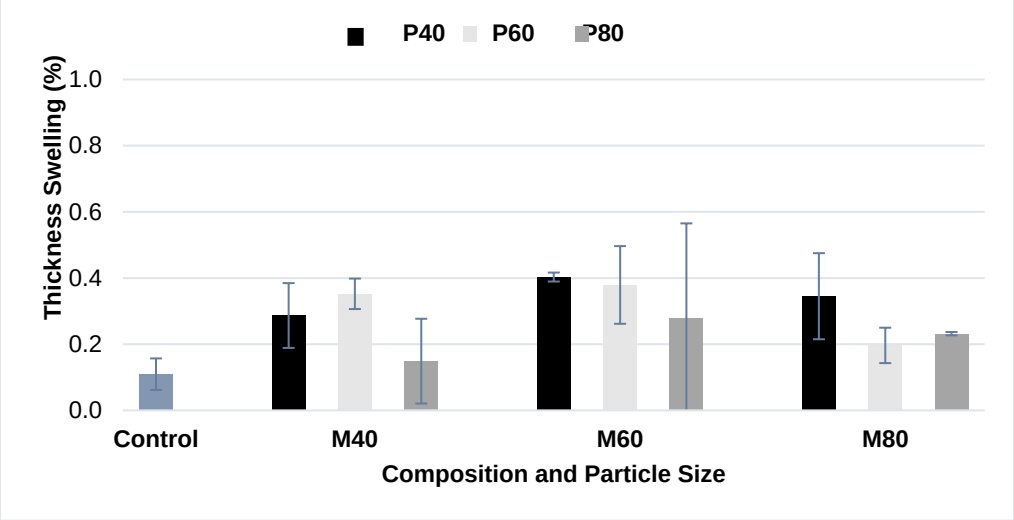

Fig. 4. Thickness swelling of BPC

Mechanical Properties

Modulus of rupture

The MOR is a board's resistance to withstand load or pressure until it breaks or deforms. The higher the value of the board's fracture strength, the greater the load it can bear before experiencing deformation (Muhamad *et al*. 2019; Ross 2021). The fracture strength values of the bark plastic composite are presented in Fig. 5. Based on the test results, the MOR value of the bark plastic composite ranged from 10.9 to 19.8 N/mm^2. Samples that met the MOR standards of JIS A 5908:2003 and SNI 03-2105-2006 for structural particle boards, which were in the range of 17.5 to 24 N/mm^2 for the control sample, M60P70, M40P80, M60P80, M80P80, and M8P70. Based on the ANOVA data, the composition treatment significantly influenced the fracture strength of the bark plastic composite. Based on Indonesian standards SNI 03-2105-2006, the composite resulting from this research is included the regular structural particle board type 17.5 - 10.5. In general, there was an increase in the MOR value of the board when the size of the filler particles became smaller. This is because smaller particle sizes have a larger surface area, leading to stronger bonding between the matrix and the filler, allowing the composite to withstand greater loads (Rahman *et al.* 2018). The formed bonding between the matrix and filler also makes the bark plastic composite stiffer (Divya *et al*. 2022). However, Fig. 5 shows a significant decrease in the MOR value as the filler fraction increases. An excessive volume fraction of fillers renders the matrix unable to fully wet the filler surfaces or leads to voids on the particle surfaces or within the matrix (Nurwendi *et al* 2016; Rahman *et al*. 2018).

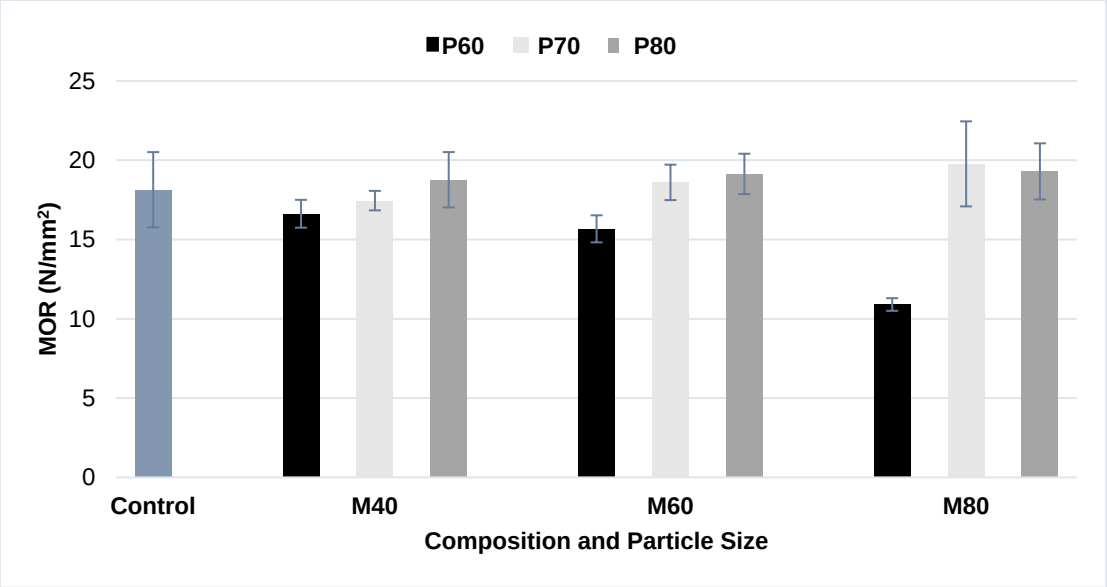

Fig. 5. Modulus of rupture of BPC

Modulus of elasticity

The MOE is the ability of a board to withstand and return to its original shape or condition after being subjected to a load or pressure. A higher MOE value represents the board's greater ability to withstand larger loads or pressures (Muhamad *et al.* 2019; Ross 2021). The values of MOE of bark plastic composite are presented in Fig. 6.

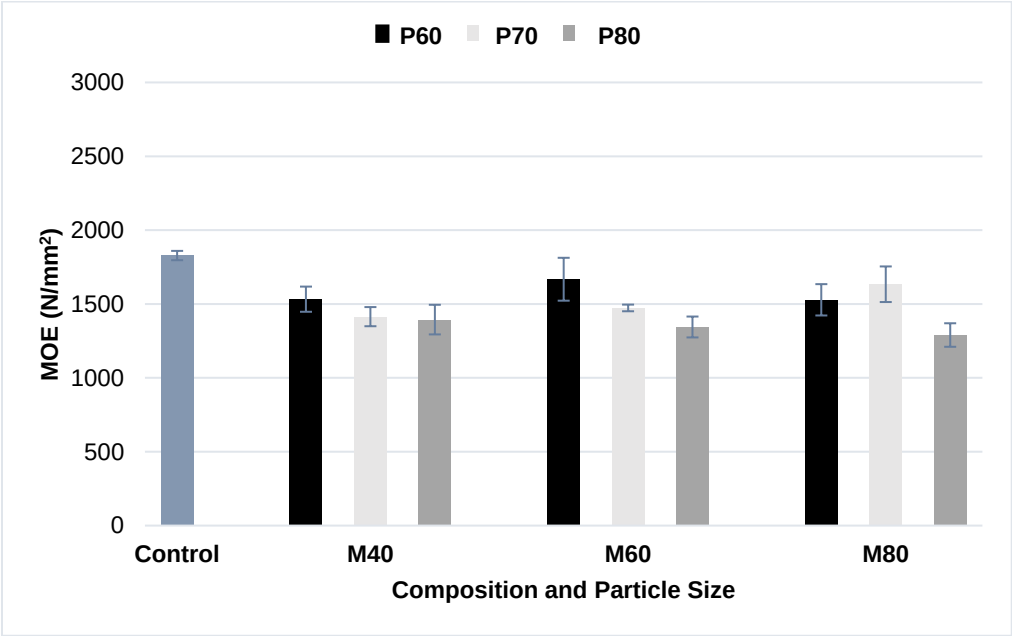

Fig. 6. Modulus of elasticity of BPC

Based on the test results, the MOE values of bark plastic composite ranged from 1,270 to 1,830 N/mm^2. None of the samples met the MOE standards of JIS A 5908:2003 and SNI 03-2105-2006 for structural particle boards, which are 3,000 to 4,000 N/mm^2. Based on the data from the ANOVA test, both composition and particle size significantly

influenced the flexural strength values of the bark plastic composite. Polypropylene plastic is a type of thermoplastic that becomes soft when heated and hardens when cooled. Polypropylene plastic consists of methyl groups (CH_3) bound to carbon atoms, forming a linear structure that prevents chain rotation. This chemical bond structure gives PP plastic its strength but low flexibility (Awad *et al.* 2019). The addition of filler causes the flexural strength value of the bark plastic composite to decrease (Fig. 6). This is due to the bonds between the filler particles and the matrix. Maleic anhydride (MAH) can enhance the bonding between filler and matrix. The formed bonds make the bark plastic composite more rigid (stiff) and less flexible (Divya *et al*. 2022; Vedrtnam *et al*. 2019). Bark plastic composite M60 and M80 with composition codes P70 and P60 exhibited a significant increase in elastic modulus compared to P80. The research conducted by Rahman *et al*. (2018) indicates that bark plastic composites made from smaller filler particle sizes and a higher filler content can enhance flexural strain values. Increased strain values indicate greater material flexibility. These results were in line with Rindayatno and Fahmi (2024), who showed that oil palm fronds WPC is suitable for use in lightweight constructions because it has respectable physical qualities and a sufficient mechanical capacity to withstand loads, despite its poor flexibility.

Internal bond

Internal bond is a test to measure the value of the internal structure's adhesive force of a board or the bond between board particles. The strength of particle board bonding is influenced by mixing, forming, and pressing processes (Muhammad *et al*. 2019). The particle board bonding referred to here is the bond between polypropylene plastic and Gmelina wood bark powder. Internal bond values are presented in Fig. 7. Based on the test results, the internal bond strength of the bark plastic composite ranged from 1.2 to 2.85 N/mm^2. All samples met the internal bond standards of JIS A 5908:2003 and SNI 03-2105-2006 for structural particle boards, which have a minimum requirement of 0.3 N/mm^2. Based on the ANOVA data, the composition treatment significantly influenced the internal bond strength of the bark plastic composite. All treated bark plastic composites exhibited values well above the minimum standard requirement. This indicates the presence of strong bonding between the matrix and the filler. The strong bonding of particles contributes to making the boards more compact and solid. The robust bonding arises from the branch groups in polypropylene plastic combined with wood fibers (Lopez *et al*. 2021). This bonding is further reinforced by the coupling agent MAH, which enhances the bonding between the matrix and filler surfaces (Elsheikh *et al*. 2022).

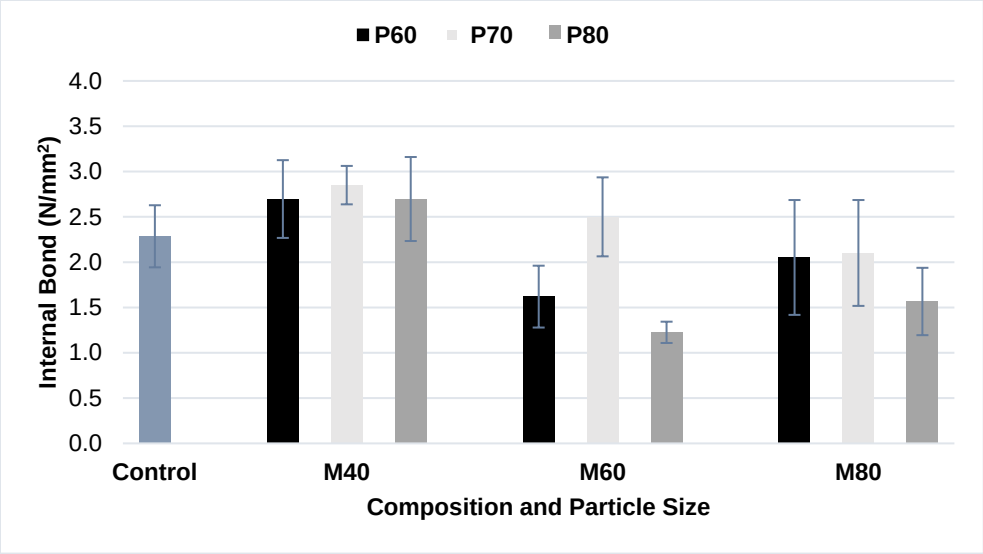

Fig. 7. Internal bond of BPC

Screw withdrawal

Screw withdrawal is a method for measuring the resistance or strength of bark plastic composite in holding a screw when the screw is pulled perpendicular to the board. This test determines the suitability of the board as a furniture material that requires the method of joining boards with screws or nails (Ross 2021). The values of screw withdrawal of the bark composite are presented in Fig. 8.

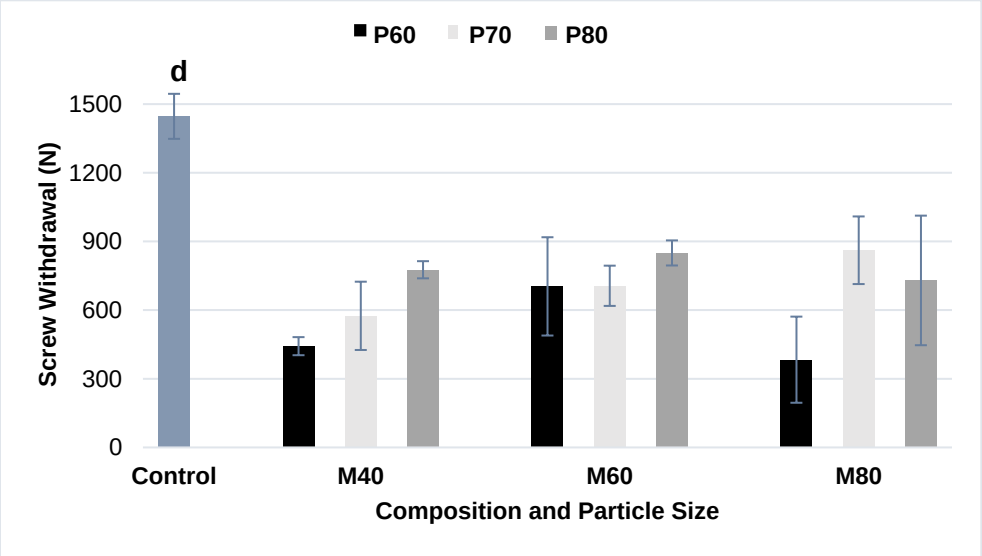

Fig. 8. Screw withdrawal of BPC

Based on the test results, the screw holding power of the bark plastic composite ranged from 383.3 to 1,446.6 N. All samples met the screw holding power standards of JIS A 5908:2003 and SNI 03-2105-2006 for structural particle boards, which is 500 N, except for samples M40P60 and M80P60. Based on the ANOVA data, the composition treatment significantly influenced the screw withdrawal of the bark plastic composite. As observed in Fig. 8, the addition of filler led to a decrease in the screw withdrawal.

Similarly, bark plastic composites with a higher filler content exhibited lower screw withdrawal. This phenomenon is due to the plastic's role as an adhesive that strengthens the bark plastic composite (Lestary *et al.* 2022).

Hardness

Hardness testing is conducted to determine the resistance of composite boards against the occurrence of structural indentation due to excessive or prolonged load (Ross 2021). The hardness values for the plastic wood composite are presented in Fig. 9. Based on the test results, the fracture toughness of the bark plastic composite ranged from 5,660 to 1,030 N. The standard of hardness value for particle board is not mentioned in the JIS and SNI standards. However, these values are equivalent to commonly grown hardwoods in Indonesia such as teak wood (*Tectona grandis*) (4,400 N) and meranti wood (*Shorea* sp.) (6,000 N), as well as common hardwoods in the United States like cherry red oak (*Quercus pagoda*) (5,500 N) and pignut hickory (*Carya glabra*) (9,500 N) (Ross 2021). Based on the ANOVA data shown in Fig. 9, the composition treatment significantly influenced the hardness value of the bark plastic composite. The bark plastic composite exhibited hardness comparable to that of hardwoods. This is a characteristic feature of plastics, which soften or melt when heated but become hard when cooled (Ross 2021). The presence of filler with a ratio to the matrix of 20% and 30% can enhance the hardness of the bark plastic composite. Filler can also increase the composite's strength through the improvement of its stiffness properties. This happens due to the formation of bonds between filler particles and the matrix. A coupling agent such as MAH also enhances the bond between filler and matrix (Divya *et al.* 2022). However, there can be a significant decrease in hardness when the filler fraction becomes larger. An excessive volume fraction leads to the matrix being unable to fully wet the surface of the filler, resulting in voids or gaps on the particle or matrix surface (Rahman *et al.* 2018). Hardness is also greatly influenced by density. Density had a positive correlation with the mechanical properties of bark plastic composites. The higher the density, the stronger the particle-matrix bond, resulting in a compact and solid board structure (Lopez *et al*. 2021).

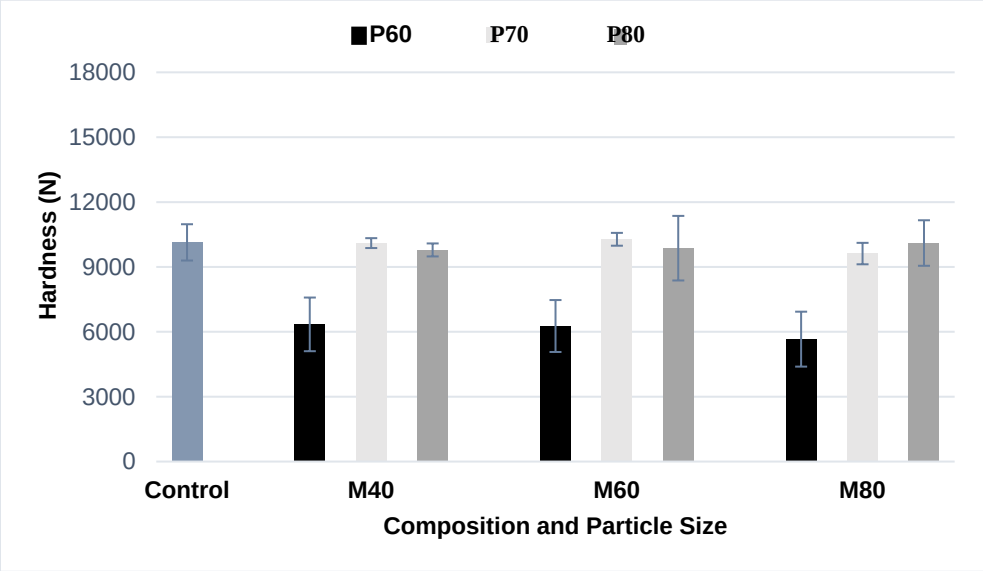

Fig. 9. Hardness of BPC

Morphological Properties

The morphology of the bark plastic composite can be observed in Figs. 10 and 11. In Fig. 10, the bark plastic composite part appears smooth, wavy, or rough. The smooth parts indicate that the matrix was capable of completely wetting the filler. However, there are certain areas (spots) that could not be wetted by the matrix due to the presence of agglomeration, resulting in a wavy, rough, and porous surface. Figure 11 illustrates the damage that occurs on the fractured surface of the composite. Some fillers are positioned non-parallel, and the end parts of the fillers appear to be disconnected or broken. This is caused by the loading during testing, which leads to the bending and fracturing of the composite. Additionally, there is an accumulation of filler that cannot be fully wetted by the matrix (Divya *et al.* 2022; Sutrisno *et al*. 2021).

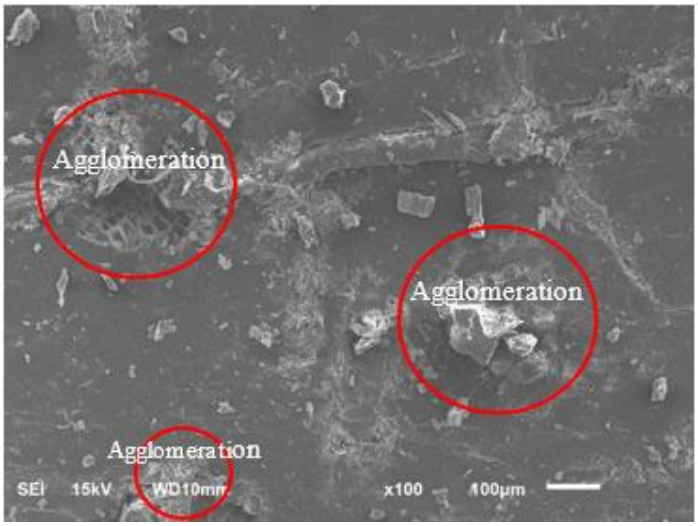

Fig. 10. Morphology of BPC, magnification 100x

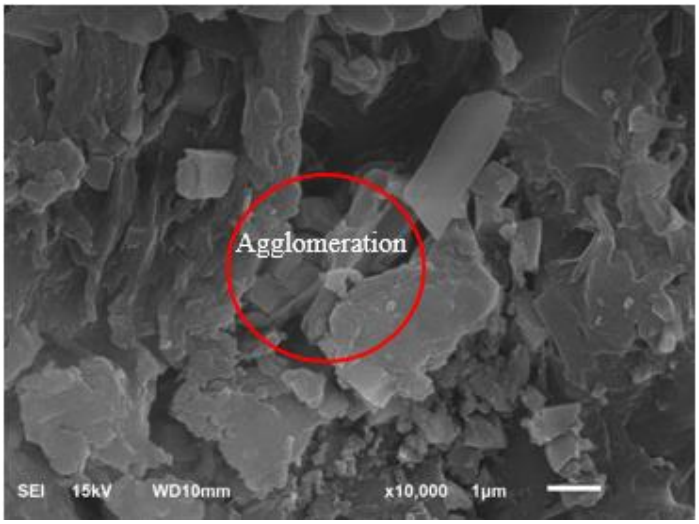

Fig. 11. Morphology of BPC, magnification 10,000x

CONCLUSIONS

1. The composition of bark powder significantly affected the value of water absorption, while particle size did not significantly affect the physical properties of the bark plastic composite. In the physical properties testing, the density, moisture content, and thickness swelling met the standards of JIS A 5908:2003 and SNI 03-2105:2006. Meanwhile, water absorption met the IS 3087:1985 standard.
2. The composition of filler and matrix significantly affected the mechanical properties, while particle size significantly affected the modulus of elasticity (MOE). Adding filler can enhance the mechanical properties of the bark plastic composite. However, excessive filler and too small particle sizes can reduce the mechanical properties of the bark plastic composite. In the internal bond test, all boards met the JIS and SNI standards. In the modulus of rupture (MOR) and screw withdrawal tests, most of the samples met both standards. However, in the MOE test, no board met both standards.
3. Based on the results of physical and mechanical testing, the M40P80 treatment (composition of filler: matrix = 20%: 80% with a particle size of 40 to 60 mesh) was judged to be the best bark plastic composite.

ACKNOWLEDGMENTS

The researchers would like to acknowledge the National Research and Innovation Agency of Indonesia (BRIN) for funding this research under the scheme of "Program Riset dan Inovasi untuk Indonesia Maju (RIIM) Gelombang I" Code File LPPM.PN-13-12-2022, Contract Number 417/IT1.B07/KS.00/2022 and 20/IV/KS/06/2022.

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Article submitted: July 18, 2024; Peer review completed: August 7, 2024; Revised version received and accepted: August 10, 2024; Published: August 22, 2024.
DOI: 10.15376.biores.19.4.7393-7407