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Experimental study of the physical and mechanical properties of particleboard reinforced with eggshell, wood, and bamboo hybrid fillers

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Abstract

The use of natural resources as particleboard materials has significantly increased due to growing environmental and sustainability concerns. This study aims to evaluate the physical and mechanical properties of particleboard made from three waste materials: eggshell particles, wood particles, and bamboo particles. The composite was formulated with the volume fractions of 10% epoxy resin, 25% Polyvinyl Acetate (PVAc) adhesive, 40% eggshell particles, and a 25% combined bamboo and wood particles. The bamboo-to-wood ratios investigated were 0:25 (B0W25), 12.5:12.5 (B12.5W12.5), and 25:0 (B25W0). Samples were prepared by cold compaction at 3 MPa for 2 hours, followed by curing at 100°C for 1 hour. The samples were evaluated for various physical properties, including density, water absorption, and thickness swelling, as well as mechanical properties such as hardness, flexural strength, flexural modulus, and flexural strain. Since multiple responses were obtained, the Data Envelopment Analysis-based Ranking (DEAR) method was used to assess composite performance. The study found that sample B25W0 exhibited the most optimal performance, with a density of 1.53 ± 0.01 g/cm³, water absorption of 8.47 ± 0.36%, thickness swelling of 6.05 ± 0.89%, hardness of 67.17 ± 0.94 Shore D, flexural strength of 12.90 ± 0.29 MPa, flexural modulus of 1.24 ± 0.03 GPa, and flexural strain of 2.23 ± 0.17%. The improvement is attributed to the alkali treatment of the bamboo particles. These results indicate that eggshell and bamboo hybrid fillers have strong potential as for structural particleboard.

Keywords:
Bamboo, eggshell, sengon wood, physical properties, mechanical properties.

1 Introduction

One weakness of particleboard currently on the market is its susceptibility to water damage. When water seeps into particleboard, it can coat the interface layer between the composite matrix and the fiber or filler materials [1]. Various studies have been conducted to minimize the adverse effects of water exposure on these materials, with thickness swelling serving as a visual indicator of damage.

Diffusion refers to the movement of dissolved substances from areas of high concentration to areas of low concentration across a concentration gradient. The use of natural fibers as composite reinforcement poses specific challenges, particularly their high-water susceptibility. Consequently, research aimed at reducing water absorption remains relevant.

One effective method to reduce water absorption is to pre-treat the organic material. Alkali treatment can initially reduce water absorption compared to untreated samples. However, after more than five days, alkali-treated samples absorb more water [2]. Yin and Li [3] evaluated pretreatments for bamboo shavings by comparing carbonization, hydrothermal treatment, and alkali treatment in a 3% NaOH environment. Alkali treatment can enhance the compatibility between bamboo and cement, thereby improving the mechanical properties of particleboard. Additionally, Maulana et al. [4] demonstrated that steam treatment of bamboo fibers significantly reduces extract content, thereby enhancing the dimensional stability and mechanical properties of particleboard.

Matrix selection is essential for controlling the water absorption percentage in composites. Sunardi et al. [5] found that using a combination of 20% epoxy resin and 15% PVAc adhesive resulted in a low thickness swelling of only 4%. However, the mechanical properties of the composites were not examined. The composite's water absorption and thickness swelling decreased when using the natural binder, citric acid, compared to sucrose and maltodextrin DE 10-15 [6]. The Urea-Formaldehyde (UF) matrix is compatible with fibers but becomes brittle when exposed to water [7]. Furthermore, the excessive use of UF resin can compromise environmental safety and sustainability [8].

A composite made from a 50% mixture of bamboo shavings and bamboo leaves exhibited the best performance. It had a density of 0.72 g/cm³, a water content of 4.29%, water absorption of 44.16%, thickness swelling of 3.45%, MOE of 2.05 GPa, MOR of 281.01 MPa, an internal bond strength of 0.15, and a weight loss of 23.94% [9]. Furthermore, incorporating bamboo particles up to 50% improved both MOR and MOE, as well as screw tensile strength, compared to panels made from 100% wood [10].

The use of "andong" bamboo and "jabon" wood in the production of particleboard through hot compaction at 150°C, 25 kg/cm², and a holding time of 10 minutes meets the criteria set by SNI 03-2105-2006, except the MOE value [11]. The combination of bamboo and wood enhances the dimensional stability and durability of the particleboard compared to boards made from bamboo alone or wood alone [12]. These two studies focused exclusively on physical properties, whereas the mechanical properties were not observed in detail.

This study builds on the strengths of previous research. While a hybrid matrix of epoxy resin and PVAc enhances the water resistance of composites, its effect on mechanical properties is relatively limited. Likewise, studies utilizing a hybrid filler of bamboo and wood particles have primarily concentrated on physical properties. The originality of this study lies in its investigation of the physical and mechanical behavior of particleboard made from eggshell, bamboo, and wood particles. This study aimed to investigate the physical and mechanical properties of particleboard made from organic waste. Combining these three fillers reduces the composite's water absorption and enhances its mechanical properties.

2 Research methodology

Particleboard is produced through a cold compaction and curing process. The resulting samples are then analyzed as particleboard material.

2.1 Materials

The study utilized environmentally friendly materials, including sengon wood particles, bamboo particles, eggshell particles, PVAc adhesive, and epoxy resin.

2.1.1 Sengon wood

The use of sengon wood sawdust in this study is due to its abundant availability in Banten. Its hardness and density range from 112 to 122 kg/cm² and 0.30 to 0.50 g/cm³, respectively, at a moisture content of 15%. In this study, the particle size of sengon wood was measured at 80 mesh. Sengon wood particle illustrated in Fig. 1.

Fig. 1. Sengon wood powder.

2.1.2 Bamboo particle

Bamboo particles were selected for their suitability for structural applications and as annvironmentally friendly alternative for construction [13]. In this study, the particle size of bamboo was measured at 80 mesh. The density of bamboo varies from 0.60 to 0.83 g/cm³, with an average density of 0.74 g/cm³. The bamboo species used in this study is Dendrocalamus asper, commonly known as betung bamboo, which was sourced from the Cilegon region. Bamboo powder is presented in Fig. 2.

Fig. 2. Bamboo powder.

2.1.3 Eggshells particle

Eggshell were collected from household waste. They were cleaned, crushed, and then sieved using an 80-mesh sieve. The inclusion of eggshell particles can improve the strength and modulus of glass fiber-reinforced polyester composites [14]. The primary chemical component of eggshells is calcium carbonate ($CaCO_3$), primarily in the form of calcite, which makes up 94%-97% of their composition. Additionally, they contain organic matter, which accounts for 3%-4.5%. Other elements found in smaller quantities include magnesium oxide (MgO) at 0.83%, sulfur trioxide (SO_3) at 0.66%, phosphorous pentoxide (P_2O_5) at 0.43%, aluminum oxide (Al_2O_3) at 0.15%, potassium oxide (K_2O) at 0.08%, silicon dioxide (SiO_2) at 0.07%, chromium trioxide (Cr_2O_3) at 0.06%, and strontium oxide (SrO) at 0.04% [15]. The density of eggshell particles is 2.55 g/cm³. In this study, the particle size of sengon wood was measured at 80 mesh. Fig. 3 shows the raw material, consisting of eggshell particles.

Fig. 3. Eggshell waste.

2.1.4 PVAc adhesives

PVAc adhesive is preferred due to its ease of use, elasticity, resistance to aging, low cost, and non-toxicity. It is also resistant to bacteria and fungi [16]. However, PVAc bonds are sensitive to humid environments and high temperatures [17]. The density of PVAc adhesive is 1.18 g/cm³. For improved performance, these adhesives are often used in combination with epoxy resins. Fig. 4 presents the PVAc adhesive.

Fig. 4. PVAc adhesive.

2.1.5 Epoxy resin

Epoxy resin has been chosen for its high specific strength, excellent adhesion, and high dimensional stability [18]. The density of epoxy resin is 1.23 g/cm³.

2.2 Samples preparation

2.2.1 Alkali treatment

Alkali treatment was used to modify the fiber surface, enhancing mechanical and thermal properties and improving adhesion to the polymer matrix. Bamboo particles were soaked in a 5% NaOH solution for 2 hours. After the soaking period, the bamboo particles were washed with running water until the pH reached 7.

2.2.2 Sample manufacturing

The composition of organic particleboard composite materials was determined by the volume fraction, as shown in Table 1. The mixing process for these materials occurs in two stages. Particulate materials were mixed in an open bucket at a speed of 490 rpm for 5 minutes. Following this, PVAc adhesive and epoxy resin were added to the mixture, which was then stirred for 20 minutes. This stirring was done using a shaft with four blades attached to a conventional milling machine. After mixing, the mixture was allowed to rest for 10 minutes to prevent leakage during compaction. This mixture was poured into a mold and subjected to 3 MPa of pressure for 120 minutes. The sample preparation process is illustrated in Fig. 5.

Table 1. Composition of particle board materials

Materials	Sample code		
	B0W25	B12.5W12.5	B25W0
Bamboo particle	0	12.5	25
Wood particle	25	12.5	0
Eggshell particle	40	40	40
PVAc adhesive	25	25	25
Epoxy resin	10	10	10

The compaction pressure for the particle board was set at 3 MPa, based on previous research reporting values of MPa [19], 3 MPa [20], and 3.63 MPa [21]. In the wood particleboard manufacturing industry, the typical compaction pressure ranges from 3.5 MPa [22]. After compaction, the samples were removed from the molds and left to cure for 24 hours. The curing process involved heating the samples in a furnace at 100°C for 60 minutes, followed by cooling to room temperature. The samples were then prepared in accordance with the relevant testing standards.

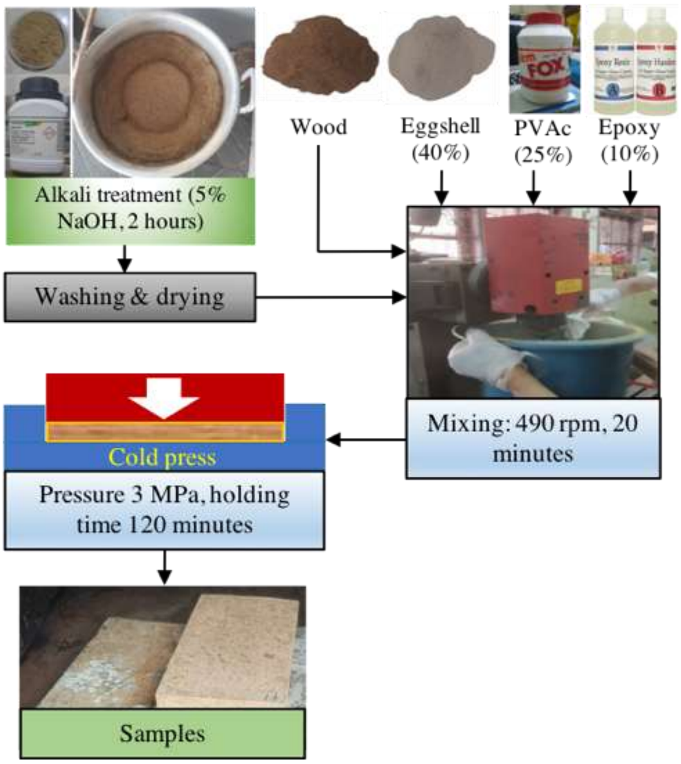

Fig. 5. The preparation process of the composite.

2.3 Material characterization

2.3.1 Density

Three samples, each measuring 30×30×30 mm, were prepared to determine the composite material's density experimentally. The samples were weighed, and the volume of each composite sample was measured. The collected data were then used to calculate the average and standard deviation in Excel. The density of the composite was determined using Eq. (1) [23, 24], where ρ is the density (g/cm^3), m is the sample weight (g), and V is the volume of the composite (cm^3).

$$\rho = \frac{m}{V} \tag{1}$$

Based on the mixture rule, the composite density can be determined using Eq. (2), where ρ_c is the composite density, ρ_i, υ_i are the density and volume fraction of each material.

$$\rho_c = \sum_{i=1}^{n} \rho_i \, \upsilon_i \tag{2}$$

2.3.2 Water absorption

For the investigation of water absorption, three composite samples measuring 30×30×10 mm were used. The procedure for testing the water absorption of composites adheres to ASTM D570 standards. Before conducting the water absorption test, the samples were heated in a furnace at 105°C for 1 hour. After heating, the samples were allowed to cool to room temperature and were then weighed. The specimens were subsequently immersed in distilled water for 24 hours at room temperature. This test was performed in a container in which the samples were positioned at least 3 cm above the water surface. After 24 hours, the samples were removed from the water, wiped dry, and weighed again. The percentage of water absorption was calculated using Eq. (3), where W_0 and W_1 are the weights of the samples before and after immersion in distilled water for 24 hours (g). The collected data were processed using statistical methods, such as mean and standard deviation, in Microsoft Excel.

$$Water\ absorption\ (\%) = \frac{W_1 - W_0}{W_0} \times 100\% \tag{3}$$

2.3.3 Thickness swelling

To evaluate thickness swelling, three composite samples measuring 30×30×10 mm were immersed in water for 24 hours. The graph displays the average and standard deviation. The thickness swelling was tested according to ASTM D570 and calculated using Eq. (4), where T_1 and T_0 are the composite thicknesses after and before immersion (mm), respectively.

$$Thickness\ swelling\ (\%) = \frac{T_1 - T_0}{T_0}\ x\ 100\% \tag{4}$$

2.3.4 Flexural strength

Flexural strength testing was performed using the three-point bending method as per ASTM D790 on a Zwick Z020 testing machine. Three samples measuring 100×10×4 mm were prepared for each variation. The graph displays the average and standard deviation. The span length was set to 80 mm, and the preload during testing was 0.2 N with a test speed of 2 mm/min. The flexural strength was calculated using Eq. (5), where P_{max} is the maximum load at failure (N), L is the span length (mm), and w and h are the specimen width and thickness (mm), respectively.

$$\sigma_{max} = \frac{3P_{max}L}{2wh^2} \tag{5}$$

2.3.5 Hardness

Hardness testing was conducted using a Shore D Durometer, in accordance with ASTM D2240. The sample size utilized was 80×50×6 mm. Testing occurred at a point at least 12 mm from the sample edge. Measurements were taken at three points on the composite surface to ensure accuracy, and the mean and standard deviation are presented when showing the experimental data.

2.3.6 Statistical analysis

The Multi Response Performance Index (MRPI) consolidates multiple responses into a single response. In this context, each response can be either the original data collected during the observation or a modified version of it, such as the Signal-to-Noise (S/N) ratio.

This study uses the Data Envelope Analysis-Based Ranking (DEAR) method for optimizing multi-response. In this method, a set of responses is mapped to the ratio of responses with the quality characteristic "larger-the better" to those with the quality characteristic "smaller-the better." The optimal level can be determined from this ratio. This ratio is equivalent to the MRPI. The optimization steps using the DEAR method [25]: (1) determine the weights for each response across all experiments using an appropriate weighting technique. The weight for the quality characteristics that follow the "smaller-the better" criterion can be calculated using Eq. (6), while the weight for those with the "larger-the better" criterion can be determined using Eq. (7); (2) transform the observed data of each response into weighted data by multiplying the observed data by its own weight; (3) divide the weighted data of the larger—the-better type with the weighted data of the smaller—the-better type or the nominal-the best type; (4) treat the value obtained in step 3 as MRPI and obtain the solution.

$$W_{Y_i} = \frac{(1/Y_i)}{\Sigma 1/Y} \tag{6}$$

$$W_{Y_i} = \frac{Y_i}{\Sigma 1/Y} \tag{7}$$

The responses in this study can be categorized according to the quality characteristics: (1) larger-the better, including hardness, flexural strength, and modulus; and (2) smaller-the better, such as density and thickness swelling. A higher MRPI value indicates better overall performance of the particle board.

3 Results and discussion

3.1 Physical properties

3.1.1 Density

Fig. 6 illustrates the density of particleboard made from organic materials, specifically bamboo, sengon wood, and eggshell particles. The highest density was observed in the B25W0 sample, which had a density of 1.53 ± 0.01 g/cm³ and contained 25% bamboo with no sengon wood particles. In contrast, the lowest density was found in the B12.5W12.5 sample, where the densities of bamboo and sengon wood particles were equal, resulting in a density of 1.36 ± 0.02 g/cm³. Additionally, the B0W25 sample, which contained no bamboo, had a density of 1.39 ± 0.01 g/cm³. These data indicate that the combination of bamboo and sengon wood particles results in the lowest overall density. Further investigation is needed to determine whether the absence of alkali treatment for the sengon wood particles is responsible for the low density in these samples.

The overall density of this particleboard exceeds 0.90 g/cm³, classifying it as high-density particleboard. This high density is likely attributed to the presence of eggshell particles, which make up 40% of the composition. The density of the eggshell particles ranges from 2.50 to 2.60 g/cm³. According to the rule of mixture (Eq. (2)), the densities of the resulting composites are the same: B0W25, B12.5W12.5, and B25W0, with values of 1.39 ± 0.01, 1.36 ± 0.02, and 1.53 ± 0.01 g/cm³, respectively. The combination of PVC with 40% eggshell particles results in a density of 1.61 ± 0.002 g/cm³ [26]. This research also indicates that increasing the loading of eggshell particles leads to higher density and porosity in the composite material. The addition of eggshell particles to the epoxy composite raises the density to 1.38 g/cm³, compared to neat epoxy of 1.15 g/cm³ [27].

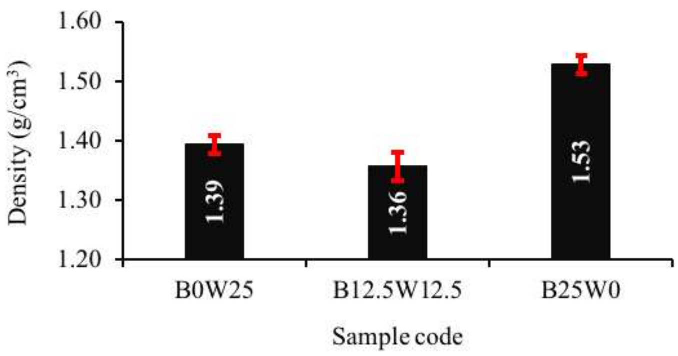

Fig. 6. The density of the composite.

According to SNI 03-2105-2006, the density of the particle board studied does not meet the standard requirement, which specifies a density range of 0.40 to 0.90 g/cm³. The particle board in question has a density exceeding 1 g/cm³ [28], categorizing it as a high-density panel. This type of particle board is suitable for various applications, including composite flooring, antistatic flooring in computer rooms, wall protection boards, wall panels, and both interior and exterior decoration.

3.1.2 Water absorption

The water-absorption percentage of the composite materials is shown in Fig. 7. Among the tested samples, hybrid B12.5W12.5 exhibited the highest water absorption rate of 8.92 ± 0.47%. In contrast, the sample B25W0 had the lowest water absorption rate at 8.47 ± 0.36%. The sample without any bamboo content, B0W25, recorded a water absorption rate of 8.70 ± 0.81%. These results suggest a compatibility issue between sengon and bamboo particles. This condition occurs because the bamboo particles undergo alkaline treatment, which restricts air diffusion into the composite.

Additionally, the presence of hydrophobic eggshell particles creates complex pathways between them, further hindering the diffusion of water molecules [29]. The water absorption percentage observed in the current study ranges from 8.47% to 8.92%. The maximum recommended water absorption according to IS 14276 is 13% for 2 hours and 25% for 24 hours [30]. This finding is quite comparable to the research by Gurmu et al. [31], which reported a water absorption rate of 7% to 10% when using a hybrid combination of sisal and bamboo fibers.

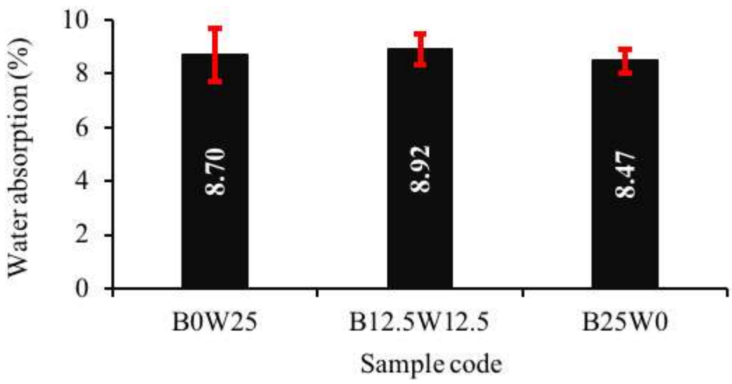

Fig. 7. Water absorption of particleboard.

The relatively low water absorption observed is attributed to the presence of eggshell particles, which can create a barrier effect against water. However, if the eggshell content is too high, it can lead to agglomeration, creating water-diffusion paths and areas of stress concentration. Yildizhan et al. [29] recommended a maximum eggshell content of 3 wt%. In contrast, a study by Sunardi et al. [32] indicated that incorporating up to 25% eggshell particles significantly reduced water absorption, but the effect on mechanical properties was not examined.

Further analysis revealed an inverse relationship between the composite's water absorption percentage and its density. Specifically, as the composite's density decreased, the percentage of water absorption increased [33]. In this study, hybridization of organic materials increased the composite's water absorption percentage. This condition arises from untreated sengon wood particles in the B12.5W12.5 composite, which are hydrophilic and absorb water. The findings of this study align with those of Foud and Salman [34]. Their study found that a composite made from a hybrid of 25%wt glass powder and 25%wt coconut powder showed greater water absorption than composites made solely from glass powder or pure coconut powder. Another study found that a hybrid of Kevlar and kenaf fibers exhibited a higher water absorption percentage than composites made of either Kevlar or kenaf fibers alone. The water absorption percentage for the composite with only kenaf fiber was 9.46%, which increased to 14.81% in the hybrid composite containing 50%wt kenaf fiber and 50%wt Kevlar fiber [35].

The lowest water absorption was observed in sample B25W0, a composite made with bamboo particles that does not contain sengon wood particles. This low water absorption can be attributed to the pretreatment applied to the bamboo particles, while the sengon wood did not undergo alkali treatment. Treatments such as 5% sodium hydroxide (NaOH) can improve the hydrophilic properties of composites made from organic materials [36]. Another study showed that treating fibers with a 5% NaOH solution for 6 hours significantly alters their surface. This treatment enhances interfacial adhesion with the matrix, resulting in a notable reduction in water absorption. Specifically, the percentage of water absorption decreases from 4.275% to 1.129% after soaking for 7 days [37].

The results of this study contrast with those of Si et al. [38], who reported that combining bamboo fiber with synthetic fiber improves water resistance. The compatibility between bamboo particles and eggshell particles was enhanced due to the alkali treatment of the bamboo particles. This aligns with a study that found that pretreating bamboo with a 3% NaOH solution improves its compatibility with cement [3]. The water absorption percentage for all samples complies with the international standard JIS A 5908-2003, which specifies a range of 5%-13% [39].

This study confirms that the hydrophilic properties of organic materials increase water absorption. Composites that include sengon wood particles show greater water absorption compared to those made solely of bamboo fibers. Therefore, it is essential to treat bamboo and wood particles with an alkali solution before use.

3.1.3 Thickness swelling

Thickness swelling is an indicator of the degradation of interfacial bonds between composite materials. As shown in Fig. 8, sample B25W0 exhibited the lowest thickness swelling value at 6.05 ± 0.89%, followed by B0W25 and B12.5W12.5 with values of 7.25 ± 0.96% and 8.37 ± 1.57%, respectively. This low thickness swelling correlates with the sample's low water absorption percentage and high density.

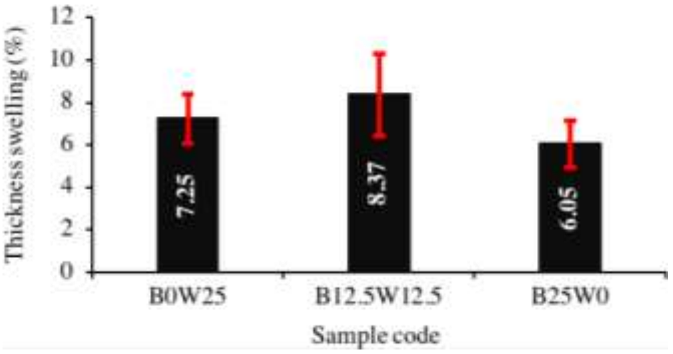

Fig. 8. The thickness swelling of particleboard.

Thickness swelling is directly proportional to the percentage of water absorption and inversely proportional to density. The B25W0 sample exhibits a thickness swelling of 6.05%, water absorption of 8.47%, and a density of 1.53 g/cm³. The reduced thickness swelling can be attributed to the alkali treatment of the bamboo particles and the incorporation of eggshell particles in the composite. Specifically, the addition of 5% eggshell particles can enhance the dimensional stability of lightweight foam concrete by 1.56% [40].

Thickness swelling occurs when water molecules diffuse into the composite through its pores, creating internal pressure at the filler-matrix interface. This pressure can lead to dimensional changes in the composite. According to the SNI 03-2015-2006 and JIS A 5908-2003 standards, the maximum allowable thickness swelling is 12% [41]. Thickness swelling serves as a critical parameter for assessing the dimensional stability of particleboard [42]. Generally, higher thickness swelling indicates lower dimensional stability in particleboard. The thickness swelling in the B12.5W12.5 sample reached 8.37%, which is the highest recorded value. This increased thickness swelling is attributed to the presence of sengon wood particles that have not been treated with alkali, which makes them more susceptible to water absorption and leads to greater thickness swelling. Additionally, Saadeh et al. [43] demonstrated that hybrid reinforcement tends to exhibit greater thickness swelling.

3.2 Mechanical properties

3.2.1 Hardness

The composite's hardness is depicted in Fig. 9. The results show that the B25W0 sample exhibited the highest hardness at 67.17 ± 0.94 Shore D, followed by the B0W25 and B12.5W12.5 samples, which recorded hardness values of 59.00 ± 0.41 and 52.50 ±0.82, respectively. This suggests that incorporating 25% bamboo particles into the composite enhances its hardness. The compatibility among eggshell particles, bamboo particles, and the matrix leads to a strong interfacial bond. Additionally, alkali treatment of bamboo particles significantly improves interfacial bonding between the matrix and particles, thereby increasing the composite's overall hardness.

The density of the composite directly influences its surface hardness; higher density results in greater surface hardness. The $CaCO_3$ composition in eggshell particles also enhances the epoxy matrix's resistance to external loads, thereby increasing hardness [29]. In comparison, the hardness of neat epoxy resin is recorded at 50 Shore D. When 2% Polyvinyl Acetate (PVAc) is added, the hardness rises to 60 Shore D [44]. The results of this study support those found by Tahir et al. [45], indicating that composite hardness increases with higher bamboo fiber content.

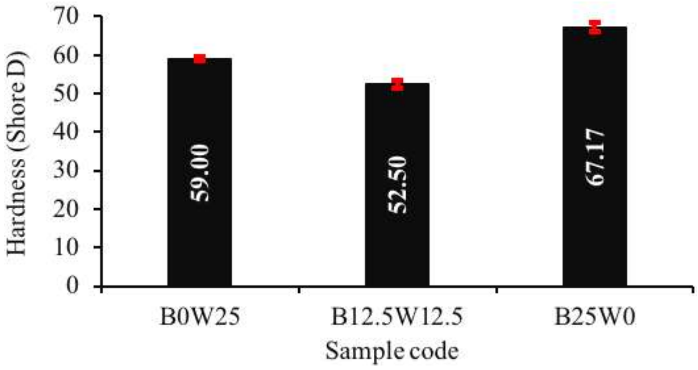

Fig. 9. The hardness of particleboard.

Moreover, the size and quantity of fillers can influence the composite's chemical and physical properties, such as reducing polymerization shrinkage and enhancing hardness. The impact of filler content on hardness depends on the amount and type of filler [46].

3.2.2 Flexural strength

The B25W0 composite, made with 25% bamboo filler and 40% eggshell particles, had the highest flexural strength of 12.90 ± 0.29 MPa. The B0W25 composite was made with 100% sengon wood filler, and the B12.5W12.5 composite with hybrid filler, with flexural strengths of 9.61 ± 1.48 and 6.59 ± 0.43 MPa, respectively, as shown in Fig. 10. The high flexural strength of the B25W0 sample can be attributed to the pretreatment of the bamboo particles with a 5% NaOH solution. Additionally, the distribution of eggshell particles within the composite also enhances the bond between the matrix and the bamboo particles.

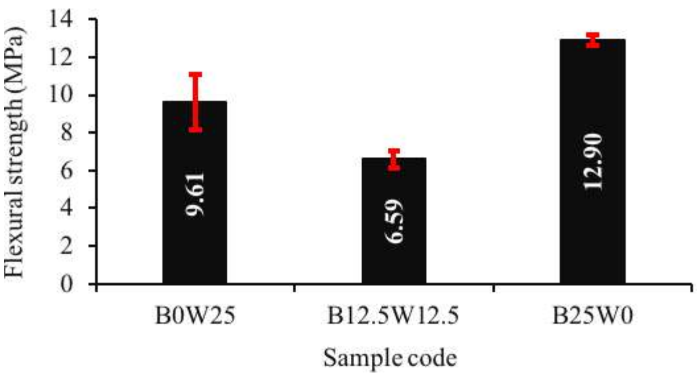

Fig. 10. The relationship between bamboo particle content and flexural strength.

According to the particle board standard SNI 03-2105-2006, the minimum flexural strength for ordinary and decorative particle board is 8.04 MPa. Only samples B0W25 and B25W0 meet the particleboard standards, while sample B12.5W12.5 does not, as its flexural strength is below 8.04 MPa. This condition can be suspected based on the high particle content in the eggshell, which reduces flexural strength due to the particles' brittleness. Further investigation is needed to understand the effects of eggshell particles, particularly on the composite's compressive strength.

The composite's flexural strength and modulus reached their highest values at a composition of 13 wt% bamboo particles with a particle size of 1.5 microns. As the size of the bamboo particles decreases, the flexural strength tends to decrease as well, especially as the proportion of bamboo particles increases [47].

The surface modification of bamboo filler through alkali treatment enhances the flexural strength of particleboard by improving the adhesive bond between the matrix and the filler. Alkali treatment of organic materials has been shown to increase both tensile and flexural strength in composites [37]. This effect is confirmed in Fig. 10. However, the combination of hybrid particles made from bamboo and sengon wood actually reduces the composite's flexural strength. This condition is believed to arise from weak interfacial bonds between bamboo and sengon wood particles and the matrix, which limit load transfer while allowingigh flexibility [48]. These findings differ from those of Gurmu et al. [31], who reported that using sisal and bamboo fibers at the same weight fraction resulted in the highest flexural strength.

3.2.3 Flexural modulus

The flexural modulus of the composite, similar to its flexural strength, reached a maximum of 1.24 ± 0.03 GPa in the B25W0 sample, which contains 25% bamboo. This was followed by the B0W25 and B12.5W12.5 samples, with flexural modulus values of 0.70 ± 0.08 GPa and 0.41 ± 0.04 GPa, respectively, as illustrated in Fig. 11. This indicates that alkali treatment of bamboo particles significantly affects their flexural modulus. Meanwhile, composites containing sengon wood have lower flexural moduli. This condition is thought to be due to the sengon wood particles not being subjected to alkali treatment, resulting in the interfacial bond between the sengon wood particles and the matrix (bamboo particles) not achieving optimal performance. Overall, this study demonstrates that the flexural modulus increases with increasing composite density.

Fang et al. [2] demonstrated that a 5 wt% alkali treatment for 30 minutes at 25°C yields optimal composite performance. The compatibility between epoxy resin and bamboo particles enhances interfacial bonding, which results in increased strength and flexural modulus compared to other samples. Khan et al. [49] found that using bamboo fiber in conjunction with an epoxy matrix produced higher tensile and flexural strengths than combinations involving epoxy with banana fiber or coir fiber.

The phenomena of hardness, flexural strength, and flexural modulus are interconnected. Fig. 11 demonstrates that a particleboard composition made entirely of bamboo particles achieves the highest flexural modulus, followed by those containing sengon wood filler and hybrid filler. Notably, the hybrid filler exhibits the lowest flexural modulus. This observation may be attributed to the bonding quality between bamboo particles and sengon wood particles. A study by de Melo et al. [50] indicates that a hybrid of bamboo and wood has a lower flexural modulus than pure wood.

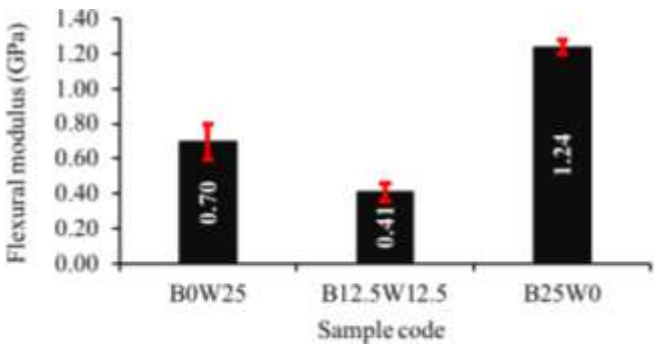

Fig. 11. The flexural modulus of particleboard.

3.2.4 Flexural strain

The composite B12.5W12.5, which contains 12.5 vol% bamboo particles and 12.5 vol% wood particles, exhibited the highest flexural strain of 4.33 ± 0.21%. This was followed by B0W25 and B25W0, which showed flexural strains of 3.40 ± 0.24% and 2.23 ± 0.17%, respectively, as illustrated in Fig. 12. The findings indicate that the B12.5W12.5 composite with hybrid fillers exhibits considerable strain, despite having lower flexural strength and modulus compared to the other samples.

The use of bamboo filler in particleboard resulted in higher MOR and MOE compared to those made with hybrid or sengon wood fillers. It is important to note that flexural strain is inversely related to MOR and MOE values. This significant flexural strain reflects the composite's considerable flexibility. Sample B25W0 exhibits excellent flexural strength and modulus. This is further supported by its low water absorption and thickness swelling, contributing to high dimensional stability. Mohammed et al. [47] found that a bamboo fiber content of 13 wt% produced the highest flexural strain when compared to contents of 9 wt% and 18 wt%.

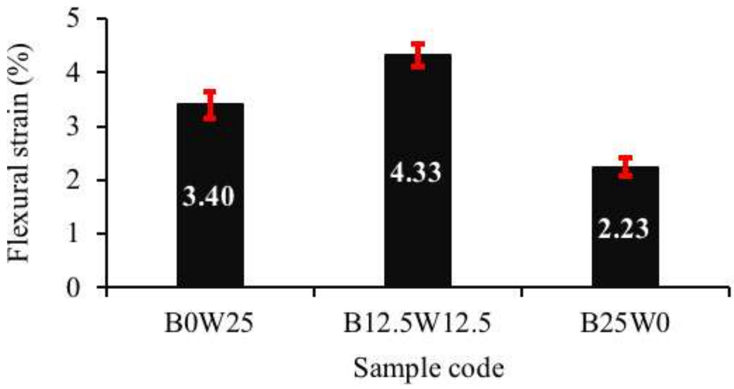

Fig. 12. The flexural strain of particleboard.

These findings contrast with a study by Almeida et al. [10], which found that a bamboo-wood composite had superior MOR and MOE than a 100% wood composite. This finding also contrasts with the study by Abdullah et al. [48], which reported that a hybrid combination of bamboo and banana fibers resulted in the highest flexural strength and the lowest strain.

3.3 Statistical analysis

Table 2 presents the average physical and mechanical performance data for the resulting composites. The samples in Runs 1, 2, and 3 correspond to B0W25, B12.5W12.5, and B25W0, respectively. Table 3 displays the weight of each response based on quality characteristics. In Table 4, the response weights are multiplied by the corresponding test results to calculate the MRPI. According to Table 4, the highest MRPI is for sample B25W0, with a value of 11.137. This MRPI indicates that sample B25W0 performs best among the other samples.

The difference in MRPI between the bamboo particle composite (B25W0) and the hybrid particle composite (B12.5W12.5) was 5.153, while the difference between the sengon wood composite (B0W25) and the hybrid composite (B12.5W12.5) was only 2.069. This MRPI indicates that bamboo, in both fiber and particle forms, holds great potential for the development of bamboo-based particle composite boards.

Table 2. The responses of physical and mechanical properties

Run	Density (D), g/cm^3	1/D	Thickness swelling (TS), %	1/TS	Hardness (H), Shore D	Flexural strength (FS), MPa	Flexural modulus (FM), GPa
1	1.39	0.72	7.25	0.14	59.00	9.61	0.70
2	1.36	0.74	8.37	0.12	52.50	6.59	0.41
3	1.53	0.66	6.05	0.17	67.17	12.90	1.24

Table 3. The responses weights

Run	Density (W_D)	Thickness swelling (W_{TS})	Hardness (W_H)	Flexural strength (W_{FS})	Flexural modulus (W_{FM})
1	0.340	0.326	0.330	0.330	0.297
2	0.349	0.283	0.294	0.226	0.175
3	0.310	0.391	0.376	0.443	0.528

Table 4. The weighted responses and MRPI

Run	D^*W_D	TS^*W_{TS}	H^*W_H	FS^*W_{FS}	FM^*W_{FM}	MRPI
1	0.474	2.366	19.483	3.174	0.207	8.052
2	0.474	2.366	15.427	1.491	0.072	5.983
3	0.474	2.366	25.250	5.719	0.653	11.137

4 Conclusions

This study demonstrates that the incorporation of hybrid organic fillers significantly influences the physical and mechanical performance of particleboard composites. The key conclusions from this study are: (1) Based on the DEAR method, the B25W0 sample exhibited the most optimal overall performance, with a density of 1.53 ± 0.01 g/cm³, thickness swelling of 6.05 ± 0.89%, hardness of 67.17 ± 0.94 Shore D, flexural strength of 12.90 ± 0.29 MPa, flexural modulus of 1.24 ± 0.03 GPa, and flexural strain of 2.23 ± 0.17%. These results highlight the strong potential of bamboo as a particleboard reinforcement material; (2) The hybrid filler composed of bamboo and eggshell particles, exhibited excellent interfacial compatibility and adhesion with between the matrix and the filler surface. Alkali treatment of sengon wood particles is essential to assess their compatibility as a filler and their influence on composite performance; (3) The densities of all composite samples did not meet the SNI 03-2105-2006 standards, ranging between 1.36 ± 0.02 and 1.53 ± 0.01 g/cm³. This elevated density is attributed to the high proportion of eggshell particles, which constitute 40 vol%; (4) The future research is necessary to address some weakness of bamboo particle and to conduct compressive strength testing to evaluate the potential of this composite as a structural material

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