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Full Length Research Article

Physical and Mechanical Properties of Oriented Flattened Bamboo Boards from Ater (*Gigantochloa atter*) and Betung (*Dendrocalamus asper*) Bamboos

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ABSTRACT

Bamboo-based composite has been used widely for building components and furniture. Oriented flattened bamboo board (OFBB) is a composite board consisting of oriented structure sheets of flattening bamboo. This study aimed to analyze the physical and mechanical properties of the OFBB from ater (*Gigantochloa atter*) and betung (*Dendrocalamus asper*) bamboo. A three-layer flattened bamboo board using the isocyanate resin with a density target of 0.6 g/cm^3 was applied. The characteristics of raw bamboo, the contact angle of OFBB, and board properties of density, moisture content, thickness swelling, and water absorption, as well as bending, internal bonding (IB), and compressive strength properties were determined to evaluate the quality of the OFBB. Based on the findings, the thin wall thickness of ater bamboo enhanced the physical and mechanical properties of the OFBB compared to the higher wall thickness of betung bamboo. Therefore, further development in bamboo composite products with those anatomical properties seems promising. The dimensional stability and bending properties of OFBB from ater bamboo met the quality of first grade of the Canadian Standard for OSB and waferboard, except for the IB strength.

1. Introduction

The demand for wood as raw materials for furniture and construction in Indonesia continues to increase along with the population growth rate. However, the wood supply has dwindled globally; ergo, it can not meet the need for raw materials (Yuan et al. 2021a). One of the materials that can be used as an ideal substitute for wood is bamboo (Ju et al. 2020) because of its high diversity of available species. There are about 31.5 million ha of bamboo forests globally, mainly across the tropics and sub-tropics (Yuan et al. 2021b). Priyanto and Abdullah (2014) reported that Indonesia has 0.72 million ha of natural bamboo forest and 1.40 million ha of plantation forest, with a total area covering around 2 million ha of bamboo forest. In Indonesia, there are also approximately 160 species of bamboo, with 38 species being induction species and 120 species being native to Indonesia (Widjaja 2012).

Bamboo is a plant that Indonesians widely used to produce various products because every part of it is useful. For example, bamboo culm can be used for building materials (He et al. 2019), bridges, engineering (Chen et al. 2020), furniture (Guan et al. 2020), and handicrafts (Chaowana 2013). The high public interest in using bamboo is due to several advantages, such as its fast growth, strong regeneration, high strength, and usefulness for protecting the environment from erosion, as well as having sociocultural and economic or livelihood aspects (Ekawati et al. 2022). In addition, bamboo has good sound-absorbing abilities and can reduce environmental pollution since it can absorb high amounts of nitrogen and carbon dioxide (CO_2) (Mutia et al. 2014). There are several types of bamboo often used in Indonesia, such as tali or apus (*Gigantochloa apus*), hitam (*G. atrovioalaceae*), andong (*G. pseudoarundinaceae*), betung (*Dendrocalamus asper*), and ater (*G. atter*) (Ohrnberger 1999; Paembonan et al. 2019; Widjaja 2006).

Ater bamboo (*Gigantochloa atter*) has green stems with white circular lines, 5–10 cm in diameter and 8 mm in wall thickness, internodes between 40–50 cm long, and high reaching up to 22 m (Eskak 2016). Ater bamboo is used as raw material for musical instruments, house walls, fences, household utensils, and handicrafts (Barly et al. 2012). In addition, the density of ater bamboo in the cross-sectional direction on the outer section is higher on the outside than the middle or inside (Barly et al. 2012). Based on these properties, ater bamboo has the potential as raw material for laminated bamboo.

Betung bamboo (*Dendrocalamus asper*) is originated from Bangladesh, India, Laos, Myanmar, Nepal, Thailand, and Vietnam. However, this bamboo has also been grown in China, Philippines, Malaysia, and Indonesia (Akinlabi 2017). Betung bamboo can reach as high as 20–30 m with an internode length of about 20–45 cm and a diameter of 8–20 cm. The wall thickness of the culm is around 6–22 mm (Javadian et al. 2019; Liese 2015). Dransfield and Widjaja (1995) stated that betung bamboo is widely used for building materials or building houses and bridges. Construction materials from betung bamboo can be in the form of whole reeds or laminated (Setyo et al. 2014).

Laminated bamboo is made from several bamboo strips (*pelupuh*), which are glued parallel to the fiber direction (Qisheng et al. 2002). *Pelupuh* boards are another term for laminated bamboo composite products made with raw materials that are peeled and combined using adhesives. Gluing the boards depends on the thickness, width, and interaction between the adhesive and the bamboo. Oriented flattened bamboo board (OFBB) can be developed by a simple method through labor-intensive manufacturing with minimal capital investment in the local community (Yuan et al. 2021a). Furthermore, manufacturing flattened boards can increase the strength of bamboo (Liliefna et al. 2020). Therefore, this research aimed to analyze the physical and mechanical properties of the OFBB from ater and betung bamboos.

2. Materials and Methods

2.1. Materials

Three years old of ater and betung bamboo culms were collected from Rumpin, Bogor, West Java, Indonesia. Bamboo length as raw materials was about 800 cm; which lower end was taken from bamboo clumps as high as about 100 cm from the ground. The adhesive used was water-based polymer isocyanate of polymeric diphenyl-methane diisocyanate (pMDI) adhesive type PI-127T with a solid content of 70.11% and hardener polyvinyl urethane type H3M obtained from PT. Polychemie Asia Pacific Permai, Cibinong, West Java, Indonesia. The ratio of the adhesive used in the form of water-based and hardener is 85:15. Isocyanate adhesive was reported suitable for manufacturing laminated boards (Darwis et al. 2014). Ater and bamboo were chosen since there were differences in their wall thicknesses. Generally, the wall thickness of ater bamboo is thinner than betung bamboo.

2.2. Manufacture of Oriented Flattened Bamboo Board (OFBB)

The green bamboo culms were cut into 200 cm long and then separated into lower and upper parts (**Fig. 1a**). The bamboo culms were then split into two sections and cleaned manually without skinning out bamboo skin (**Fig. 1b** and **Fig. 1c**) before being flattened using a bamboo crusher (**Fig. 1d**). Flattened bamboos were then cut using a table saw and arranged into flattened bamboo sheets with a length of 35 cm and were dried using an oven at 60°C for 72 h to reach a moisture content of < 10%. The density of bamboo samples as raw material was determined using a bamboo strip, which was not flattened, with 10 replications from random samples.

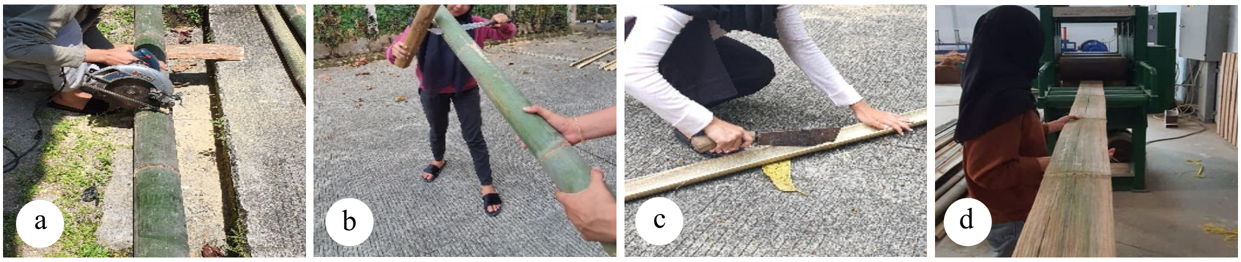

Fig. 1. (a) cutting bamboo culms to 200 cm, (b) splitting bamboo culms into two sections, (c) cleaning the bamboo node, (d) flattening bamboo with a bamboo crusher.

A flattened bamboo board with 35 cm × 35 cm × 2 cm dimension (**Fig. 2**) was arranged following the arrangement oriented to grain with three layers of flattened bamboo each board (Subyakto et al. 2016).

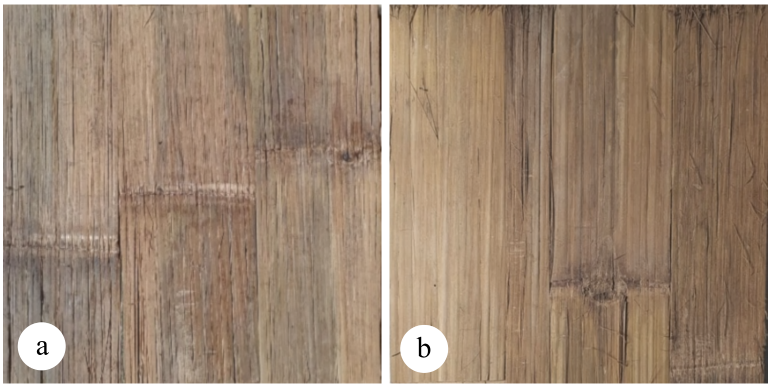

Fig. 2. Oriented flattened bamboo board: (a) ater bamboo (b) betung bamboo.

The outer surface of the skin bamboo was placed on both composite board outer layers. Each layer of the flattened board was given water-based polymer isocyanate (WBPI) of polymeric diphenyl-methane diisocyanate (pMDI) adhesive with a glue spread rate of 280 g/m^2, which was applied using a foam brush with the double spread technique. It was then hot-pressed at 180°C with a pressure of 5 MPa for 20 ± 2 minutes and a target density of 0.6 g/cm^3. Considering the chosen type of adhesive, glue spread rate, and pressed type applied followed the previous studies (Febrianto et al. 2010; Herawati et al. 2010; Liliefna et al. 2020), who conducted research on laminated and oriented strand board from wood and bamboo. After the hot-pressing process, the boards were conditioned at room temperature for two weeks to remove residual stresses caused by the compression process and even out the moisture content in the boards (Malau et al. 2003). Five samples of replicate boards were prepared for each bamboo species.

2.3. Evaluation of Physical and Mechanical Properties

Physical properties were evaluated according to Japanese Industrial Standard JIS A 5908-2003, including moisture content (MC), density, thickness swelling (TS), and water absorption (WA) after 2 h and 24 h of immersion in water (Nugroho and Ando 2000). The mechanical properties evaluated included modulus of elasticity (MOE), modulus of rupture (MOR), internal bond, and compressive strength. One-point loading static bending test for modulus of elasticity (MOE) and modulus of rupture (MOR) was carried out based on American Standard ASTM 5456-99, internal bonding (IB) strength evaluation was based on EN 300-1997, and compressive strength evaluation was based on ASTM D 1037-1999. The sample was then compared with the minimum requirements based on JIS A 5809-2003 and CSA O437.0-1993 standards, as displayed in **Table 1**.

Table 1. Minimum requirements based on international standards

Physical and Mechanical Properties	Unit	Standard requirements	
		CSA O437.0	JIS A 5908
Moisture content	%	< 15	5 - 13
Density	g/m^3	-	0.4 – 0.9
Thickness swelling (24 h)	%	< 15	< 12
MOE	MPa	4416	4000
MOR	MPa	22.96	24.00
IB strength	MPa	0.34	0.30

Notes: CSA O437.0 = standard for OSB and waferboard; JIS A 5908 = standard for particleboards.

2.3.1. Density

The samples of (5 × 5 × 2) cm^3 were measured based on the air-dried state to obtain its volume (*Va*). The samples were then weighed to obtain air-dried weight (*Wa*). The density (*D*) value of the samples was calculated by Equation 1.

$$D\ (g/cm^3) = \frac{Wa}{Va} \quad (1)$$

2.3.2. Moisture content

The samples of (5 × 5 × 2) cm^3 were measured based on weight before oven-drying (*Wa*) and after the oven-drying (*Wd*) at 103 ± 2°C for 24 h. The moisture content (*MC*) value was calculated by Equation 2.

$$MC\ (\%) = \frac{Wa - Wd}{Wd} \times 100\% \quad (2)$$

2.3.3. Thickness swelling

The samples of (5 × 5 × 2) cm^3 were measured based on thickness before (*T1*) and after being immersed for 2 h and 24 h. After immersing, samples were drained, and the thickness was measured again (*T2*). The thickness swelling (*TS*) value was calculated by Equation 3.

$$TS\ (\%) = \frac{T2 - T1}{T1} \times 100\% \quad (3)$$

2.3.4. Water absorption

The samples of (5 × 5 × 2) cm^3 were weighed (*W1*) and immersed for 2 h and 24 h. After immersing, the samples were drained and weighed again (*W2*). The water absorption (*WA*) value was calculated by Equation 4.

$$WA\ (\%) = \frac{W2 - W1}{W1} \times 100\% \quad (4)$$

2.3.5. Modulus of elasticity

The samples of (32 × 5 × 2) cm^3 were tested using Universal Testing Machine (UTM, Instron) with a load speed of 9 mm/min and a span length of 15 times the thickness, but not less than 15 cm with one-point loading. The MOE was calculated by Equation 5.

$$MOE\ (MPa) = \frac{\Delta PL^3}{4\Delta Ybh^3} \quad (5)$$

where ΔP is the load under proportion limit (N), L is span length (mm), Δy is deflection (mm), b is sample width (mm), and h is sample thickness (mm).

2.3.6. Modulus of rupture

The samples of (32 × 5 × 2) cm^3 were evaluated together with the MOE testing. The loading was continued until the sample reached the maximum load (P). The MOR value was then calculated by Equation 6.

$$MOR\ (MPa) = \frac{3PL}{2bh^2} \quad (6)$$

2.3.7. Internal bonding (IB) strength

The samples of (5 × 5 × 2) cm^3 were glued to two wooden blocks with epoxy adhesive and allowed to dry for 24 h. The two blocks were then pulled perpendicular to the surface of the sample at a load speed of 2 mm/min until maximum load. The IB strength was calculated by Equation 7.

$$IB\ (MPa) = \frac{P}{2bl} \quad (7)$$

where l is the sample length (mm).

2.3.8. Compressive strength

The samples of (8 × 2.5 × 2) cm^3 were measured in parallel to grain directions by placing the samples vertically. The samples were tested with a cross-head speed of 1 mm/min until maximum load. The compressive strength values were calculated by Equation 8.

$$Compressive\ strength\ (MPa) = \frac{Pmax}{bl} \quad (8)$$

2.3.9. Contact angle measurement

The contact angle measurement was carried out to quantify adhesive wettability on the surface material. The test was conducted to indicate compatibility between the filler and matrix in the composite, which is related to physical interaction. Kaymakci and Ayrimilis (2014) mentioned that there were two kinds of interaction between filler and matrix in the composite, i.e., physical interaction (mechanical interlocking) and chemical-bonding interaction. Water is used considering the similarity of liquid polar characteristics between water and the adhesive. The contact angle of distilled water drop test on the surface of OFBB ater and betung bamboo was measured by a video measuring system with a high-resolution Charge Coupled Device (CCD) camera. The test was conducted by placing the OFBB specimen on the top of a table in front of the CCD camera. Furthermore, the distilled water was dropped by a syringe with a screwing method to obtain the same droplet volume of 0.05 ml. Video images of the drop shape on the OFBB surface were captured by the CCD camera and saved for 180 s. The captured video images were cut into individual images at intervals of 10 s. In addition, the contact angle of the individual drop images was measured by the Image-J 1.46 software with the DropSnake plugin method.

2.4. Data Analysis

The mean values of the physical-mechanical properties of the samples were compared with the minimum values required by standard norms, as set out in **Table 1**. Data analysis was assessed through analysis of variance (ANOVA) with a further comparison of means by Student's t-test ($p < 0.05$). All data analyses were performed using SPSS 26.0 statistical software.

3. Results and Discussion

3.1. Bamboo Materials Characteristics

The three-year-old of ater bamboo had culms with a length of the internodes between 53–65.50 cm and a wall thickness between 5–9 mm. Meanwhile, the betung bamboo had a length of internodes between 31.50–56 cm and a wall thickness between 7–15 mm (**Table 2**). Eskak (2016) stated that the length of the internode of ater bamboo ranged from 40–50 cm with a wall thickness of 6–10 mm. The study by Marsoem et al. (2015) reported that the length of the internodes at the bottom ranged from 26.5–30.0 cm for 40 months and the longest internode ranging from 57.0–59.7 cm, with the wall thickness ranging from 12.8–17.1 mm. The wall thickness of betung bamboo (5 years old) at the top, middle, and bottom was 11.2 mm, 21.1 mm, and 27.4 mm, respectively (Maulana et al. 2022). Meanwhile, Widjaja et al. (2020) reported that the internode length of betung bamboo ranged from 40–50 cm with a wall thickness of up to 15 mm. Rifqi et al. (2020) found a similar length of internode, which showed a length variation between of 30–50 cm. Marsoem et al. (2015) also reported that the internodes in the bottom culms were always the shortest but had the thickest walls.

Table 2. General characteristics of bamboo culms of two bamboo species

Bamboo Species	Wall Thickness (mm)			Internode Length (cm)		
	Upper part	Lower part	Average	Upper part	Lower part	Average
Ater	5.00 ± 0.06	9.00 ± 0.07	7.00 ± 0.14	65.50 ± 1.92	53.00 ± 2.31	59.40 ± 3.16
Betung	7.00 ± 0.09	15.00 ± 0.12	10.80 ± 0.21	56.00 ± 4.93	31.50 ± 2.68	42.30 ± 5.68

The geometric values of flattened bamboo species are presented in **Table 3.** The thickness of flattened ater and betung bamboo varies between 0.51–1.11 cm and 0.51–0.99 cm, and the width between 6.15–18.60 cm and 5.50–22.10 cm, respectively. The length of 35 cm was the same for the strip flattened materials. The density of un-flattened bamboo as raw materials is 0.79 g/cm^3 for ater bamboo and 0.70 g/cm^3 for betung bamboo. Generally, the average geometric values of flattened bamboo and strip density of ater and betung bamboo are higher than that of betung bamboo. The higher density value of ater bamboo is presumably related to the anatomical structure of bamboo. Bamboo culms anatomically consist of the vascular bundle and parenchymal, which affect bamboo characteristics (Liese 1998). A study by Maulana et al. (2022) reported that the vascular bundle type of betung bamboo exhibited a type IV vascular bundle. Meanwhile, ater bamboo was dominated by type III (Sutardi et al. 2015). The vascular bundle type III had the highest vascular bundle density than the vascular bundle type IV (Maulana et al. 2022). Smaller vascular bundles tend to be denser in distribution, and the density and mechanical strength are excellent. Therefore, the average geometric values of flattened bamboo and strip density of ater bamboo are higher than betung bamboo.

Table 3. The geometry of flattened bamboo

Bamboo Species	Thickness (cm)			Width (cm)			Length (cm)	Density (g/cm^3)†
	Min	Max	Average	Min	Max	Average		
Ater	0.51	1.11	0.78 ± 0.12	6.15	18.60	12.58 ± 3.25	35 ± 0.00	0.79 ± 0.13
Betung	0.51	0.99	0.74 ± 0.13	5.50	22.10	10.56 ± 5.41	35 ± 0.00	0.70 ± 0.08

Notes: Min = minimum value, Max = maximum value, †= un-flattened bamboo strips density.

3.2. Contact Angle

The contact angle (CA) of a surface can be used to analyze the wettability of OFBB to liquids. The wettability of a surface indicates the condition that determines the extent to which the fluid will be spread on the surface (Marra 1992). The average CA of distilled water droplets on the outer surface of OFBB shows that the contact angle on the OFBB of ater bamboo (36.55°) is lower than betung (43.45°) bamboo (**Fig. 3**).

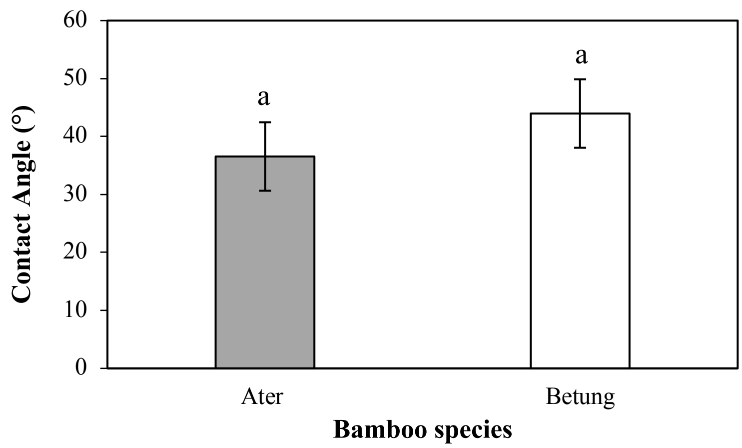

Fig. 3. Contact angle of OFBB with different bamboo species. (Note: values followed by the same letters are statistically not significantly different at $p < 0.05$).

This information means that the wettability OFBB of ater bamboo was better than betung bamboo. The example for measurement for the CA of the water droplet is illustrated in **Fig. 4**.

OFBB of betung bamboo possessed a contact angle of more than 90° at 0 s wetting process, while the OFBB of ater bamboo had CA of 63.98°–82.13° at 0 s. A plotting for showing the evolution of CA over time is expected in **Fig. 5**. A contact angle of more than 90° indicates the liquid does not wet the surface well (Yuan and Lee 2013).

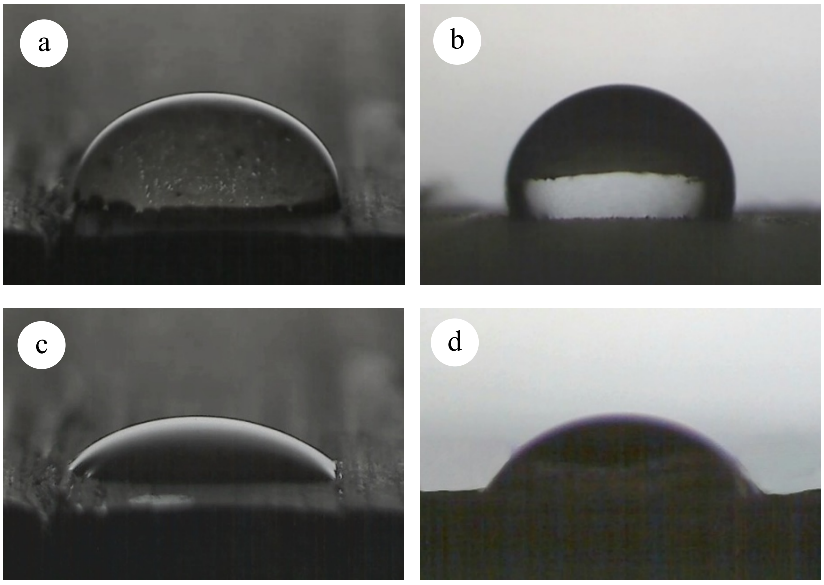

Fig. 4. Measurement of contact angle of a water droplet: (a) and (b) at the 0 s the first time water reaches the surface board for OFBB ater and betung, respectively; (c) and (d) at the 180 s as the water absorbed for OFBB ater and betung, respectively.

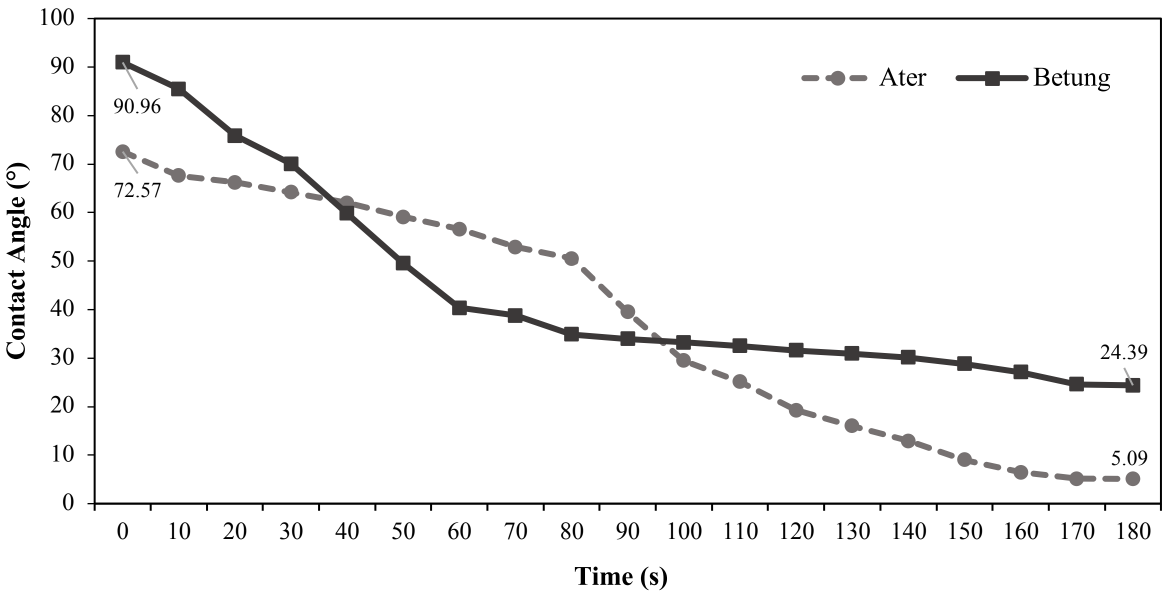

Fig. 5. Dynamic contact angle of OFBB from ater and betung bamboos.

In this study, the contact angle of OFBB betung was higher than OFBB ater which related to the lower IB strength of betung board than of ater OFBB. Some factors could affect the CA values in bamboo products, such as bamboo surface condition (inner or outer), bamboo skin, and the chemical compound bamboo. A study by Deng et al. (2015) reported contact angle of the outer surface of bamboo bundle sheets with the different removing extent of bamboo green varied from 46.50°–87.28°. Another study by Du et al. (2013) showed that the contact angle of the bamboo strip of *Phyllostachys pubescens* ranged from 49°–52° at 2 s. Anwar et al. (2009) studied on ply-bamboo and revealed that a higher contact angle could lead to partially cured adhesive remaining on the sheet surface while filling voids and parenchyma cells. The contact angle of more than 90° in bamboo makes excessive adhesive penetration, which then causes a higher tendency for a starved joint. Meanwhile, in our study, the glue spreading on the inner and outer surfaces (double spread) presumably could affect the wettability of OFBB. The adhesive on both sides has resulted in excess adhesive filling the gap exceeding the optimal limit for penetrating adhesives. The lower CA indicated perfect wetting, which means better hydrophilicity (Karlinasari et al. 2021). In OFBB, ater bamboo board had a lower CA value, indicating that it has better hydrophilicity than betung bamboo. In addition, the isocyanate is a polar adhesive, as is water, so the CA value can be referenced as the ability of the liquid to penetrate the material. Meanwhile, the CA value of liquids is dependent on viscosity. Isocyanate has a high viscosity than other liquids (Ruhendi et al. 2007). Gavrilovic et al. (2012) stated that the CA increase as fluid viscosity increase.

A comparison of contact angle was also made between parts and surface in the culm (Chaowana et al. 2015), the outer surface (bamboo skin) and inside surface (bamboo pith) (Li et al. 2015), height levels and surface (Marasigan et al. 2020). Those studies reported that the CA of the inner surface was lower than that of the outer surface, the CA of the bottom culm lower than the top culm, and the CA of nodes less than the internodes. Ying (1996) mentioned that the outer bamboo had compacted vascular bundles and the amount was greater than the inner bamboo, which made the contact angle of the outer bamboo greater than the inner bamboo (pith). This could lead the value of the internal bond of ater and betung bamboo to be lower than the standard. According to Faizal et al. (2015), high silica content also contributes to the increase in the contact angle. Fatriasari and Hermiati (2006) reported that the silica content of betung bamboo reached 3.51% more than the other five bamboo species, namely tali, hitam, kuning, andong, and ampel bamboo. According to Kamthai (2007), the ash content of bamboo can also be referred to as silica content. Other studies by Subekti et al. (2015) reported that the ash content of betung bamboo and ater bamboo were 3.55% and 1.47%, respectively. However, the statistical test results in this study showed that the bamboo species of OFBB did not have a significant difference in the contact angle.

3.3. Physical Properties

3.3.1. Density

Density is the ratio between the mass and volume of the composite board. **Fig. 6** displays that the OFBB density of ater bamboo is higher at 0.70 g/cm^3 than betung bamboo at 0.62 g/cm^3. Statistical analysis found that bamboo species had a significant effect (α = 5%) on board density. The JIS A 5908 standard requires a board density of 0.4–0.9 g/cm^3. The board density followed the targeted standard of 0.6 g/cm^3. Iswanto et al. (2019) found similar densities for other OSB products, showing board densities between 0.61–0.69 g/cm^3. Another previous study by Cahyadi et al. (2012) showed that the density of laminated zephyr bamboo varied from 0.6–0.7 g/cm^3. The density of the raw material is one factor that affects the board's density and overall properties. The density of ater and betung bamboo raw materials used in this study were 0.79 g/cm^3 and 0.70 g/cm^3, respectively (**Table 3**). The board density value is highly dependent on the density of the raw material used, in addition to the amount of compression applied during sheet production, which also affects the properties of the board (Bowyer et al. 2003).

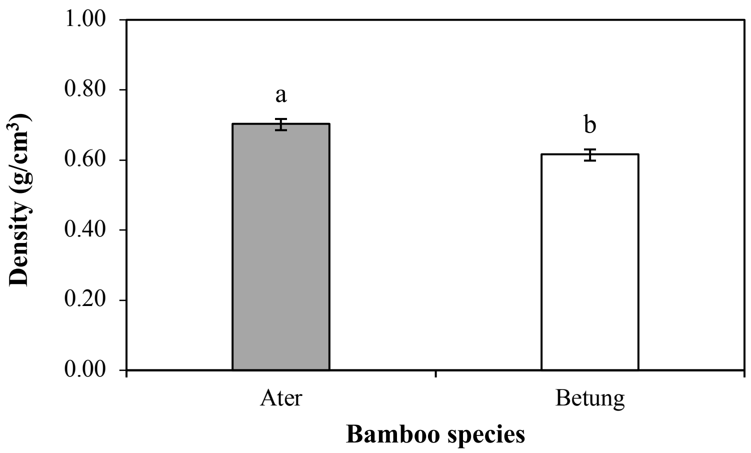

Fig. 6. The density value of OFBB with two bamboo species (Note: values followed by different letters are statistically different at $p < 0.05$).

3.3.2. Moisture content

The MC value of the OFBB of ater and betung bamboo was 9.84% and 8.94%, respectively (**Fig. 7**). Generally, the higher moisture content will reduce the strength of the materials (Tsoumis 1991). Similar moisture content was found by Sulastiningsih et al. (2019), which shows OSB made from *Gigantochloa pseudoarundinaca* with different strand lengths ranging from 9–9.7%. Another study by Sumardi et al. (2022) showed that the MC of LBL zephyr and ply-bamboo zephyr were 11.74% and 11.63%, respectively.

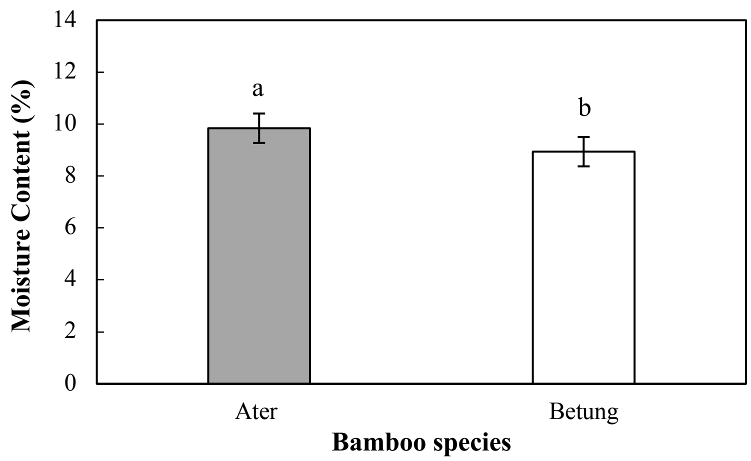

Fig. 7. Moisture content of OFBB with two bamboo species (Note: values followed by different letters are statistically different at $p < 0.05$).

The MC affected the mechanical properties of OFBB, while the physical properties influenced the dimensional stability of OFBB. The ANOVA results showed that the bamboo species significantly affected the MC value of OFBB. The MC of both species of OFBB in this research was in line with the JIS A 5908 and CSA O437.0 (**Table 1**).

3.3.3. Thickness swelling

Thickness swelling (TS) and water absorption (WA) are important parameters to evaluate the dimensional stability of composite panels. The result showed that OFBB from ater bamboo pointed out a lower value than betung bamboo, both after 2 h and 24 h of immersion (**Fig. 8**). The

ANOVA (α = 5%) from the comparison test showed that the OFBB from ater and betung bamboo was not significantly different for thickness swelling. The TS values were in line with the JIS A 5908 and CSA O437.0 for TS after water immersion, as shown in **Table 1**. The EN 300: 1997 for OSB/3 also mentioned that the TS after 24 h water immersion should be ≤ 15% (CEN 1997).

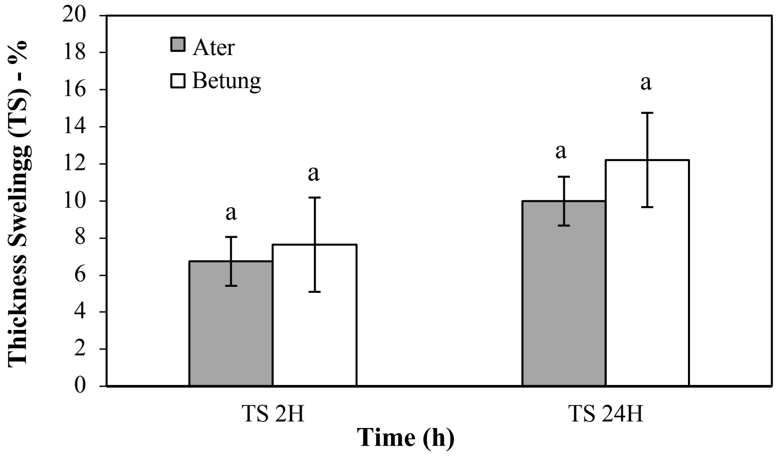

Fig. 8 The thickness swelling value of OFBB with different bamboo species (Note: values followed by different letters are statistically different at $p < 0.05$).

Febrianto et al. (2012) showed that the TS of OSB made from *Dendrocalamus asper* with different strand lengths after 2 h and 24 h of immersion ranged from 4.30–6.25% and 12.92–14.94%, respectively. Hariz et al. (2021) also showed that the 24 h TS of OSB from *Dendrocalamus asper* and *Bambusa vulgaris* with different resin content ranged from 8.22–13.47%. Another study by Chung and Wang (2018) also reported the 24 h TS of OSB from *Phyllostachys pubescens* with different densities ranging from 7.93–17.32%. Another study by Malanit et al. (2010) showed that the 24 h TS of oriented strand lumber (OSL) from *Dendrocalamus asper* and pMDI adhesive with different resin content ranged from 2.3–4.5%. The isocyanate adhesive used in this study was known to be water-resistant. However, since the long size of raw materials and the gaps between composing strips, it was possible that not all boards were covered by adhesive. Therefore, it can lead the water easily enter either through the pores or cell lumen of bamboo.

3.3.4. Water absorption

The water absorption test determines the use of laminated boards as exterior or interior materials (Wardani et al. 2013). Water absorption has a value that is linear to the thickness of swelling. The higher the thickness swelling value, the higher the water absorption value. The value of water absorption of OFBB made with ater and betung bamboo after 2 h immersion was 20.69% and 38.60%, and after 24 h immersion was 43.10% and 71.32%, respectively (**Fig. 9**). The ANOVA (α = 5%) showed that bamboo species not significantly different for water absorption value of OFBB. The isocyanate adhesive absorption is not optimal, causing more excellent water absorption into the strand or larger gaps between strands (Barbuta et al. 2011; Febrianto et al. 2015; Parubak 2009). Cahyadi et al. (2012) reported that isocyanate adhesive with the addition of melamine could decrease water absorption values which causes the isocyanate adhesive to be quite thick. In contrast, the thinner adhesive can penetrate more easily into bamboo.

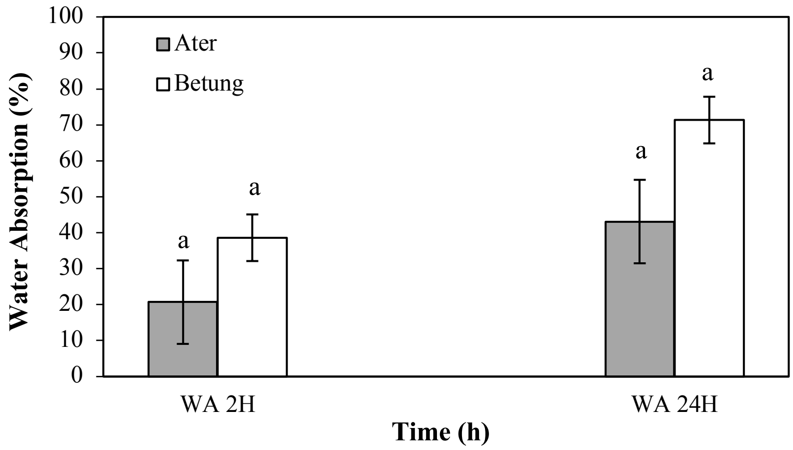

Fig. 9. The water absorption value of OFBB with different bamboo species (Note: values followed by different letters are statistically different at $p < 0.05$).

3.4. Mechanical Properties

3.4.1. Bending strength

The bending properties of MOE and MOR values of OFBB are illustrated in **Fig. 10** and **Fig. 11**. The highest mechanical bending properties values are found in OFBB from ater bamboo. OFBB ater and betung bamboo MOE were 4722.82 MPa and 3267.70 MPa, respectively. Meanwhile, the MOR value was 29.31 MPa for ater bamboo and 22.76 MPa for betung bamboo. Based on **Table 1**, OFBB from bamboo ater met the standards of CSA O437.0 (Grade O-1) and JIS A 5908. The ANOVA (α = 5%) from the comparison test showed that the OFBB made with ater and betung bamboo in this study significantly affected the MOE and MOR values.

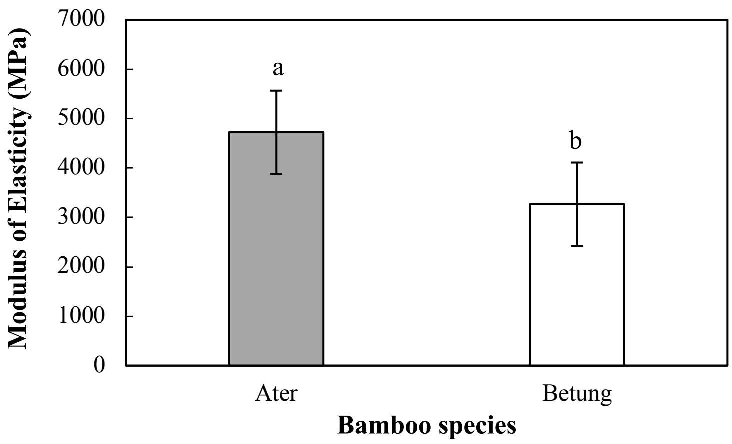

Fig. 10. Modulus of elasticity of OFBB with different bamboo species (Note: values followed by the same letters are statistically not significantly different at $p < 0.05$).

A study by Maulana (2020) reported that the MOE and MOR of bamboo OSB (BOSB) with isocyanate adhesive ranged from 4611–8101 MPa and 24–46 MPa, respectively. In comparison, other studies showed the MOE and MOR of plybamboo zephyr with core bamboo strip were 6665.66 MPa and 43.23 MPa (Sumardi 2020). Sumardi (2022) reported that the ply bamboo zephyr/flattened bamboo had 6967 MPa for MOE and 42.81 MPa for MOR were 6967 MPa and 42.81 MPa. The lower research result compared to previous studies of other bamboo strip products is presumably due to the differences between glue spread and processing methods. A study by

Baskara et al. (2022) reported that the higher resin content could increase the MOE value. Therefore, the adhesive penetrating flattened bamboo should have more glue spread than a board with bamboo strip and BOSB. Additionally, the spreading process with the double spread technique can cause two layers of flattened bamboo to dry out when they are glued. Any damage to the adhesive line could result in a non-optimal value in holding the maximum load (Sumawa et al. 2019).

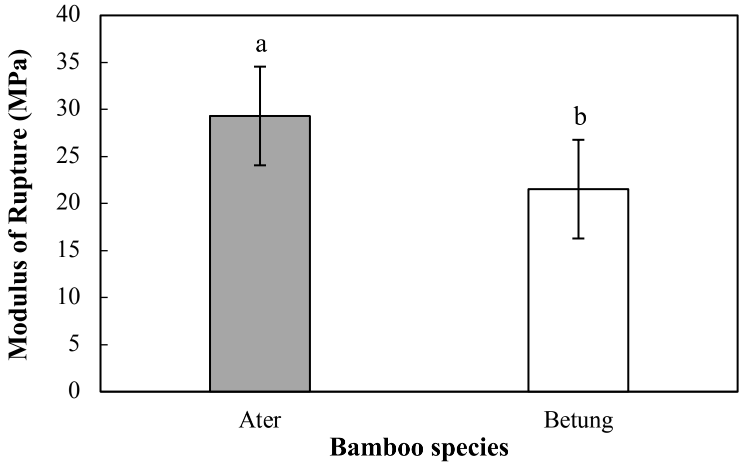

Fig. 11. Modulus of rupture of OFBB with different bamboo species (Note: values followed by the same letters are statistically not significantly different at $p < 0.05$).

3.4.2. Internal bonding strength

The result showed that the OFBB of ater bamboo had an internal bonding (IB) strength of 0.23 MPa, while the OFBB of betung bamboo was 0.22 MPa (**Fig. 12**). The IB strength test demonstrates the bonding strength of the mixing, shaping, and compression processes (Bowyer et al. 2003). The IB strength of both species of OFBB in this research could not reach the standards of CSA O437.0 (Grade O-1) and JIS A 5908. The ANOVA (α = 5%) of OFBB made from ater and betung bamboo in this study were not significantly different for IB strength value.

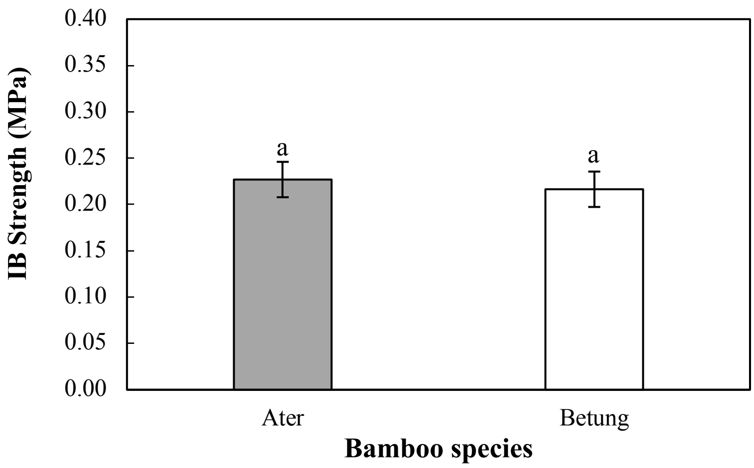

Fig. 12. Internal bonding (IB) strength of OFBB with different bamboo species (Note: values followed by the same letters are statistically not significantly different at $p < 0.05$).

Bowyer et al. (2003) stated that good layer forming and mixing would result in stronger IB strength between strands. In this study, the low value of an IB strength was thought to be related to the failure of the adhesive to penetrate the flattened bamboo. It can be caused by the isocyanate—which functions as an adhesive—that cannot penetrate the pores of the bamboo. Consequently, the part between the bamboo layer and the core becomes more easily detached due to the absence of a strong bonding. In addition, the fact that the outer surface of the bamboo skin contains silica while the inner surface contains wax can reduce the adhesive strength (Nugroho and Ando 2000). Aisyah et al. (2021) reported that the IB strength of OSB with isocyanate adhesive without steam treatment has lower than with steam treatment. Our study conducted that the manufacturer of flattened bamboo did not clean the outer and inner surfaces of the bamboo before it was made into boards. Likewise, Ruh and Ra (2009) also showed that the IB strength of veneer-bamboo zephyr of *Phyllostachys nigra* with phenol-formaldehyde adhesive with a density of 0.68 g/cm^3 and 0.72 g/cm^3 were 0.23 MPa and 0.28 MPa, respectively. Another study by Nugroho and Ando (2000) showed IB strength of bamboo zephyr board with a density of 0.6 g/cm^3 varies from 0.49–0.73 MPa. On the other hand, a study by Ramatia et al. (2020) reported that the IB strength of OSB made of *Dendrocalamus asper* with phenol formaldehyde with different adhesive levels varied from 0.21–0.86 MPa. Meanwhile, the IB strength of laminated bamboo lumber of *Dendrocalamus sericeus* with formation outer-outer layer were 0.29 MPa, and the outer-inner layer was 0.42 MPa (Chaowana et al. 2015). Pizzi (1983) explained that the adhesive system depends on polymerization and bonding between materials and adhesive.

3.4.3. Compressive strength

The compressive strength parallels t the grain to determine the optimum load that can be carried (Tsoumis 1991). The study found that the compressive strength of ater and betung bamboos were 22.03 MPa and 14.80 MPa, respectively (**Fig. 13**).

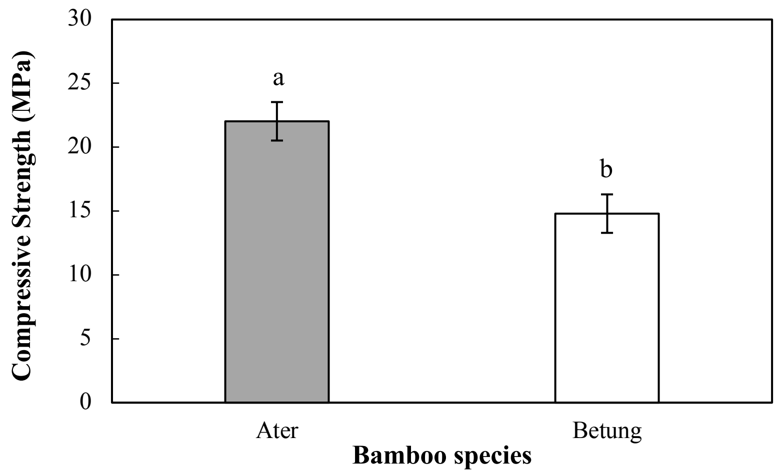

Fig. 13. Compressive strength of OFBB with different bamboo species (Note: values followed by the same letters are statistically not significantly different at $p < 0.05$).

The ANOVA revealed a significant difference between OFBB ater and OFBB betung for compressive strength. Sulastiningsih and Santoso (2012) mentioned that bamboo species and pre-treatment influence the compressive strength of bamboo boards. Our study pointed out lower compressive strength values than other bamboo strip products. Sulastiningsih et al. (2018) found that the compressive strength of a three-layers bamboo strip was 64.47 MPa, while the compressive strength of a laminated bamboo board made of *G. pseudoarundinacea* bamboo strips glued with urea formaldehyde had an average value of 56.2 MPa (Sulastiningsih and Santoso 2012). Meanwhile, Li et al. (2013) reported compressive strength of laminated board varied from 56.62–61.09 MPa.

4. Conclusions

Bamboo species in OFBB manufacture affected the value of the physical and mechanical properties of OFBB. Studies on two bamboo species with different wall thicknesses, which are made into the oriented flattened bamboo board (OFBB), showed that thin-walled ater bamboo has better board properties than thicker betung bamboo for both physical and mechanical properties in condition the un-cleaned bamboo skin. OFBB from thin-walled can reduce the TS and WA and increase the MOE, MOR, and compressive strength. Except for the IB strength values, all properties of ater-oriented flattened bamboo boards met the requirements listed in the first grade of the Canadian Standard (CSA 0437.0 (Grade O-1)) for OSB and waferboard, while the betung OFBB properties were below the standard. In further studies, removing and cleaning the bamboo skin and combining outer-inner surface bamboo with variation layer numbers and various types of bamboo can be done to improve the OFBB properties.

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