# The effect of heating temperature on the physical and mechanical characteristics of plybamboo prepared from betung bamboo (*Dendrocalamus asper*)

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**Abstract**. This research was conducted to evaluate the effect of heating temperature on the physical and mechanical characteristics of plybamboo boards as an effort to reduce the use of wood and develop composite products as a wood substitute material. The material used was betung bamboo (*Dendrocalamus asper*) processed using PVAc adhesive. Hygrothermal treatment was carried out at 150 °C, 160 °C, and 170 °C for one hour on bamboo strips. Subsequently, the bamboo strips were assembled into three layers perpendicular to the fibers, and adhesive was applied and compressed using cold pressing. The physical and mechanical properties of plybamboo boards were evaluated according to JAS 234: 2003 standards. The test results showed that hygrothermal treatment tended to affect the physical and mechanical properties of plybamboo boards. The hygrothermal treatment at 160 °C had the best impact, producing values closest to JAS: 234 standards, resulting in reduced moisture content, water absorption, thickness expansion, and delamination. Additionally, the heat treatment at 160 °C also provided the best improvement in density, MOR, and MOE of plybamboo boards. According to JAS:003 (2003) standards, the properties of plyboard did not yet meet the criteria as a wood substitute material.

## 1 Introduction

Bamboo is a lignocellulosic plant that can be utilized as a building material, serving as a substitute for wood. Bamboo shares many characteristics with wood [1]. It has a high abundance in Indonesia. In 2021, the total bamboo production reached 50,156,068.00 million culms, distributed across Java, Bali, and the Lesser Sunda Islands [2]. Bamboo has advantages such as rapid growth, strong structure, hardness, ease of splitting, lightweight, flexibility, and affordability [3–6]. However, bamboo has a small stem diameter, low splitting strength, and extractive substances, making it susceptible to termite attacks [7–9]. The small and hollow stem diameter makes bamboo difficult to process using conventional wood processing methods [10]. Therefore, converting bamboo into different forms is necessary to address its small diameter and enhance its utility.

Form conversion is an approach to utilizing bamboo to overcome its limitations in terms of small diameter. Lamination technology involves processing bamboo into laminated bamboo, which can transform bamboo into beams or boards [11]. Bamboo in the form of laminates is easily shaped, and its dimensions can be adjusted based on the bamboo type [6]. Previous research has successfully utilized bamboo laminates to create various products like Cross Laminated Bamboo (CLB), Laminated Bamboo Lumber (LBL), and bamboo scrimber [12–15]. Lamination technology improves bamboo's properties, making it suitable as a wood substitute equivalent to strong wood class I [11].

The properties of laminated panels, including bamboo laminated panels, are influenced by various factors. Factors affecting LBB properties include bamboo species, adhesive weight, structural composition, layer structure, pre-treatment, and extractive content [16–21]. Extractive substances in bamboo include sugars, starch, tannins, resins, pectin, wood colorants, acids, oils, and fats [22]. Extractive content in bamboo can reduce the fiber-to-fiber bonding strength, affecting its overall strength [23]. Sugars in bamboo's extractives can act as a food source for wood-destroying organisms like fungi, termites, and beetles, decreasing laminated bamboo quality [24]. Hence, a treatment is necessary to reduce the extractive content in bamboo to improve laminated bamboo quality.

Heat treatment is commonly used to enhance bamboo properties as a wood substitute. Research has reported that heat treatment using an oven at an optimal temperature of 120 °C for three hours improved the modulus of rupture (MOR) of moso bamboo laminas and strips [25]. Another study by Zhang et al. applied heat treatment to moso bamboo strips at optimal temperatures of 120 °C and 160 °C for one hour, resulting in increased modulus of elasticity (MOE) and MOR [26]. Another research

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demonstrated that heat treatment at 180 °C for one or two hours enhanced resistance to fungal attacks and compressive strength of bamboo culms [27]. Several studies have highlighted that temperature and time are crucial factors affecting bamboo's physical and mechanical properties. Therefore, heat treatment with appropriate time and temperature should be performed to enhance the dimensional stability and mechanical properties of plybamboo. This study aims to analyze the physical and mechanical properties of heat-treated plybamboo board prepared from betung bamboo (*Dendrocalamus asper*).

## 2 Materials and method

### 2.1 Materials

This research utilizes four-year-old betung bamboo *(D. asper*) obtained from Asem Kamal Hamlet, Sukadana Village, Sukadana Subdistrict, East Lampung Regency, and the adhesive used is of the Polyvinyl Acetate (PVAc) type, with the brand Crona version 234-SR. The PVAc (Crona 234) adhesive is specially formulated for finger jointing, laminating, and assembling. It is a water-based PVAc adhesive readily soluble in water (water base).

The equipment used in this research includes an oven as the heat treatment medium and a Universal Testing Machine (UTM) for testing mechanical properties such as MOE and MOR. Physical property testing involves using various tools, including a caliper for measuring length, a scale for measuring weight, a basin for immersing test specimens, and a desiccator for cooling down specimens after treatment. In addition to the main equipment, this study utilizes supporting tools such as a cold press, iron plates, aluminum foil, and a brush to assist in the laminating process. A saw is used as a cutting tool for bamboo, a tape measure is used as a length measurement tool, and a knife is used to clean bamboo strips from outer and inner skin layers.

### 2.2 Research phases

#### *2.2.1 Material preparation*

The main material, betung bamboo, was prepared and cut into bamboo slats without including the bamboo nodes, with dimensions of (30 x 2 x 0.5) $cm^3$. The bamboo slats were then cleaned from their outer and inner skin to facilitate the bonding process. Subsequently, the bamboo slats were dried under sunlight until they reached a moisture content of 16-18%

#### *2.2.2 Heat treatment on bamboo slats*

The prepared bamboo slats were weighed, and their dimensions were measured before placing them in an oven. This study used three different temperature levels: 150 °C, 160 °C, and 170 °C. The bamboo slats samples were placed in the oven at the specified temperature for one hour. The determination of the treatment temperature is based on Wang et al. [28] research, where the treatment of hemicellulose and lignin content in bamboo begins to be affected by heat at a temperature of 140 °C. Furthermore, it is suspected that heat treatment also reduces the level of extractive substances. The presence of extractive substances in composite products can have a detrimental effect. This statement is in line with Maulana et al. [24] research, where heat treatment at temperatures higher than a certain threshold can reduce the level of extractive substances, positively impacting adhesive penetration in composite products.

#### *2.2.3 Adhesive preparation*

In this study, the adhesive used was PVAc type adhesive with Crona brand 234-SR which was sprinkled on the surface of the bamboo layer with a pumpkin weight of 160 $g.m^{-2}$. Investment is done by means of a single spread or investment on one of the surfaces to be glued. The adhesive required for each sheet is determined based on the surface area of the coating and the weight of the adhesive flask using the equation (1).

$$Adesiv\ Needs = adhesive\ area \times painted\ weight \quad (1)$$

#### *2.2.4 Bamboo slats formation*

The heatley treated bamboo slats were arranged into a layered board with dimensions of (30 x 30 x 1.5) $cm^3$. The board consisted of 3 layers of bamboo arranged perpendicular to each other, with approximately 15 bamboo slats in each layer. The bamboo slats arrangement was bonded using Crona 234 adhesive and then compressed.

#### *2.2.5 Compression*

The bamboo strips, which have been arranged in such a way and coated with adhesive, are compressed with a pressure of 25 $kg/cm^2$ until the desired thickness is achieved for three hours.

#### *2.2.6 Conditioning*

The compressed bamboo slat layers were allowed to cool and form a layered board, which was conditioned in a closed room for 48 hours to relieve any residual stress from the compression process and adjust the local moisture content.

#### *2.2.7 Specimen preparation*

The plybamboo board was subjected to physical and mechanical tests after conditioning. The test specimens were prepared in accordance with the ASTM-D143 (2005) standard [30]. The specimen types and dimensions are shown in Fig. 1. The use of the ASTM-D143 standard is based on the dimensions of the plybamboo board produced, which are (30 x 30 x 1.5) $cm^3$.

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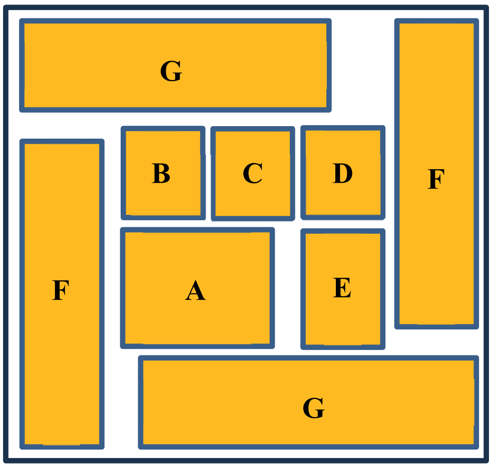


**Fig. 1.** Test sample creation scheme.

Explanation:

| | | |
|---|---|---|
| A | : | Specimen for moisture content and density (10 x 10 x 1.5) $cm^3$ |
| B | : | Specimen for thickness swelling (5 x 5 x 1.5) $cm^3$ |
| C | : | Specimen for dry shear strength (5 x 5 x 1.5) $cm^3$ |
| D | : | Specimen for wet shear strength (5 x 5 x 1.5) $cm^3$ |
| E | : | Backup test example (10 x 5 x 1.5) $cm^3$ |
| F | : | Specimen for parallel-to-grain MOE and MOR (20 x 5 x 1.5) $cm^3$ |
| G | : | Specimen for perpendicular-to-grain MOE and MOR (20 x 5 x 1.5) $cm^3$ |

### *2.3 Plybamboo board testing*

The research involved testing both the physical and mechanical properties of the plybamboo board. Physical properties tested included moisture content, density, and dimensional stability. Mechanical properties tested were MOE and MOR parallel (//) and perpendicular (⊥) to grain directions. The preparation of test specimens followed the American Standard Test Methods (ASTM D-143 2005) for Standard Methods of Testing Small Clear Specimens of Timber [29]. The physical and mechanical properties testing values followed JAS-003 for Glue Laminated Timber [30].

#### *2.3.1 Moisture content*

The dry weight of the test specimen (T1) was determined, and then the specimen was dried in an oven at (103 ±2) °C for 24 hours or until a constant weight was achieved (T2). The oven-dried specimen was cooled for about 15 minutes in a desiccator and then weighed again. Moisture content was calculated using the equation (2).

$$Moisture\ Content\ (\%) = \frac{(T1\text{-}T2)}{T2} \times 100 \quad (2)$$

#### *2.3.2 Density*

Density was calculated by dividing the oven-dry weight (ODW) by the oven-dry specimen volume (ODV) volume. The volume of the test specimen was measured by multiplying its length, width, and thickness, which were measured using a caliper. The weight was obtained using a digital scale. Density was calculated using the equation (3).

$$Density = \frac{ODW}{ODV} \quad (3)$$

#### *2.3.3 Dimensional stability*

Thickness swelling (TS) of the plybamboo board was determined by comparing the initial thickness (T1) before immersion and the final thickness (T2) after immersion in water for 24 hours. Thickness swelling was calculated using the equation (4).

$$TS = \frac{T2\text{-}T1}{T1} X\ 100\% \quad (4)$$

Water absorption (WA) was determined by weighing the test specimen before immersion (W1) and after immersion (W2) in water for 24 hours. Water absorption was calculated using the equation (5).

$$WA = \frac{W2\text{-}W1}{W2} x\ 100\% \quad (5)$$

#### *2.3.4 Delamination*

Delamination testing involved immersing the test samples in water for 6 hours, followed by drying in an oven at 40 °C for 18 hours. After drying, the sample test measured the length of the delamination and the total length of the adhesive plane. Delamination data were calculated using the equation (6).

$$Delamination\ (\%) = \frac{Length\ of\ the\ delamination}{Total\ length\ of\ the\ adhesive\ plane} x\ 100\% \quad (6)$$

#### *2.3.5 Modulus of Rupture*

The MOR testing for LBB was conducted simultaneously with MOE testing using the same test specimens. MOR was calculated using the equation (7).

$$MOR = \frac{3PL}{2bh^2} \quad (7)$$

Explanation:

| | | |
|---|---|---|
| MOR | : | Modulus of rupture ($kg/cm^2$) will be converted into MPa |
| P | : | Maximum load (kg) |
| L | : | Support span (cm) |
| B | : | Width of the test specimen (cm) |
| h | : | Thickness of the test specimen (cm) |

#### *2.3.6 Modulus of Elasticity*

MOE testing for LBB was performed using a one-point loading bending test. MOE was calculated using the equation:

$$MOE = \frac{\Delta PL^3}{4\Delta Ybh^3} \quad (8)$$

Explanation:
MOE : Modulus of elasticity (kg/cm²) will be converted into MPa
ΔP : Load before proportionality (kg)
L : Support span (cm)
ΔY : Deflection at the load before proportionality (cm)
B : Width of the test specimen (cm)
h : Thickness of the test specimen (cm)

### *2.4 Analysis procedure*

The experimental design followed a Completely Randomized Design (CRD) with one factor (temperature) at three levels (150, 160, and 170 °C). The tests were repeated three times.

## 3 Result and discussion

### 3.1 Physical properties

#### *3.1.1 Moisture content*

Moisture content affects the properties of bamboo laminated boards. The moisture content testing in this research ranges from 8.70% to 11.17%. The highest moisture content was observed in untreated plybamboo boards at 11.17%, while the lowest moisture content was found in plybamboo boards treated with hygrothermal at 170 °C, measuring 8.70% (Fig. 2). Overall, the moisture content in plybamboo boards met the JAS 003 standard [30] of <14%. The ANOVA analysis indicates that hygrothermal treatment significantly affects the moisture content of plybamboo boards, with a significance level of <0.001. These results are similar to the research of Wulandari et al. [18], which produced layered bamboo boards using *D. asper* with an average moisture content value of 13.746%.

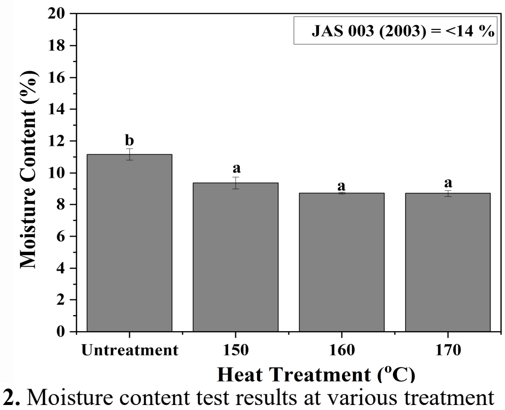


**Fig. 2.** Moisture content test results at various treatment temperatures; Different letters indicate a significant difference.

Moisture content testing shows that hygrothermal treatment tends to reduce the average moisture content in plybamboo boards compared to untreated boards. This is in line with research by Yang et al. [31], which suggests that hygrothermal treatment leads to the evaporation of water within the bamboo cell cavities, thus reducing the moisture content of plybamboo boards. Hygrothermal treatment also causes some hemicellulose content that binds cellulose microfibrils to degrade during heat treatment [32], [33]. Hemicellulose's hydroxyl groups have a water-binding property, so reducing these groups in plybamboo boards results in reduced moisture content. This aligns with the research by Korkut et al. [34], which states that heat treatment decreases the number of hydroxyl groups in hemicellulose, leading to increased dimensional stability. The study by Shangguan et al. [15] also indicates that moisture content in bamboo laminates decreases with increasing heat treatment temperature.

#### *3.1.2 Density*

The average density of plybamboo boards ranges from 0.51 to 0.63 g/cm$^3$, with the highest density observed in boards treated at 160 °C, measuring 0.63 g/cm$^3$, and the lowest density in boards treated at 170 °C, with a value of 0.51 g/cm$^3$ (Fig. 3) The ANOVA analysis ($\alpha$=0.05) indicates a significant difference with a significance level of 0.002. According to the DMRT, plybamboo boards treated with hygrothermal at 150 °C and 160 °C show significant differences compared to other plybamboo boards. These results align with research conducted by Yang et al. [35], who produce unidirectional round bamboo stick boards the result is that heat treatment can increase the density value of layered bamboo boards as the treatment temperature increases.

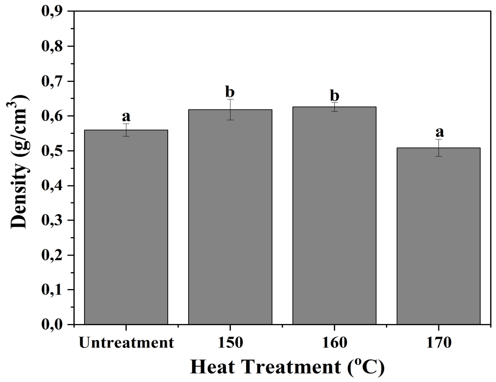


**Fig. 3.** Density test results at various treatment temperatures; Different letters indicate a significant difference.

Hygrothermal treatment tends to increase the density of plybamboo boards compared to untreated boards. The density of plybamboo boards can be influenced by their moisture content. Kamal et al. [19] reported that heat treatment causes moisture in the bamboo cell cavities to evaporate. Other studies report that, in addition to moisture content, the extractive substance content in bamboo laminates decreases, leading to increased adhesive penetration and higher density [24]. The extractive substances in bamboo laminates can hinder the adhesive from penetrating deeper into the fibers. Reducing the extractive substance content makes it easier for the adhesive to penetrate the cell cavities, resulting in increased density [36].

However, at a temperature of 170 °C, the density of plybamboo boards experiences a significant decrease. The high treatment temperature can affect the cell components, which aligns with the research by Lee et al.

[37], which states that high-temperature heat treatment begins to degrade the cell wall polysaccharides, causing a reduction in the density of plybamboo boards.

#### *3.1.3 Dimensional stability*

Dimensional stability can be measured through the thickness swelling and water absorption of plybamboo boards. The results indicate that the thickness swelling and water absorption values range from 9.73% to 15.73% and 37.23% to 50.38%, respectively, as shown in Fig. 4. The ANOVA analysis (α=0.05) shows significance values of 0.209 for thickness swelling and 0.037 for water absorption. The DMRT showed that hygrothermal treatment significantly impacts the water absorption of plybamboo boards for all treatment temperatures.

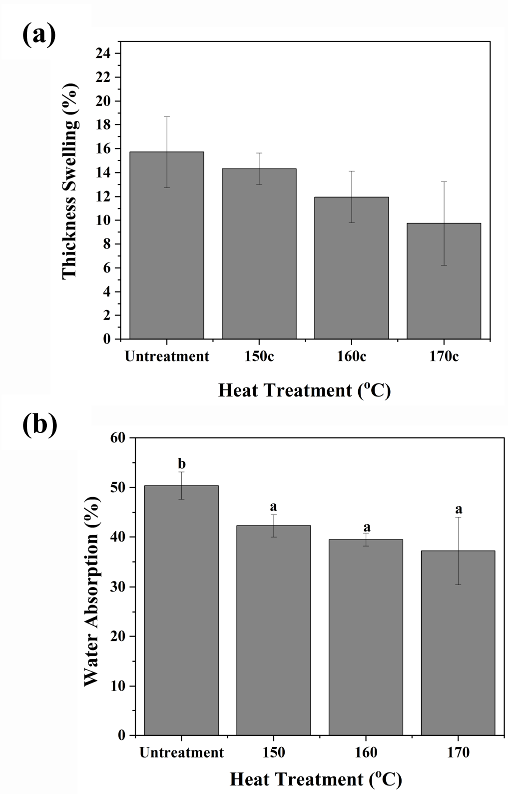


**Fig 4.** Dimensional stability test results at various treatment temperatures; (a) Thickness swelling test results, (b) water absorption test results; Different letters indicate a significant difference.

The results indicate that plybamboo boards treated with hygrothermal treatment have lower thickness swelling and water absorption values than untreated boards. The decrease in thickness swelling values may be due to the hygrothermal treatment affecting dimensional stability by degrading hydroxyl groups, resulting in increased hydrophobic properties [37–39]. This aligns with the findings of Akgül et al [40], which report that hygrothermal treatment increases hydrophobic properties in plybamboo, leading to increased stability. Research conducted by Yang et al. [35], reported that bamboo treated with heat will cause a decrease in the value of water absorption and the value of thickness swelling along with an increase in density. Besides that, the decrease is also caused by the increase in the hydrophobic properties of bamboo along with heat treatment.

#### *3.1.4 Delamination*

Delamination is a crucial factor for assessing the durability of laminated boards. According to Vick [41], delamination tests are an indicator of adhesive resistance to thickness swelling due to moisture in laminated boards. Delamination tests for plybamboo boards show average values ranging from 6.50% to 27.57%, with the lowest delamination observed in boards treated at 170 °C, as shown in Fig. 5. The ANOVA analysis (α=0.05) indicates that hygrothermal treatment significantly affects the delamination values of plybamboo boards, with a significance level of 0.013. The DMRT test shows that hygrothermal treatment significantly impacts delamination values in plybamboo boards for all treatment temperatures. According to JAS-003 [30], the minimum value for delamination is less than 33.3%, and as a result, the overall delamination value of plybamboo boards meets the standard.

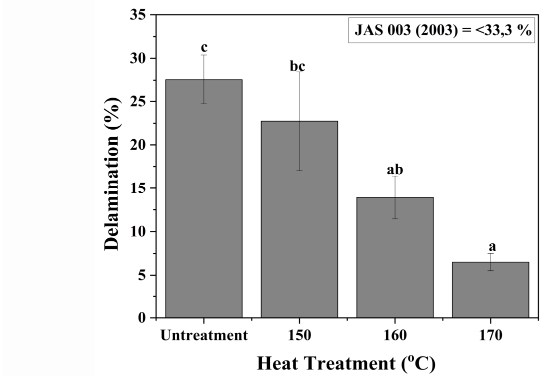


**Fig 5.** Delamination test results at various treatment temperatures; Different letters indicate a significant difference.

The decrease in delamination values is closely related to the values of thickness swelling and water absorption (Fig. 4.), where lower values of thickness swelling and water absorption lead to improved delamination values. This can be attributed to the type of adhesive used, which is Polyvinyl Acetate (PVAc), known for its sensitivity to moisture. This statement is consistent with the findings of Hanif and Rozalina [42], who stated that PVAc adhesive is susceptible to moisture. Therefore, the lower moisture content in plybamboo boards will improve the adhesion of the boards. Ruhedi et al. [4] added that PVAc adhesive is weak in high-humidity environments, making it suitable for interior products. Based on these findings, the use of PVAc adhesive in this research contributes to the high delamination values in the plybamboo boards.

### 3.2 Mechanical properties

#### *3.2.1 The MOR and MOE values*

The MOR in plybamboo boards is obtained by measuring the boards strength in resisting loads. Their physical properties influenced the MOR and MOE values in plybamboo boards. The MOR test results in the fiber parallel and fiber perpendicular directions show average values between 19.67-35.574 MPa and 14.86-20.57 MPa (Fig. 6). Similarly, the MOE test results in the fiber parallel and perpendicular directions indicate average values of 1,615.943-2,744.75 MPa and 552.03-867.93 MPa (Fig. 7).

Based on the JAS:003 standard [30], only the MOR values in the fiber parallel direction with treatment temperatures of 150 °C and 160 °C meet the standard with MOR > 244 kg/cm$^2$ (Fig. 6.). However, the MOE values do not meet the standard overall, as they should be > 50,000 kg/cm$^2$ JAS-003 [30] (Fig. 7.). The ANOVA analysis (α=0.05) shows that hygrothermal treatment results in a significant difference in the MOR and MOE values of plybamboo boards in the fiber parallel direction but does not significantly affect the perpendicular direction. The significance levels for MOR and MOE in the fiber parallel direction are 0.05 and 0.025, while for the fiber perpendicular direction, they are 0.158 and 0.233. Further, Duncan tests show that hygrothermal treatment significantly impacts the mechanical properties of plybamboo boards in the fiber parallel direction but not in the fiber perpendicular direction. The results of this study are similar to the research of Shangguan et al. [15], where heat treatment with a temperature of 160 ºC gives the highest improvement in mechanical properties.

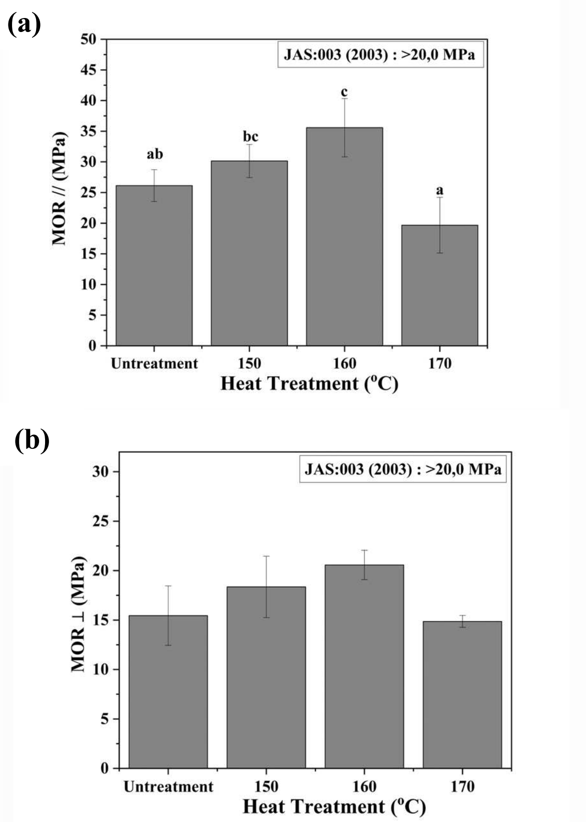


**Fig 6.** The MOR value parallel (a) and perpendicular (b) directions; Different letters indicate a significant difference.

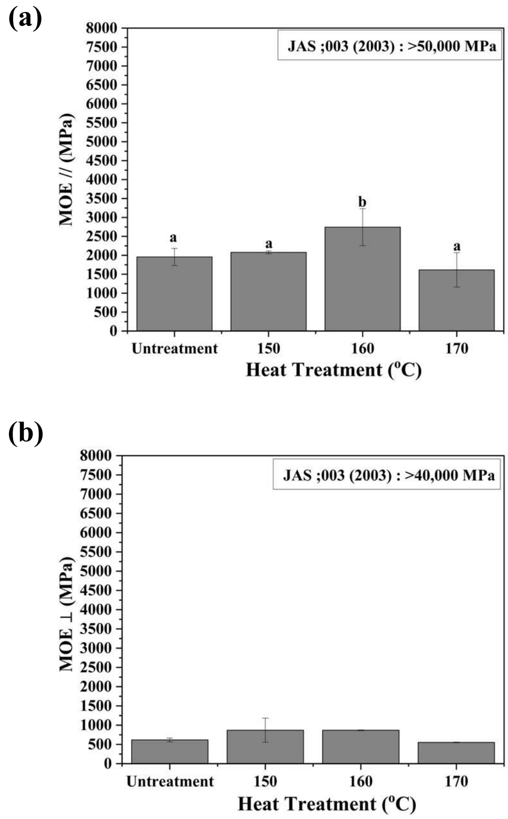


**Fig 7.** The MOE value parallel (a) and perpendicular (b) directions; Different letters indicate a significant difference.

The increase in MOR and MOE values is closely related to the density of plybamboo boards (Fig. 3.). The mechanical properties increase at treatment temperatures of 150 °C and 160 °C but decrease at a treatment temperature of 170 °C. This aligns with the research by Yang et al. [31], which reports that higher density is directly proportional to higher mechanical properties. Besides density, MOR and MOE values can be influenced by moisture content. According to Abdurachman & Najib [43], the moisture content is inversely related to the density and mechanical properties, meaning that lower moisture content results in higher density and mechanical properties. Based on Hanif & Rozalina [42], PVAc adhesive can provide high adhesive strength; thus, it can positively influence the MOR and MOE values of plybamboo boards.

Different MOR and MOE values are observed in the direction of bamboo fibers. The results demonstrate differences between values tested in the fiber parallel and perpendicular directions, with the latter having relatively lower values. This difference is due to the composition of the plybamboo board layers, and imperfect bonding can also affect the MOR values of the boards [44]. Research by Sulastiningsih et al [45], [46], reports that using layers in the fiber parallel direction results in higher values than using the fiber perpendicular direction.

## 4 Conclusion

The research results indicate that hygrothermal treatment impacts the physical and mechanical properties of plybamboo boards. The best treatment among the hygrothermal treatments was the one at 160 °C, resulting in values closest to meeting the JAS-003 standards. This treatment led to a decrease in moisture content, water absorption, thickness swelling, and delamination. The 160 °C heat treatment also improved the density, MOR, and MOE values of the plybamboo boards. However, based on the JAS-003 standards (2003), the properties of the laminated boards do not yet meet the standards required for wood substitution materials.

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