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Physical and Mechanical Properties of Bamboo Oriented Strand Board Under Various Post-Thermal Treatment Duration

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ABSTRACT

Post-treatment of bamboo-oriented strand board (BOSB) through thermal modification can be an alternative to improve BOSB quality. This study aimed to analyze the effect of post-thermal treatment duration on the physical and mechanical properties of BOSB. Three-layers BOSB with a target density of 0.7 g/cm^3 was made with the core layer perpendicular to the surface and bonded with 8% phenol-formaldehyde resin. The BOSB produced was then thermally-modified at 160°C for 1, 2, and 3 h. The physical and mechanical properties of BOSB were determined based on JIS A 5908-2003 standard. The results showed that the physical properties of the thermally-modified BOSB increased while the mechanical properties decreased compared to the untreated BOSB. The moisture content (MC), water absorption (WA), and thickness swelling (TS) of BOSB decreased with the increase in post-thermal treatment duration. The decrease in MC, WA, and TS of the thermally-modified BOSB reached 38.60%, 11.92%, and 33.26%, respectively. In addition, the decrease in modulus of elasticity (MOE), modulus of rupture (MOR), and internal bonding of the thermally-modified BOSB reached 19.18%, 23.15%, and 53.51%, respectively. The results showed that TS, MOE, and MOR of the thermally-modified BOSB still could meet the 0437.0 standards for commercial OSB (Grade O-1).

1. Introduction

Bamboo is a non-timber forest product that can be used as an alternative raw material to wood products. Bamboo has rapid growth and can be harvested within 3-5 years. Statistics Indonesia (2020) stated that the estimated number of bamboos in Indonesia reached 11.30 million stems. There are 161 species of bamboo in Indonesia, which may increase its potential with intensive identification (Widjaja et al. 2014). Some advantages of using bamboo as a raw material for wood products include good strength, hardness, woodworking, and finishing properties

(Febrianto et al. 2017). However, bamboo has a limited diameter and thickness compared to wood and limited use as a construction material requiring broad dimensions (Febrianto et al. 2017). Therefore, one of the wood products that can utilize bamboo as a raw material is composite products.

Oriented strand board (OSB) is a composite product suitable to be developed from bamboo. Previous studies on bamboo-oriented strand board (BOSB) showed that BOSB had better physical and mechanical properties than wood OSB (Adrin et al. 2013; Febrianto et al. 2015). However, BOSB still uses methylene diphenyl isocyanate (MDI) resin, which is quite expensive. Experiments using cheaper adhesives such as phenol-formaldehyde (PF) resin have been carried out, but higher concentrations were required (Adrin et al. 2013). This phenomenon was because bamboo has a high extractive content which reduces the quality of BOSB adhesion (Fatrawana et al. 2019; Maulana et al. 2017; Murda et al. 2018). Therefore, the adhesive penetration to BOSB was not optimized. Our previous studies showed that pre-thermal treatment, such as steam modification on bamboo strands, reduced extractive substances, thereby improving the dimensional stability and mechanical properties of BOSB (Maulana et al. 2016, 2017, 2018). Pre-thermal treatment on woody materials converted free sugars into furan intermediates and furan resins (Maloney 1993). As a result, the dimensional stability of BOSB is continually improved to get the result optimally. Steam pretreatment on the bamboo strand followed by sodium hydroxide (NaOH) solution rinsing showed excellent dimensional stability of BOSB (Fatrawana et al. 2019; Maulana et al. 2019, 2021). This phenomenon is due to the removed hemicellulose and extractive contents from the strands during steaming and washing with a 1% NaOH responsible for the BOSB improved dimensional stability (Fatrawana et al. 2019).

The influence of pre-thermal treatment, such as steam pretreatment on strands, has been investigated for BOSB properties. However, another alternative thermal treatment, such as post-thermal treatment, has the excellent potential to enhance the suitability of bamboo as OSB raw materials. Post-thermal treatment is an environmentally friendly technique because it does not use chemicals. The hygrothermal treatment has been shown to improve the dimensional stability of OSB (Ye et al. 2020). The studies related to the post-thermal treatment of OSB have been carried out. Aro et al. (2014) reported that post-thermal treatment of OSB reduced the water absorption (WA) and thickness swelling (TS) by 27% and 46%, respectively. Thermally-modified OSB from poplar (*Populus* spp.) reduced TS from 5.4–11% (Aro et al. 2014). This phenomenon occured due to the chemical components change, increasing cellulose's crystalline area and facilitating water accessibility (Cetera et al. 2018; Lee et al. 2018). Another study also showed that the thermal modification reduced biological attacks due to OSB becoming more hydrophobic (Aro et al. 2014). However, a study about post-thermal treatment of BOSB has not been reported. Therefore, this study aimed to evaluate the effect of post-thermal treatment duration on BOSB's physical and mechanical properties.

2. Materials and Methods

2.1. Materials

The four-year-old Betung (*Dendrocalamus asper*) bamboo was obtained from Sukabumi, West Java, Indonesia. The phenol-formaldehyde (PF) resin with a solid content of 43% was obtained from PT. PAI. The additional materials in this study were epoxy adhesive and paraffin.

2.2. BOSB Manufacturing

The bamboo strands with dimensions 70 mm × 25 mm × 0.5 mm were air-dried until reaching moisture content of ± 14%. The bamboo strands were then dried at 60-70°C for three days until it reached moisture content of less than 5%. One hundred modified strand samples were taken randomly to determine the slenderness and aspect ratios. The target density of the BOSB was 0.7 g/cm^3. The size of the three-layers BOSB produced was 30 cm × 30 cm × 0.9 cm (length x width x thickness). The bamboo strand with a mixture of 8% PF and paraffin is divided into three parts and arranged perpendicularly. The shelling ratio of BOSB was 50:50. The addition of paraffin was 1% of the dry weight of the strands. The board was hot-pressed with a pressure of 25 kg/cm^2 at 135°C for 10 min. The BOSB was then conditioned at room temperature for ten days.

2.3. Post-Thermal Treatment of BOSB

After conditioning, the BOSB was thermally-modified at 160°C for 1, 2, and 3 h. Untreated BOSB (0 h) was also prepared for comparison. The modified board was then conditioned for ± 10 days.

2.4. Physical and Mechanical Evaluation of BOSB

The physical and mechanical properties of the BOSB were evaluated based on the Japanese Industrial Standard (JIS) A 5908-2003 standard (JSA 2003). The physical properties evaluated were moisture content, density, water absorption, and thickness swelling, while the mechanical properties evaluated were modulus of elasticity, modulus of rupture, and internal bonding. The dimensional stability and mechanical properties were then compared to the OSB commercial standard CSA 0437.0 (Grade O-1) (SBA 2004).

2.4.1. Moisture content

The moisture content (MC) of the BOSB samples was evaluated by measuring sample weight before and after the oven-drying at 103 ± 2°C for 24 h. The MC value was calculated using Equation 1.

$$MC\ (\%) = \frac{Initial\ weight\ (g) - Oven\text{-}dried\ weight\ (g)}{Oven\text{-}dried\ weight\ (g)} \times 100\% \quad (1)$$

2.4.2. Density

Density was measured based on air-dried weight and air-dried volume. The density value was calculated using Equation 2.

$$Density\ (g/cm^3) = \frac{Air\text{-}dried\ weight\ (g)}{Air\text{-}dried\ volume\ (cm^3)} \quad (2)$$

2.4.3. Water absorption

The water absorption (WA) of the BOSB sample was measured before and after immersion weight for 24 h. The WA value was calculated using Equation 3.

$$WA\ (\%) = \frac{Weight\ after\ immersion\ (g) - Weight\ before\ immersion\ (g)}{Weight\ before\ immersion\ (g)} \times 100\% \quad (3)$$

2.4.4. Thickness swelling

The thickness swelling (TS) of the BOSB sample was measured before and after immersion for 24 h. The sample was measured at the same point before immersion following JIS A 5908-2003 standard. The TS value was calculated using Equation 4.

$$TS\ (\%) = \frac{\text{Thickness after immersion (g)} - \text{Thickness before immersion (g)}}{\text{Thickness before immersion (g)}} \times 100\% \quad (4)$$

2.4.5. Modulus of elasticity and modulus of rupture

The modulus of elasticity (MOE) and modulus of rupture (MOR) of BOSB sample were measured in parallel and perpendicular to grain directions. The testing was determined by one-point loading with a universal testing machine (UTM, Chun Yen Co., Ltd., Taichung, Taiwan). The testing load speed of 10 mm/min and a span length of 15 cm. The MOE and MOR values were calculated using Equation 5 and Equation 6, respectively.

$$MOE\ (MPa) = \frac{\Delta P \times L^3}{4\Delta y \times b \times h^3} \quad (5)$$

$$MOR\ (MPa) = \frac{3P \times L}{2b \times h^2} \quad (6)$$

where ΔP is the difference between the upper and lower limits of the load within the proportional range (N), Δy is the deflection at the center of the test span corresponding to ΔP (mm), P is the maximum load (N), L is the span length between the supports, b is the sample width (mm), and h is the sample thickness (mm).

2.4.6. Internal bonding strength

The BOSB sample was glued into two wooden blocks with epoxy adhesive for 24 h. The sample was then pulled perpendicular to the surface with a universal testing machine (UTM, Chun Yen Co., Ltd, Taichung, Taiwan). The testing load speed of 2 mm/min until maximum load. The internal bonding (IB) strength value was calculated using Equation 7.

$$IB\ strength\ (MPa) = \frac{\text{Maximum load (N)}}{2 \times \text{Sample width (mm)} \times \text{Sample thickness (mm)}} \quad (7)$$

2.5. Data analysis

The data were analyzed using SPSS statistics (Version 22, IBM). Data on the physical and mechanical properties were analyzed using a completely randomized design. Four variations of post-thermal treatment duration (0, 1, 2, and 3 h) were tested. Data were analyzed using ANOVA. Duncan's multiple range test was conducted to obtain the difference values between treatments at the 5% significance level. Each treatment was performed in three replicates.

3. Results and Discussion

3.1. Strand Geometry

The slenderness ratio (SR) and aspect ratio (AR) values were 115.8 and 3.24, respectively, with the strand distribution shown in **Fig 1**. The value of AR and SR suggests the suitability for

BOSB raw materials. A previous study showed that strand SR values of 76.6 and 73.8 could produce BOSB with good physical and mechanical properties (Febrianto et al. 2015). The strands with a high SR and minimum AR had good inter-strand contact and could produce a high MOE and MOR of BOSB.

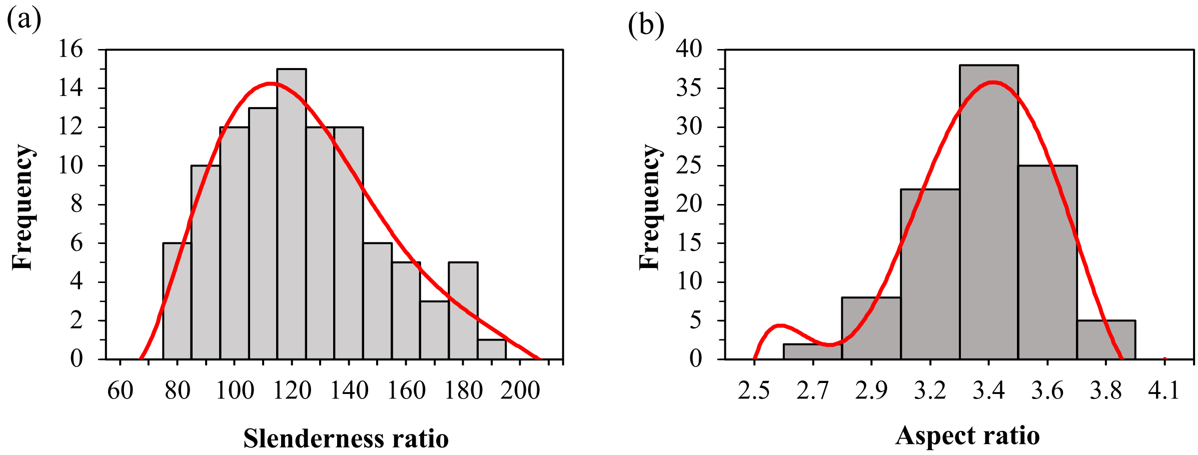

Fig 1. (a) slenderness ratio and (b) aspect ratio distribution in the bamboo strands.

3.2. Physical Properties of Thermally-Modified BOSB

3.2.1. Moisture content and density

The moisture content (MC) and density values of thermally-modified BOSB were 6.05%–9.86% and 0.64–0.67 g/cm^3, respectively (**Fig 2**). The MC values of thermally-modified BOSB decreased with increasing treatment duration. Furthermore, the density value of thermally-modified BOSB was lower than untreated OSB. The analysis of variance ($p < 0.05$) showed that treatment duration affected the moisture content and density of thermally-modified BOSB. Duncan's multiple range tests showed that the MC values of untreated BOSB and thermally-modified BOSB for 1, 2, and 3 h were significantly different. Furthermore, the density values of thermally-modified BOSB for 1 and 2 h differed from thermally-modified BOSB for 3 h and untreated BOSB. The percentage decrease in MC and density of thermally-modified BOSB was 13.42–38.60% and 1.36–5.09%, respectively, compared to untreated BOSB.

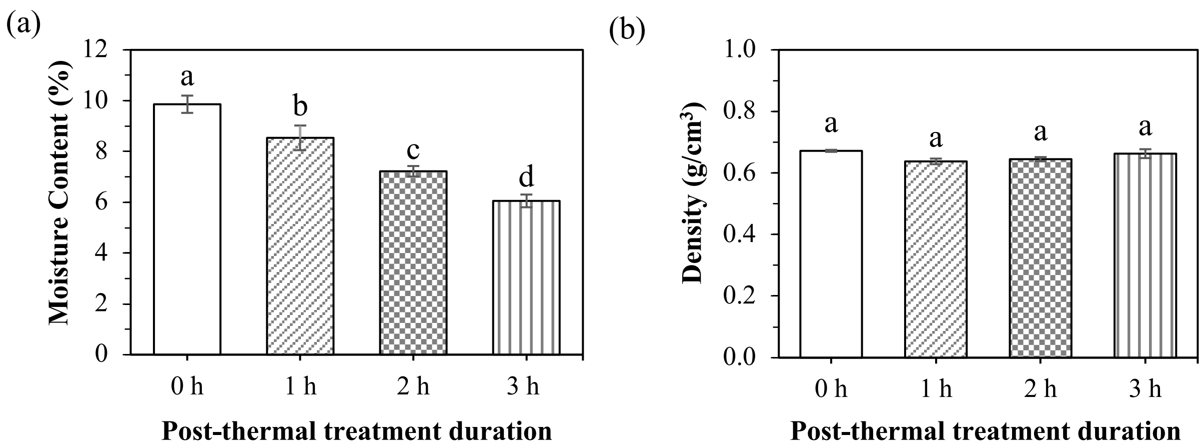

Fig 2. The moisture content (a) and density (b) of BOSB under various post-thermal treatment duration (different letters showed a significant difference).

The longer post-thermal treatment duration could reduce the BOSB moisture content. This phenomenon is presumably because the longer the thermal treatment, the lower the hydroxyl group, and the BOSB will absorb less water vapor. Mendes et al. (2013) reported that the longer the thermally-modified on the OSB, the lower the value of the MC of the board. Thermal treatment affected free hydroxyl group reduction and hygroscopicity; the MC decreased (Guo et al. 2021). In addition, the density value of thermally-modified BOSB was lower than untreated BOSB. The thermal modification of BOSB causes changes in chemical components to reduce the board's weight. This phenomenon was in line with the study conducted by Hidayat et al. (2016), stating that thermally-modified *Cylicodiscus gabunensis* wood experienced more weight loss with increasing treatment duration. The density value of thermally-modified wood decreases due to reducing moisture content and the loss of various organic compounds that evaporate or are degraded during the heating process (Mendes et al. 2013).

3.2.2. Water absorption and thickness swelling

The water absorption (WA) and thickness swelling (TS) values of thermally-modified BOSB were 25.20–28.61% and 4.50–6.74%, respectively (**Fig 3**). The WA and TS values of thermally-modified BOSB decreased with increasing treatment duration. The analysis of variance ($p < 0.05$) showed that treatment duration did not significantly affect the WA of thermally-modified BOSB. However, treatment duration affected the TS of BOSB. Duncan's multiple range tests showed that the TS value of thermally-modified BOSB for 0 and 1 h differed from the thermally-modified BOSB for 2 and 3 h. The percentage decrease in WA and TS values of thermally-modified BOSB was 5.70–11.92% and 3.83–33.26%, respectively, compared to untreated BOSB. The TS values of treated-modified BOSB met the commercial OSB standard CSA 0437 (Grade O-1) that required a maximum TS value of 15% (SBA 2004).

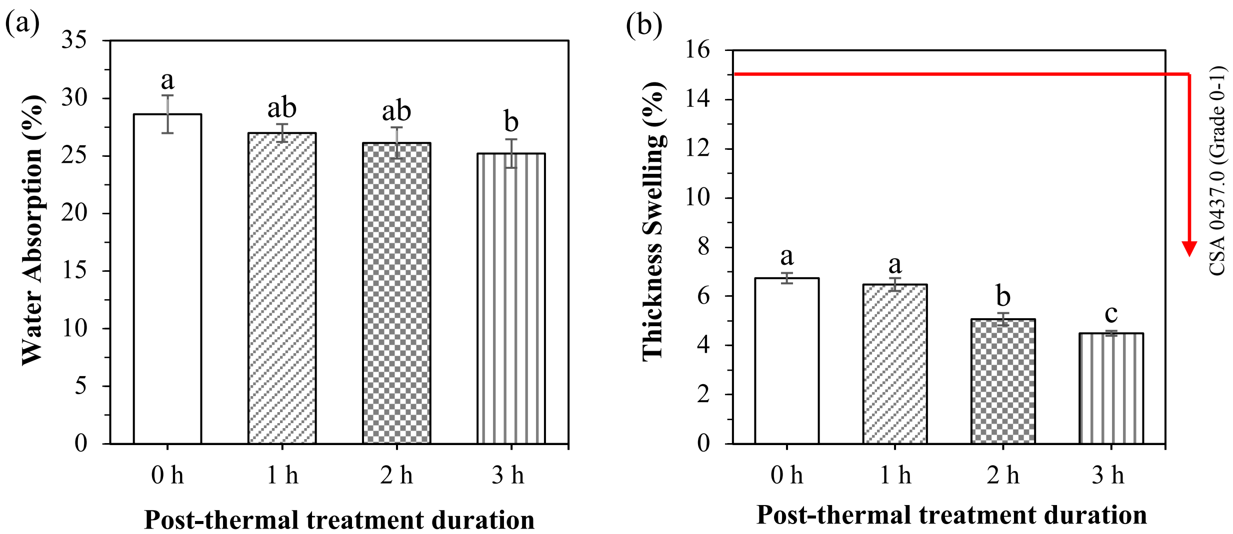

Fig 3. The WA (a) and TS (b) of BOSB under various post-thermal treatment duration (different letters showed a significant difference).

The WA values decrease of thermally-modified BOSB were insignificant, while the TS values decrease of thermally-modified BOSB were significant. The longer thermal treatment duration caused the changing of bamboo components. Carvalho et al. (2015) stated that thermal treatment could decrease the WA and TS post-thermal treatment particleboard from sugarcane bagasse even if a shorter duration were applied. The value of TS decreased due to chemical changes and decreased hydroxyl groups due to heat treatment. Increasing cellulose crystallinity inhibits the water molecules' accessibility to hydroxyl groups (Kasemsiri et al. 2012; Lee et al. 2018). Baiti et al. (2021) stated that the surface bamboo strand was heated longer and is more hydrophobic.

3.3. Mechanical Properties Thermally-Modified Bamboo OSB

3.3.1. Modulus of elasticity and modulus of rupture

The modulus of elasticity (MOE) parallel and perpendicular values of thermally-modified BOSB were 6041–7750 MPa and 1993–2446 MPa, respectively (**Fig 4**). The modulus of rupture (MOR) parallel and perpendicular to the grain directions was 40.54–51.43 MPa dan 21.79–28.35 MPa, respectively (**Fig 5**). The MOE and MOR values of thermally-modified BOSB decreased with increasing treatment duration. The analysis of variance ($p < 0.05$) showed that treatment duration affected the MOE parallel, MOE perpendicular, and MOR perpendicular of thermally-modified bamboo OSB. However, treatment duration did not significantly affect the MOR parallel of thermally-modified BOSB. Duncan's multiple range tests showed that the MOE parallel value of thermally-modified BOSB for 2 and 3 h differed from the thermally-modified BOSB for 1 h and untreated BOSB. Furthermore, the MOE perpendicular value of thermally-modified BOSB for 3 h differed from the thermally-modified BOSB for 1 h, 2 h, and untreated BOSB. Duncan's multiple range tests showed that the MOR perpendicular value of thermally-modified BOSB for 2 h and 3 h differed from the thermally-modified BOSB for 1 h and untreated BOSB.

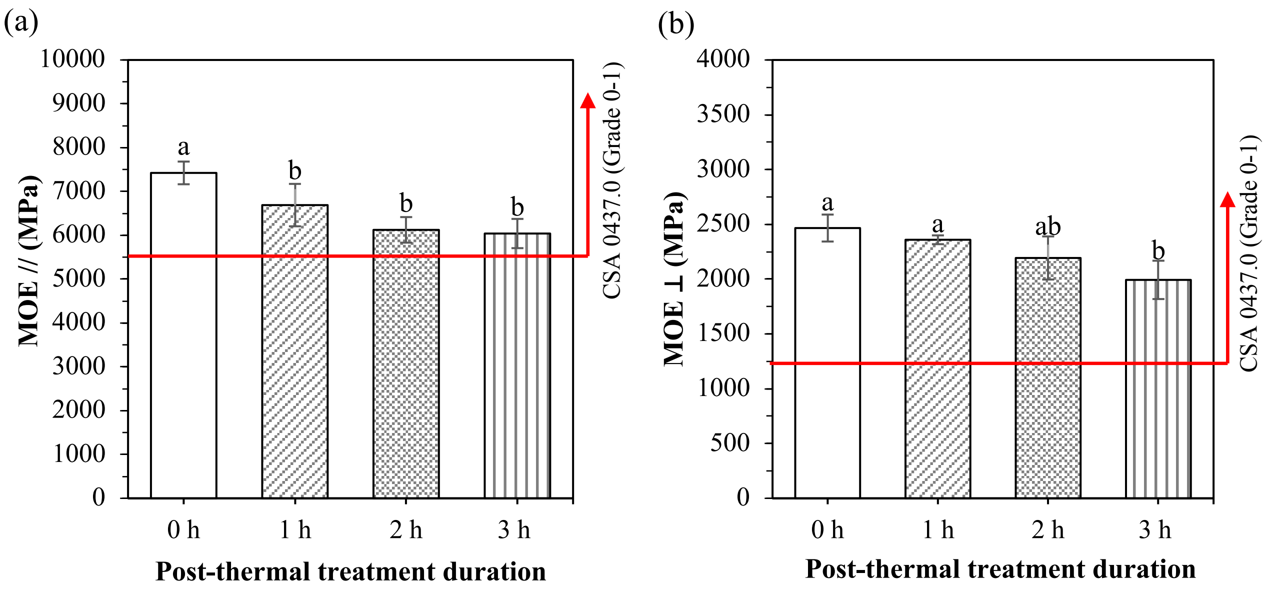

Fig 4. The MOE parallel (//) (a) and perpendicular (⊥) (b) of BOSB under various post-thermal treatment duration (different letters showed a significant difference).

The decrease in MOE parallel, MOE perpendicular, MOR parallel, and MOR perpendicular values of thermally-modified BOSB was 9.89–18.63%, 4.33–19.18%, 4.79–10.65%, and 5.95–23.15%, respectively, compared to untreated BOSB. The MOE and MOR values of thermally-modified BOSB were lower than untreated BOSB. However, all MOE and MOR values of thermally-modified BOSB met the commercial OSB standard CSA 0437 (Grade O-1) (SBA 2004).

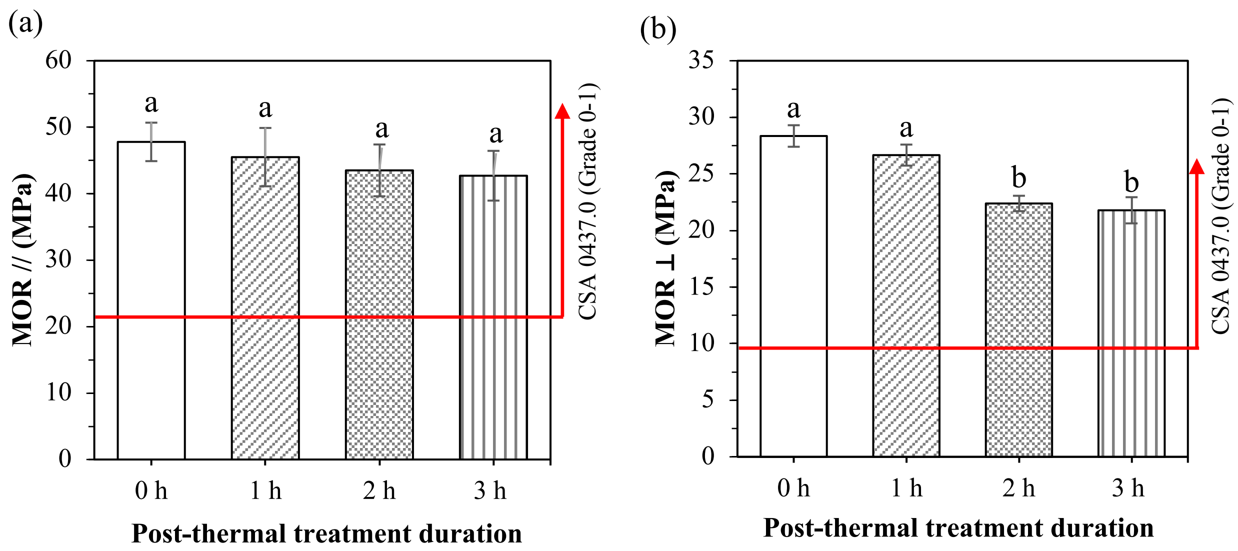

Fig 5. The MOR parallel (//) (a) and perpendicular (⊥) (b) of BOSB under various post-thermal treatment duration (different letters showed a significant difference).

The thermal modification resulted in a reduction in mechanical properties. The long thermal treatment duration reduced the strength and stiffness of thermally-modified wood. Generally, its changes are related to the degradation of the wood substance, particularly hemicellulose degradation (Hidayat et al. 2017; Kubovský et al. 2020). The MOE value of thermally-modified wood decreased due to the increase in hemicellulose degradation and cellulose crystallinity, causing the wood to become more brittle and stiffer (Aro et al. 2014). In addition, mechanical properties decrease due to adhesive degradation with more prolonged heating. The PF resins used in BOSB may deteriorate, resulting in a decrease in composite strength.

3.3.2. Internal bonding strength

The internal bonding (IB) strength values of thermally-modified BOSB were 0.19–0.40 MPa (**Fig 6**). The IB strength values of thermally-modified BOSB decreased with increasing treatment duration. The analysis of variance ($p < 0.05$) showed that treatment duration affected the IB strength values of thermally-modified BOSB. Duncan's multiple range tests showed that the IB strength values of thermally-modified BOSB for 3 h differed from the thermally-modified BOSB for 1 h, 2 h, and untreated OSB. The percentage decrease in IB strength values of thermally-modified BOSB was 25.15–53.51% compared to untreated BOSB. The IB strength values of thermally-modified BOSB for 1 h, 2 h, and 3 h decreased respectively by 0.10 MPa, 0.14 MPa, and 0.21 MPa compared to untreated BOSB. All IB strength values of thermally-modified BOSB did not meet the commercial OSB standard CSA 0437 (Grade O-1) (SBA 2004).

The IB strength values of thermally-modified BOSB decreased with increasing treatment duration. The changes in the chemical components of BOSB with increasing thermal treatment duration caused the adhesive between strands to become brittle, thereby reducing the IB strength values of BOSB. Cao et al. (2022) stated that thermal treatment of wood reduced the ability of the wood to resist cracks or pores when tensile loads are applied. It is due to the increased brittleness of thermally-modified wood. The IB strength values of post-thermal treatment for 4 h on OSB scots pine (*Pinus sylvestris*) were 16.7% lower than untreated OSB (Direske et al. 2018). Cetera et al. (2018) reported that the decrease in IB strength values of thermally-modified OSB from poplar strands might be due to the thermal degradation of the adhesive, so it is necessary to use a different adhesive with higher thermal stability.

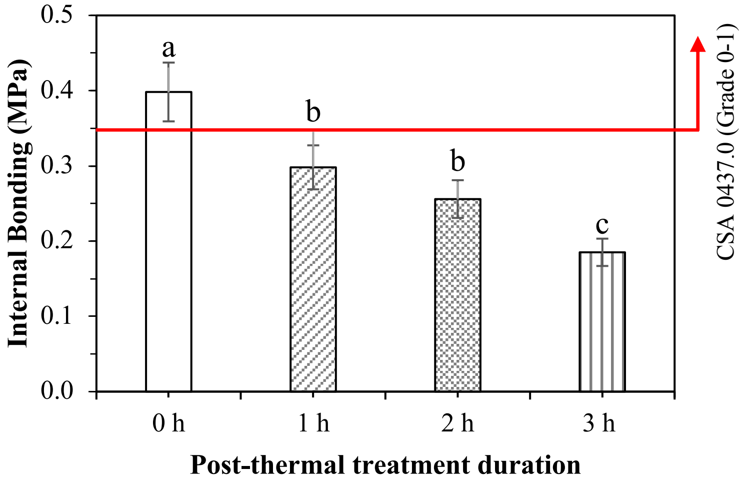

Fig 6. The IB strength of BOSB under various post-thermal treatment duration (different letters showed a significant difference).

4. Conclusions

Duration of BOSB post-thermal treatment significantly affected the physical and mechanical properties except for the WA and MOR parallel of BOSB. The post-thermal treatment duration improved the physical properties of BOSB, particularly MC and TS. The results revealed that the TS value of BOSB decreased with increasing post-thermal treatment duration. In addition, the MOE and MOR values of BOSB decreased due to thermal treatment. However, all MOE and MOR values still could meet the CSA standard 0437.0 standards for commercial OSB (Grade O-1). The IB strength values of BOSB post-thermal treatment were lower than untreated BOSB. The longer post-thermal treatment duration could increase the physical properties of BOSB. This study suggested that post-thermal treatment of BOSB for 3 h can be an alternative to improve the dimensional stability of BOSB. However, thermally-modified BOSB is not suggested for structural applications because one of the mechanical properties of BOSB did not meet the CSA 0437.0, namely the IB strength.

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