Properties of Dual-species Bamboo-Oriented Strand Boards Bonded with Phenol Formaldehyde Adhesive under Various Compression Ratios

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Physical and mechanical properties were evaluated for bamboo-oriented strand boards (BOSB) prepared with combinations of two contrasting bamboo species and bonded with phenol formaldehyde resin under various compression ratios. The strands from the culms of *Gigantochloa pseudoarundinacea* and *Dendrocalamus asper* bamboo were steam-treated at a temperature of 126 °C and a pressure of 0.14 MPa for 1 h and then washed with a 1% NaOH solution. Three-layer dual-species bamboo-oriented strand boards with a shelling ratio of 25 to 50 to 25 (face to core to back) were manufactured with different compression ratios using an 8% phenol formaldehyde adhesive and 1% paraffin. The slenderness ratio and aspect ratio were evaluated by measuring 100 random strands to determine uniformity. The solidity profiles of the dual-species bamboo-oriented strand boards (thickness direction) were relatively uniform. The modulus of rupture, modulus of elasticity, and internal bond values of the dual-species bamboo-oriented strand boards increased as the compression ratio increased, but the water absorption and thickness swelling decreased. The dual-species bamboo-oriented strand boards prepared with compression ratios of 1.44 to 1.25 and 1.54 to 1.33 met all the requirements of CSA standard 0437 (2011). The optimum compression ratio for the preparation of dual-species bamboo-oriented strand boards was 1.44 to 1.25.

Keywords: Compression ratio; Dendrocalamus asper; Gigantochloa pseudoarundinacea; Bamboo-oriented strand board (BOSB); Phenol formaldehyde resin

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INTRODUCTION

Bamboo is a non-wood forest product that plays an essential role as an alternative wood resource. Bamboo has several advantages over wood, such as a faster growth rate with a shorter cycle, a lower production cost, straight stems, easy processability, and high adaptability to poor soil conditions (Hunter 2003; Febrianto *et al*. 2017). However, bamboo has several disadvantages, particularly in its construction components. It has a relatively small diameter and an internal hole; therefore, bamboo utilization is limited, and it is challenging to use it in wide-dimension products. The conversion of bamboo into composite products is an efficient alternative to overcome this disadvantage.

Chaowana (2013) reported that bamboo has a high potential to be developed into a composite product; bamboo-oriented strand board (BOSB) is one of those promising composite products. Bamboo-oriented strand boards have better mechanical properties than wood-oriented strand boards (OSBs) when prepared using similar process parameters (Febrianto *et al.* 2009; Adrin *et al.* 2013). However, the production of BOSBs still uses an uneconomical methylene diphenyl diisocyanate (MDI) adhesive. Research using low-cost adhesives, *e.g.*, phenol formaldehyde (PF), has been performed, but higher concentrations are needed to meet commercial OSB standards (Adrin *et al.* 2013). Steam treatment of the strands could be an effective pre-treatment to improve the quality of PF-bonded BOSBs (Maulana *et al.* 2016, 2017). In addition, steam treatment increases the durability of the BOSBs to weathering as well as its resistance against *Coptotermes curvignathus* and *Cryptotermes cynocephalus* termites (Febrianto *et al.* 2013; Maulana *et al.* 2019a). Furthermore, steam treatment followed by rinsing with a 1% NaOH solution improves the quality of the BOSB and meeting commercial OSB standards (Fatrawana *et al.* 2019).

A series of studies have shown that the strand from a single bamboo species is a suitable raw material for BOSB production. In previous studies by the authors, Andong (*Gigantochloa pseudoarundinacea*) and Betung (*Dendrocalamus asper*) bamboos were exceptionally promising raw materials for the production of BOSBs (Febrianto *et al.* 2012; Adrin *et al.* 2013; Febrianto *et al.* 2015; Maulana *et al.* 2017; Fatrawana *et al.* 2019; Maulana *et al.* 2019a,b). The BOSBs manufactured from Betung bamboo with steam treatment followed by rinsing with a 1% NaOH solution had reasonable properties in terms of commercial utilization (Fatrawana *et al.* 2019; Maulana *et al.* 2021a). The BOSBs manufactured with steam-treated Andong bamboo strands also had reasonable physical and mechanical properties (Maulana *et al.* 2016, 2017). These bamboos have quite different densities (Park *et al.* 2018) and different types of vascular bundles. Betung bamboo has type IV vascular bundles (Febrianto *et al.* 2017), while Andong bamboo has type III vascular bundles (Maulana *et al.* 2021b).

In BOSB manufacturing, the raw material density is greatly influenced by the compression ratio, which affects the quality of the BOSBs. The compression ratio is the ratio between the board density and the raw material density (Hse 1975). Several studies have shown that the mechanical properties of OSBs increase as the compression ratio increases (Sumardi *et al.* 2007; Hiziroglu 2009; Jin *et al.* 2009; Chen *et al.* 2010; Maulana *et al.* 2020). Kelly (1977) suggested a compression ratio of at least 1.2 to produce composite boards with satisfactory properties. Maloney (1993) stated that a compression ratio of 1.3 results in optimum conditions for particleboard manufacturing.

Several studies on OSB made from combination raw material have been conducted and showed good OSB properties (Amusant *et al.* 2009; Arnould *et al.* 2010; Febrianto *et al.* 2010; Bufalino *et al.* 2015; Suhadi *et al.* 2018; Lunguleasa *et al.* 2020). However, to date, information on the preparation conditions and properties of three-layer BOSBs from different bamboo species, specifically for each layer, has not been reported. The optimum compression ratio for the preparation of dual-species BOSBs using phenol formaldehyde resin has also not been reported. Therefore, in this study, the authors prepared and evaluated the properties of dual-species bamboo-oriented strand boards (DSBOSBs) using phenol formaldehyde resin under different compression ratios to improve the quality of BOSBs in order to increase the utilization of bamboo resources.

EXPERIMENTAL

Materials

Four-year-old *Gigantochloa pseudoarundinacea* culms with a density of 0.60 g/cm^3 and *Dendrocalamus asper* culms with a density of 0.52 g/cm^3 were obtained from Sukabumi, West Java, Indonesia. A PF adhesive with a solid content of 43.1% and paraffin were obtained from the PT Pamolite Adhesive Industry (East Java, Indonesia). The properties of PF and paraffin for adhesives are shown in Tables 1 and 2, respectively.

Table 1. Properties of PF Adhesive

Parameter	Unit	Specification	Result
pH (25 °C)	-	10.0-13.0	12,30
Viscosity (25 °C)	Poise	1.8-2.4	2.25
Gelation Time (135 °C)	Minute	5.15	12'24"
Resin Content (135 °C)	%	41.0-44.0	43.1
Specific Gravity 25 °C/ 4 °C)	-	1190-1200	1200

Table 2. Properties of Paraffin

Parameter	Specification	Result
Oil content (%wt)	0.5 Max	0.43
Melting point (°C)	52 Min	52.8
Color in Saybolt	+28 Min	+29

Strand Preparation

The bamboo culms were sliced into strands using a sharp machete and scissors with the target dimensions: 70 mm long, 25 mm wide, and 0.5 mm thick. The strands were steam-treated in an autoclave at a temperature of 126 °C under a pressure of 0.14 MPa for 1 h, followed by washing with a 1% NaOH solution. The strands were subsequently air-dried for 7 d and oven-dried at a temperature of 60 to 80 °C for 36 h to obtain a moisture content of less than 5%. The strand geometry of 100 strands was determined based on the aspect ratio (AR) and slenderness ratio (SR) (Maloney 1993).

Dual-species Bamboo-Oriented Strand Boards (DSBOSB) Manufacturing

The DSBOSBs, with dimensions of 30 cm × 30 cm × 0.9 cm, were manufactured according to a previous study (Maulana *et al*. 2019b). The target density and compression ratio of the boards are listed in Table 3.

Table 3. Preparation Conditions for the Dual-species Bamboo-Oriented Strand Boards (DSBOSBs)

Surface Strand Density (g/cm^3)	Core Strand Density (g/cm^3)	DSBOSB Target Density (g/cm^3)	Compression Ratio (Surface to Core)
0.52	0.60	0.60	1.15 to 1.00
0.52	0.60	0.65	1.25 to 1.08
0.52	0.60	0.70	1.35 to 1.17
0.52	0.60	0.75	1.44 to 1.25
0.52	0.60	0.80	1.54 to 1.33

A PF resin with an 8% concentration was used, and 1% paraffin was added. The strands were mixed with the resin using a spray gun in a rotary blender. In this study, *G. pseudoarundinacea* strands with a density of 0.60 g/cm^3 constituted the core layer, while *D. asper* strands with a density of 0.52 g/cm^3 constituted the surface layer. The three layers of DSBOSBs were made with *D. asper*: *G. pseudoarundinacea*: *D. asper* (face: core: back) with a shelling ratio of 25 to 50 to 25. The boards were compressed using a hot press at a temperature of 135 °C under a specific pressure of 2.45 MPa for 9 min. The boards were conditioned at room temperature for 14 d to eliminate residual stress. Each treatment was carried out in three replications.

Solidity Evaluation of the Dual-species Bamboo-Oriented Strand Boards (DSBOSB)

Combined bamboo-oriented strand board samples with dimensions of 7 cm (length) × 1 cm (width) × 1 cm (thickness) were used for the solidity evaluation. The solidity evaluation was carried out in regard to the thickness (as shown in Fig. 1). The solidity of DSBOSB was examined using a micro-CT SkyScan 1173 (Hamamatsu L9181-02, Japan) at 45 kV and 45 µA. The scanning camera resolution was set at 33.49 µm/pixel with a depth of 16 bits. The images obtained were reconstructed and analyzed using NRecon software (version 1.7.1.0, Bruker MicroCT, Kontich, Belgium) and CT analyzer software (version 1.16.4.1, Bruker MicroCT, Kontich, Belgium). The solidity of the DSBOSBs was calculated from the results of the CT analysis using Microsoft Excel.

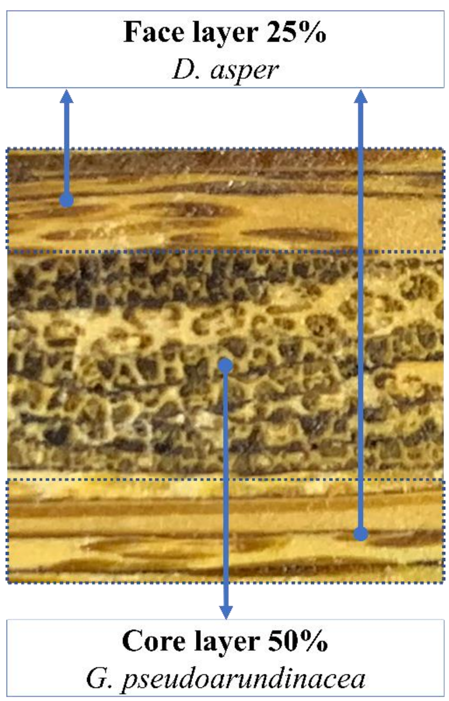

Fig. 1. Side perspective of a DSBOSB sample

Evaluation of the Physical and Mechanical Properties

The physical and mechanical properties of DSBOSBs were evaluated according to the JIS A standard 5908:2003 (JIS 2003). The physical properties, *i.e.*, the density, moisture content (MC), water absorption (WA), and thick swelling (TS), as well as the mechanical properties, *i.e.*, the modulus of elasticity (MOE) and modulus of rupture (MOR) parallel and perpendicular to the grain, and the internal bond (IB) strength were examined using a universal testing machine (UTM) (Chun Yen CY-6040A4, Chun Yen Testing Machines Co., Ltd., Taiwan) with a crosshead speed of 10 mm/min. Each parameter was evaluated using three samples. All parameters measured were compared to those of the CSA O437.0 (2011) (Grade O-1) standard for OSB panels (SBA 2005).

Data Analysis

The experimental design used in this study was a simple completely randomized design (CRD) with a single factor (the compression ratio). The data obtained in this research was statistically analyzed using the analysis of variance (ANOVA) followed by Duncan's multiple range test to determine any significant differences. Statistical analysis was performed using IBM SPSS Statistics Software (Version 22, IBM Co., Armonk, NY).

RESULTS AND DISCUSSION

Strand Geometry

The frequency of the slenderness ratio (SR) and aspect ratio (AR) values are presented in Fig. 2. The average SR and AR values were 115.4 and 3.0 for *G. pseudoarundinacea* strands and 114.3 and 3.0 for *D. asper* strands, respectively. The AR and SR values of the strands indicated good suitability of the BOSB raw material. Strands with a high SR result in good inter-strand contact and produce a composite board with a high MOE and MOR (Maloney 1993; Beck *et al*. 2009). Febrianto *et al*. (2015) manufactured BOSBs with suitable physical and mechanical properties from *G. pseudoarundinacea* and *D. asper* with comparatively smaller SR values (76.6 and 73.8, respectively). The AR value is also an essential parameter that affects the MOE value of the BOSB (Juliana *et al*. 2012). A minimum AR value of 3 is sufficient to produce a composite panel with high mechanical properties (Kuklewski *et al*. 1985).

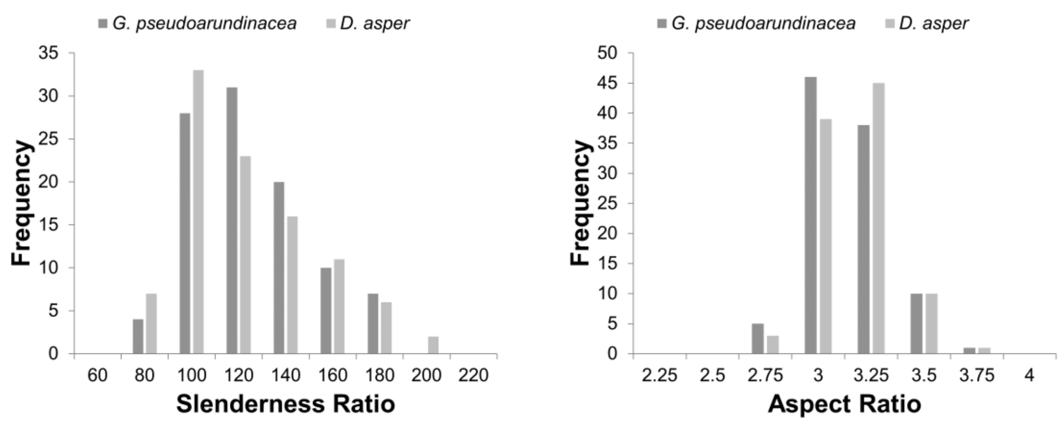

Fig. 2. Frequency of the SR and AR in the bamboo strands

Physical Properties of the Dual-species Bamboo-Oriented Strand Boards (DSBOSB)

The solidity profiles of the DSBOSBs (thickness) are shown in Fig. 3. The solidity values of the DSBOSBs with different densities were relatively uniform among the layers.

Figure 4 shows the density and moisture content of the DSBOSBs manufactured under various compression ratios. The density of the DSBOSBs ranged between 0.61 g/cm^3 and 0.81 g/cm^3 (Fig. 4a). A high-density board from the same raw material resulted in a higher compression ratio. There were significant differences in the density among DSBOSBs with different compression ratios. The moisture content of the DSBOSBs ranged between 11.5% and 12.3% (Fig. 4b), and there were no significant differences among the DSBOSBs.

The water absorption (WA) and thickness swelling (TS) values of the DSBOSBs manufactured under various compression ratios are shown in Fig. 5. In general, the WA and TS were closely related to the dimensional stability of the composite materials. The WA and TS of the DSBOSBs increased as the compression ratio increased.

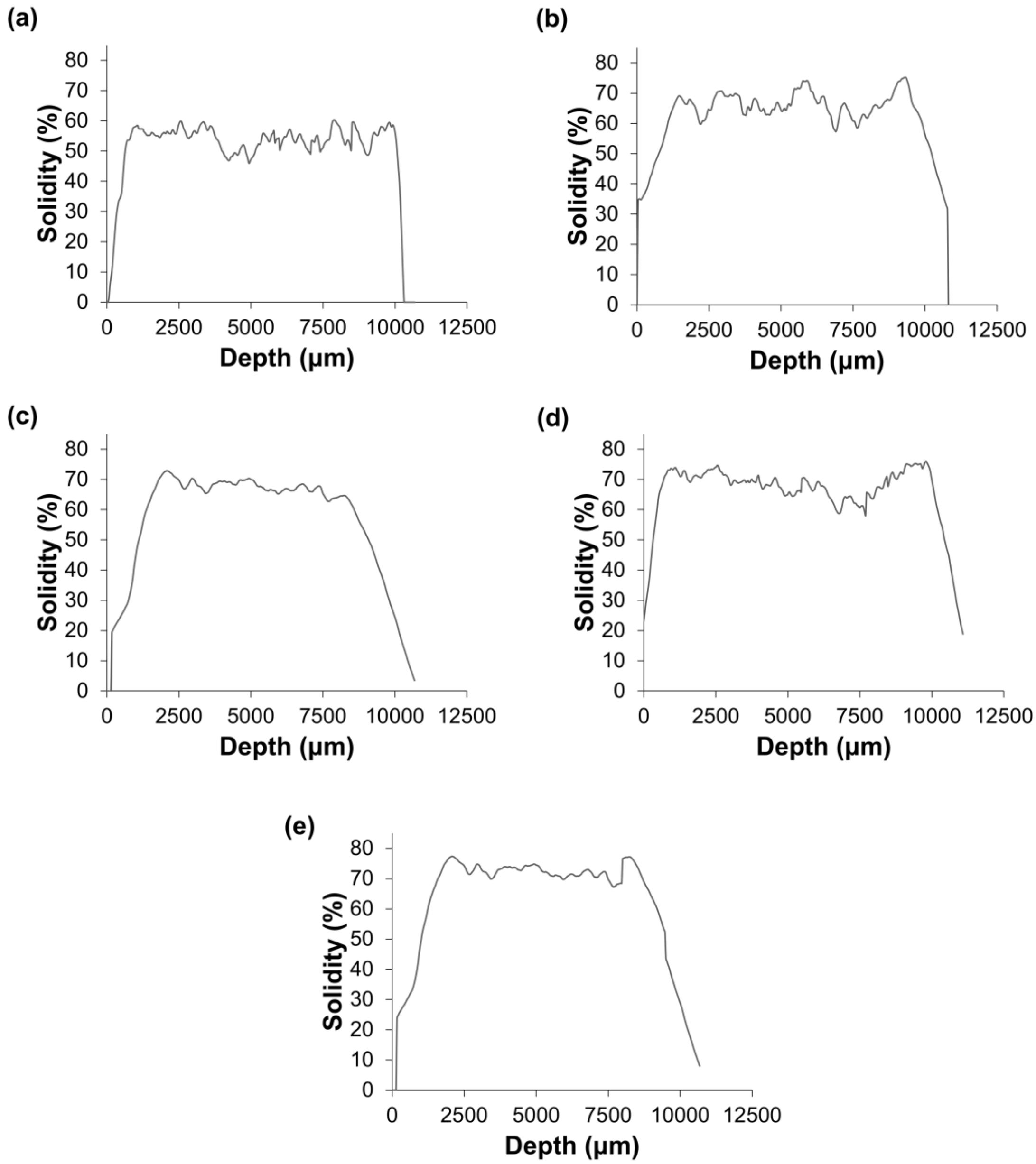

Fig. 3. Solidity profiles of the DSBOSBs by density: (a) 0.60 g/cm^3 (b) 0.65 g/cm^3; (c) 0.70 g/cm^3; (d) 0.75 g/cm^3; and (e) 0.80 g/cm^3

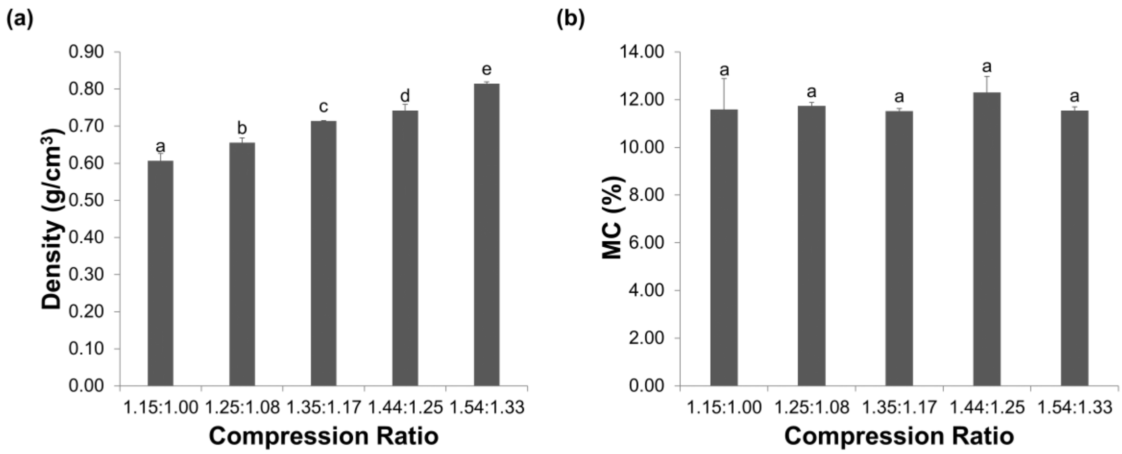

Fig. 4. Density (a) and MC (b) of the DSBOSBs manufactured under various compression ratios. Different letters designate a significant difference level of $p < 0.05$ according to Duncan multiple range test and ANOVA.

The water absorption value ranged between 39% and 44% (Fig. 5a). The lowest WA value was found in the DSBOSB with a compression ratio of 1.15 to 1.00, while the highest value was found in the board with a compression ratio of 1.54 to 1.33. There were significant differences in the WA values among DSBOSBs with different compression ratios.

The TS values ranged between 5.53% and 9.68% (Fig. 5b). The lowest TS value was observed in the board with a compression ratio of 1.15 to 1.00, while the highest value was found in the board with a compression ratio of 1.54 to 1.33. All the DSBOSBs manufactured in this study met the OSB commercial standard CSA 0437 (Grade O-1) (2011), which requires a TS value of less than 15% (Structural Board Association 2005). There were significant differences in the TS values of the DSBOSBs with different compression ratios.

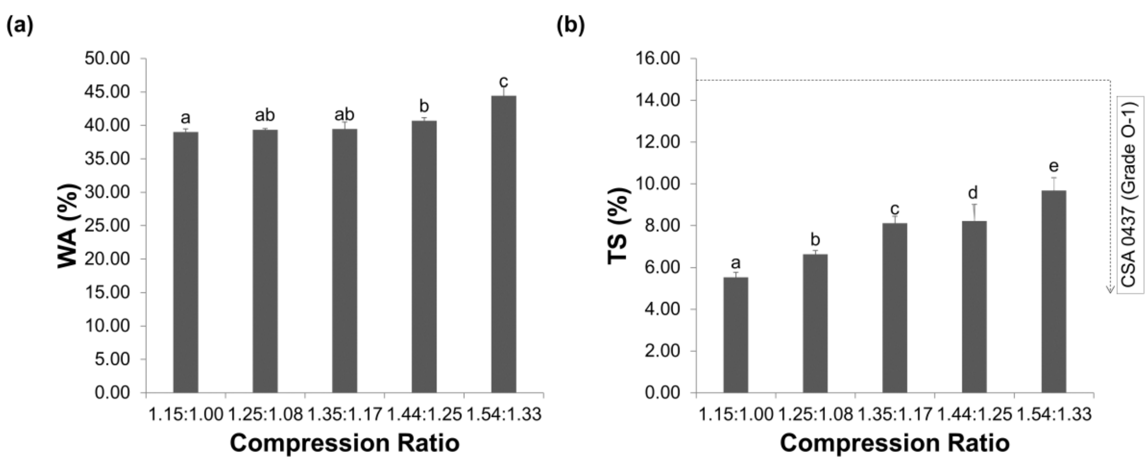

Fig. 5. The water absorption (WA) (a) and thickness swelling (TS) (b) of the DSBOSBs manufactured under various compression ratios. Different letters designate a significant difference level of $p < 0.05$ according to Duncan multiple range test and ANOVA.

In this study, the manufactured DSBOSBs showed excellent dimensional stability and met the OSB commercial standards for dimensional stability parameters. However, under the same preparation conditions in terms of density, resin content, and shelling ratio, the dimensional stability of the DSBOSBs was lower than that of the BOSBs from a single bamboo strand type (26.8% in WA and 2.8% in TS) (Maulana *et al*. 2019b). These differences might be attributed to discrepancies in the anatomical structure and extractive content of the bamboo materials. *G. pseudoarundinacea* has type III vascular bundles (Maulana *et al.* 2021), whereas *D. asper* has type IV vascular bundles (Febrianto *et al.* 2017). In addition, *G. pseudoarundinacea* had a higher 1% NaOH soluble extractive value than *D. asper* (22.57% and 19.42%, respectively) (Maulana *et al*. 2017).

The magnitude of shrinkage and swelling increases as the density of a woody material increases (Schulgasser and Witztum 2015). Therefore, the DSBOSBs with a higher compression ratio showed higher densities and lower dimensional stability, owing to the increased density. This phenomenon corresponded with previous reports stating that the TS value increases as the compression ratio of the boards increases (Gatchell *et al.* 1966; Halligan and Schniewind 1972; Hse 1975).

Figure 5a shows that the WA of DSBOSBs increased slightly as the compression ratio increased. The phenomenon was in line with the research of Xu *et al.* (1996), who reported that the surface layer of the OSB panel, which had a higher density, had a higher WA. In addition, Chung and Wang (2019) reported that the WA of biocomposite product with a compression ratio of 1.89 had a WA value of 42.57%, while the composite with a compression ratio of 1.68 was 41.8%. Xu *et al.* (1996) stated that more water was taken up in the high-density regions because more wood material was available in these regions.

Mechanical Properties of the Dual-species Bamboo-Oriented Strand Boards (DSBOSB)

Figure 6 shows the modulus of elasticity (MOE) values of the DSBOSBs in parallel and perpendicular directions to the grain. The MOE values parallel to the grain met the requirements of OSB commercial standard CSA 0437 (Grade O-1) (2011), except for the DSBOSBs with compression ratios of 1.15 to 1.00 and 1.25 to 1.08. The MOE values in the perpendicular direction met the requirements of the same standard, except the DSBOSBs with a compression ratio of 1.15 to 1.00.

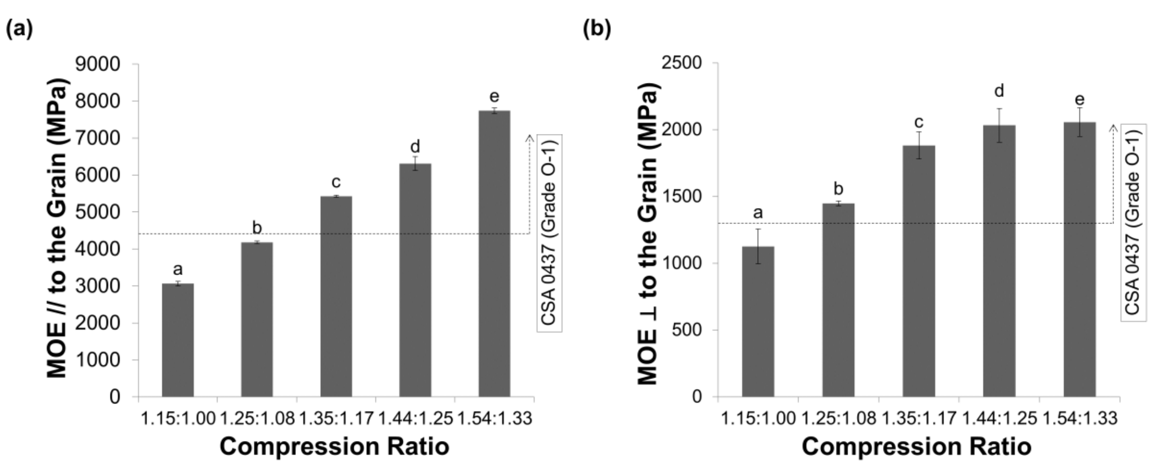

Fig. 6. The modulus of elasticity parallel (a) and perpendicular (b) to the grain of the DSBOSBs manufactured under various compression ratios. Different letters designate a significant difference level of $p < 0.05$ according to Duncan multiple range test and ANOVA.

The modulus of rupture (MOR) values of the DSBOSBs were 15 MPa to 43 MPa and 10 MPa to 18 MPa in parallel and perpendicular directions to the grain, respectively (Fig. 7). The MOR values perpendicular to the grain of all manufactured DSBOSBs met the requirements of the OSB commercial standard CSA 0437 (Grade O-1) (2011), which required a minimum of 9.41 MPa. However, for the MOR values parallel to the grain, only the DSBOSBs with compression ratios of 1.35 to 1.17, 1.44 to 1.25, and 1.54 to 1.33 met the requirements (a minimum MOR of 22.95 MPa). There were significant differences in the MOE and MOR values of the DSBOSBs in both parallel and perpendicular directions to the grain among the compression ratios. The highest MOE and MOR values were observed in the DSBOSBs with a compression ratio of 1.54 to 1.33. In contrast, the lowest values were observed in the DSBOSBs with a compression ratio of 1.15 to 1.00 in both parallel and perpendicular directions to the grain.

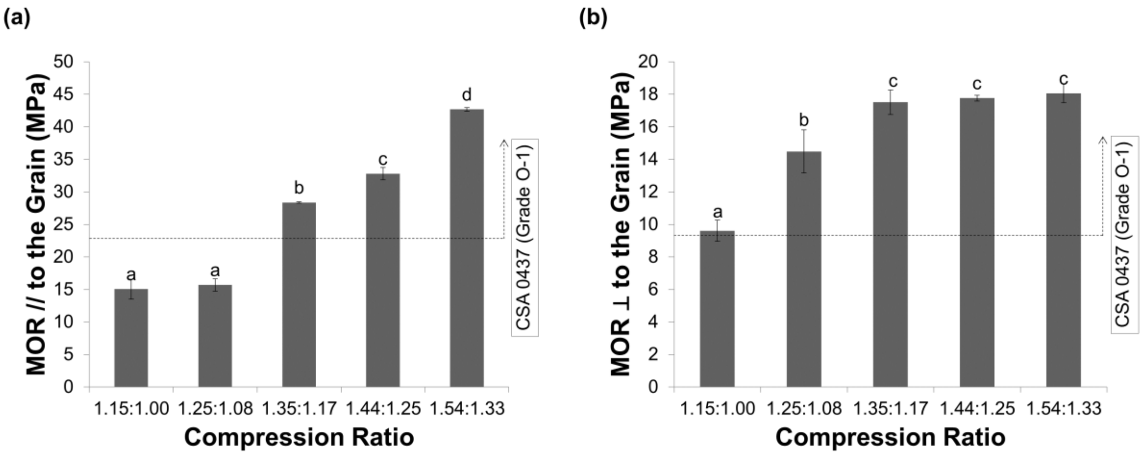

Fig. 7. The modulus of rupture parallel (a) and perpendicular (b) to the grain of the DSBOSBs manufactured under various compression ratios. Different letters designate a significant difference level of $p < 0.05$ according to Duncan multiple range test and ANOVA.

Similar to the dimensional stability, the MOE and MOR values of the manufactured DSBOSBs were lower than those of the BOSBs manufactured from the strands of a single bamboo species with identical preparation conditions in terms of density, resin content, and shelling ratio (Maulana *et al*. 2019b). The parallel and perpendicular MOE values of the BOSBs from *D. asper* were 6561 and 2188 MPa, respectively while the parallel and perpendicular MOR values were 29.28 and 19.30 MPa, respectively (Maulana *et al*. 2019b). The MOE and MOR values of the DSBOSBs with a compression ratio of 1.54 to 1.33 were higher than the MOE and MOR of the single BOSBs. These results might be attributed to the differences in the layer structure and density of the BOSBs.

Although the DSBOSBs and single BOSBs with different layer structures were prepared using the same method, the OSBs manufactured from homogeneous materials had steeper density profiles, *i.e.*, a higher density at the surface layer and a lower density at the core layer (Febrianto *et al*. 2010). Chen *et al*. (2010) also reported that OSBs with steeper density profiles resulted in higher MOE and MOR values.

In this study, there was an increase in the MOR values as the compression ratio increased. The higher the compression ratio of the DSBOSBs, the higher the density. Sumardi *et al*. (2007) reported that the bending strength of the BOSBs manufactured from *Phyllostachys pubescens* increased as the compression ratio increases. In a study on wood

OSBs, high compression ratios also produced high mechanical properties (Vital *et al*. 1974; Hiziroglu 2009; Jin *et al*. 2009; Chen *et al*. 2010).

The internal bonding (IB) values of the DSBOSBs ranged from 0.30 MPa to 0.36 MPa (Fig. 8). The DSBOSBs with compression ratios of 1.44 to 1.25 and 1.54 to 1.33 met the requirements of the OSB commercial standard CSA 0437 (Grade O-1) (2011), which requires an IB of at least 0.34 MPa.

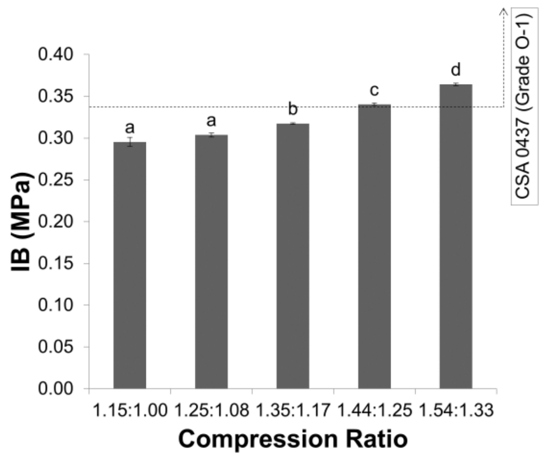

Fig. 8. Internal bond strength of the DSBOSBs manufactured under various compression ratios. Different letters designate a significant difference level of $p < 0.05$ according to Duncan multiple range test and ANOVA.

The results showed an increase in the IB value as the compression ratio increased. A higher compression ratio increased the board density, which was attributed to an increase in the IB value. Sumardi *et al*. (2007) reported similar results in the BOSBs manufactured from *Phyllostachys pubescens*, showing the increase in IB strength was due to an increase in the compression ratio. Chen *et al*. (2010) also reported that there was an increase in the IB value of OSBs manufactured from *Populus grandidentata* as the compression ratio increased. The increase in IB value due to an increased compression ratio not only occurred in OSB but also in a random strand board (Hiziroglu 2009; Jin *et al*. 2009).

In this study, the DSBOSBs with compression ratios of 1.44 to 1.25 and 1.54 to 1.33 met all the requirements of the commercial OSB standard CSA 0437 (Grade O-1) (2011). The increase in the compression ratio resulted in a more compact board but required more raw materials. These results suggest that DSBOSBs using phenol formaldehyde resin are suitable for commercial purposes.

CONCLUSIONS

1. The solidity profiles (thickness) of the dual-species bamboo oriented strand boards (DSBOSBs) with different densities were relatively uniform among the layers.
2. Increasing the compression ratio in the manufactured DSBOSBs improved all the mechanical properties, *i.e.*, the MOE, MOR, and IB values, in contrast with the dimensional stability, *i.e.*, the WA and TS of 24 h immersion in water.
3. The DSBOSBs with compression ratios of 1.44 to 1.25 and 1.54 to 1.33 met all the requirements of the commercial OSB standard CSA 0437 (Grade O-1) and the optimum compression ratio for the preparation of DSBOSBs was 1.44 to 1.25.

4. In conclusion, the DSBOSBs from *G. pseudoarundinacea* and *D. asper* strand for each layer using phenol formaldehyde resin were successfully prepared and might be applied for the commercial utilization.

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