Properties of Oriented Strand Board from Alkali-washed Bamboo Strands after Steam Treatment

Muhammad Iqbal Maulana,[a] Rio Ardiansyah Murda,[a] Byantara Darsan Purusatama,[b] Rita Kartika Sari,[a] Deded Sarip Nawawi,[a] Siti Nikmatin,[c,d] Wahyu Hidayat,[e] Seung Hwan Lee,[b] Fauzi Febrianto,[a,]* and Nam Hun Kim [b,]*

Effects of alkali washing were determined after steam treatment of Betung bamboo strands relative to the properties of the bamboo oriented strand boards (BOSBs). The strands were subjected to steam treatment at 126 °C for 1 h under 0.14 MPa of pressure, followed by washing with sodium hydroxide solution at concentrations ranging from 1% to 5% for 30 s. Three-layer BOSBs were manufactured with a target density of approximately 0.7 g/cm^3 using 8% phenol formaldehyde resin with the addition of 1% wax. The shelling ratio of the BOSBs was set to be 1:1:1. The physical and mechanical properties increased significantly with the alkali washing treatment at concentrations from 1% to 3%, and the greatest properties were obtained by washing at 3% alkali concentration. However, the washing treatment at concentrations of 4% and 5% reduced the physical and mechanical properties of the BOSBs.

Keywords: Alkali washing; Betung bamboo; Oriented strand board; NaOH concentration; Steam modification

*Contact information: a: Department of Forest Products, Faculty of Forestry and Environment, IPB University (Bogor Agricultural University), Bogor, Indonesia; b: Department of Forest Biomaterials Engineering, College of Forest and Environmental Science, Kangwon National University, Chuncheon 24341, Republic of Korea; c: Department of Physics, Faculty of Mathematics and Natural Sciences, IPB University (Bogor Agricultural University), Bogor, Indonesia; d: Surfactant and Bioenergy Research Center, IPB University (Bogor Agricultural University), Bogor, Indonesia; e: Department of Forestry, Faculty of Agriculture, Lampung University, Jalan Sumantri Brojonegoro 1, Bandar Lampung 35145, Indonesia; *Corresponding authors: febrianto76@yahoo.com; kimnh@kangwon.ac.kr*

INTRODUCTION

Bamboo is a potential alternative raw material for biocomposites owing to its rapid growth, abundant availability, widespread occurrence, and high tensile strength (Liese 1987). Because of its small diameter, tubular shape, and thin culm, the utilization of solid bamboo is limited, and it is more suitable as a raw material for the manufacture of composites. Recently, oriented strand boards (OSBs) from bamboo have been widely developed worldwide. In a previous study, the strength and quality of the OSBs from Betung bamboo satisfied the Grade O-2 criteria of the CSA 0437.0 (2011) standards (Adrin *et al*. 2013), and the properties tended to be better than those of the OSBs from wood (Iswanto *et al.* 2010; Febrianto *et al*. 2012, 2013, 2015).

In general, bamboo is rich in starch and other extractives, which may be responsible for the low dimensional stability and poor mechanical properties of bamboo oriented strand boards (BOSBs) (Febrianto *et al*. 2015). To improve the properties of BOSBs, pre-treatment of bamboo strands may be necessary to reduce the undesirable chemical components in the bamboo strands. Steam treatment is a potential pretreatment for removing these components (Rowell 2004). For example, steam treatment of Betung bamboo strands effectively reduced the content of extractives and improved the physical and mechanical properties of BOSBs (Febrianto *et al*. 2015; Maulana *et al*. 2016, 2017); however, some of the extractive substances were deposited and accumulated on the surfaces of the bamboo strands after the steam treatment. This undesirable phenomenon can affect the bonding process by inhibiting the penetration of adhesives into the bamboo strands (Pizzi 1983).

The quality of adhesion is a determining factor influencing the properties of OSBs. The removal of inhibiting substances from the surfaces of bamboo strands may facilitate a better bonding process to produce superior properties in BOSBs. Fatrawana *et al*. (2019) reported that the steam process followed by alkali washing with 1% NaOH reduced the content of extractives in Betung bamboo strands and improved the physical and mechanical properties of the BOSBs. The polymer structure of the cellulose is swollen by alkaline solutions even at room temperature conditions (Zhang *et al.* 2013). Hydroxyl ions from alkaline solutions are believed to cause cellulose to swell, disrupt the hydrogen bonds of cellulose with other polysaccharides, and hydrolyze the esters linked to the polysaccharide (Bergmans *et al.* 1996). Thus, the starch component of bamboo could be removed effectively in alkali treatment. Higher alkaline concentration results in a higher decrease in the amount of sugar (Chen *et al.* 2016). In addition, alkali washing treatment, even over a short period with 1% NaOH solution, increased the pH of the bamboo strands, which can improve the bonding quality of BOSBs with alkaline-curing adhesives such as phenol formaldehyde (Maulana *et al*. 2018; Murda *et al*. 2018). It is suggested that washing with an NaOH solution after steam treatment could be a promising solution to enhance the bonding properties of BOSBs. Therefore, this study was conducted to investigate the effect of alkali washing after steam treatment on the properties of BOSBs in relation to the changes in the chemical components in the steamed bamboo strands.

EXPERIMENTAL

Materials

Four-year-old Betung bamboo (*Dendrocalamus asper*) culms were harvested from the Sukabumi district, West Java, Indonesia. Bamboo strands were prepared from the internode without the outer bamboo skin and node. Phenol formaldehyde as the adhesive and paraffin additive as a wax were used.

Strand Treatment

Steam treatment for the bamboo strands was applied in an autoclave at 126 °C for 1 h under a pressure of 0.14 MPa, followed by the alkali washing treatment with NaOH solution at concentrations of 1%, 2%, 3%, 4%, and 5% for 30 s. Steam-treated samples without washing (0%) were also prepared as a control. The treated bamboo strands were allowed to air dried and then oven dried for 36 h to obtain a moisture content of less than 5%.

Preparation of BOSBs

Bamboo oriented strand boards with dimensions of 30 cm (length) × 30 cm (width) × 1 cm (thickness) were manufactured with a target density of 0.7 g/cm^3. Phenol formaldehyde resin with a solids content of 42% and a resin content of 8% was used as a binder. An addition of 1% wax was performed to increase the dimensional stability of the boards. The mats, with a shelling ratio of 1:1:1, were hot-pressed under a specific pressure of 2.45 MPa at 135 °C for 10 min.

Evaluation of Board Properties

Evaluation of the physical and mechanical properties of the BOSBs was conducted in accordance with the JIS A 5908 (2003) standards. Board samples were conditioned at 25 to 30 °C and 60% to 65% relative humidity for 2 weeks prior to the testing. The physical properties evaluated included density, moisture content, water absorption (WA), and thickness swelling (TS). The mechanical properties examined were modulus of elasticity (MOE), modulus of rupture (MOR), and internal bonding (IB). Each value was obtained from four replications. All parameters measured were compared to those of the CSA 0437.0 (2011) (Grade O-2) standard for OSB panels (SBA 2005).

Data Analysis

The experiment was a completely randomized design with one factor: NaOH concentration of six levels. Analysis of variance (ANOVA) was used for the statistical analysis of the data obtained. Duncan's multiple range test was performed to determine significant differences among variables.

RESULTS AND DISCUSSION

Strand Geometry

Table 1 shows the geometric characteristics of the Betung bamboo strands used in this study. The strands were considered as having a good geometry for manufacturing OSBs based on the slenderness ratio and aspect ratio values. Oriented strand boards made from strands with slenderness ratio values ranging from 60 to 100 have good physical and mechanical properties (Febrianto *et al*. 2015). A high value for the slenderness ratio ensures good contact between the strands, producing a strong board (Maloney 1993). In this study, the aspect ratio value of the strands matched the value of 3 required for good strands (Kuklewski *et al*. 1985).

Table 1. Geometric Characteristics of the Bamboo Strands

Parameter	Average
Length (cm)	7.0 (0.1)
Width (cm)	2.4 (0.2)
Thickness (cm)	0.1 (0.0)
Slenderness Ratio	105.8 (27.6)
Aspect Ratio	3.0 (0.2)

Note: the values in parentheses show the standard deviation.

Physical Properties

Board density is influenced by the amount of pressure applied, the number of particles in the mat, the adhesive content, and additives (Kelly 1977). In this study, the densities of the BOSBs ranged from 0.71 to 0.74 g/cm^3, depending on the treatment of the strands, which met the target density of 0.7 g/cm^3. According to Maloney (1993), a board with a density ranging from 0.59 to 0.80 g/cm^3 is categorized as a medium density board.

Analysis of variance showed that the steam and alkali washing treatments did not have significant effects on the board density.

As shown in Fig. 1, the moisture content of the BOSBs after conditioning ranged from 10.1% to 16.9%. The moisture content of the BOSBs increased with increasing concentration of the NaOH solution. Based on the ANOVA results, the different alkali concentrations had a very significant effect ($p < 0.01$) on the moisture content of the BOSBs. This increase in moisture content might be attributed to the removal of lignin on the surfaces of the bamboo strands after alkali washing with greater concentrations of NaOH. Maryanti *et al*. (2011) and Maulana *et al*. (2020) reported that a high concentration of NaOH causes the removal of lignin from the surfaces of bamboo strands.

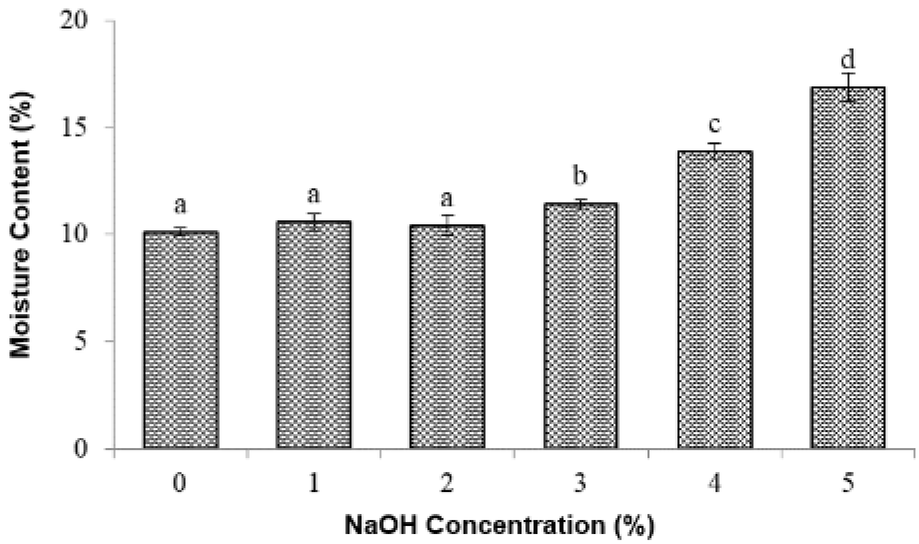

Fig. 1. Effect of NaOH concentration in the alkali washing treatment after steam treatment on the moisture content of the BOSBs. Different letters show significant differences between treatments according to Duncan's multiple range test at a confidence interval of 5%. Error bars show standard deviations.

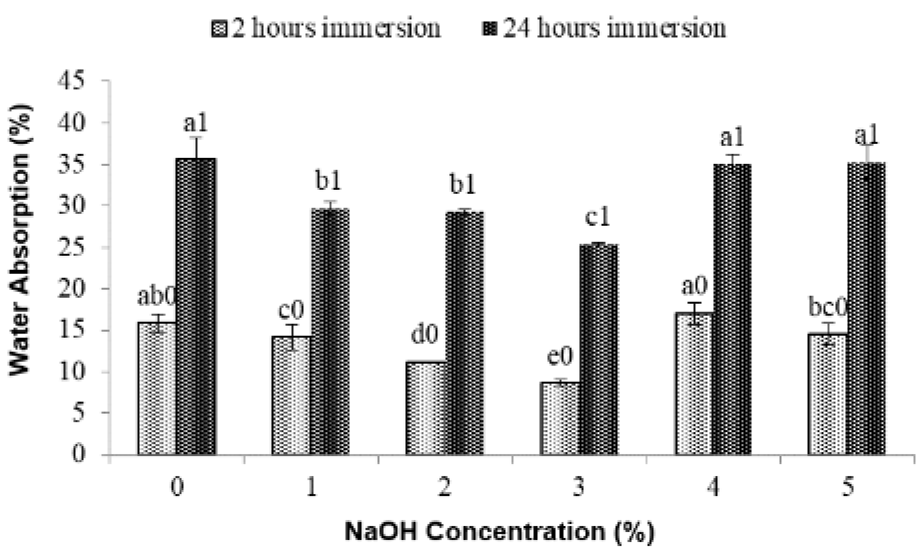

Fig. 2. Effect of NaOH concentration in the alkali washing treatment after steam treatment on the WA capacity of the BOSBs

The WA values of the BOSBs after immersion in water for 2 and 24 h were 8.6% to 17.0% and 25.4% to 35.7%, respectively, as shown in Fig. 2. The alkali washing with 1% to 3% NaOH decreased the WA of the BOSBs, whereas the WA values after washing with 4% and 5% NaOH solutions were similar to those without alkali washing treatment. The results of the ANOVA ($\alpha = 0.05$) showed that alkali washing at various NaOH concentrations had a significant effect on the WA value.

The TS values of the BOSBs after immersion in water for 2 h and 24 h were 1.1% to 1.9% and 3.2% to 6.8%, respectively, as shown in Fig. 3. Smaller TS values indicate greater dimensional stability in the boards. All TS values of the BOSBs satisfied the requirement of the CSA 0437.0 (2011) standards (Grade O-2), which is a maximum of 15% TS (SBA 2005). The results of the ANOVA ($\alpha = 0.05$) showed that the alkali washing treatment had a significant effect ($p < 0.05$) on the TS value of the BOSB. The positive effect of a decrease in the TS value of BOSBs was observed for the washing treatments with concentrations of 1% to 3% NaOH. However, the negative effect of increasing TS values was observed for the BOSBs washed with 4% and 5% NaOH solutions.

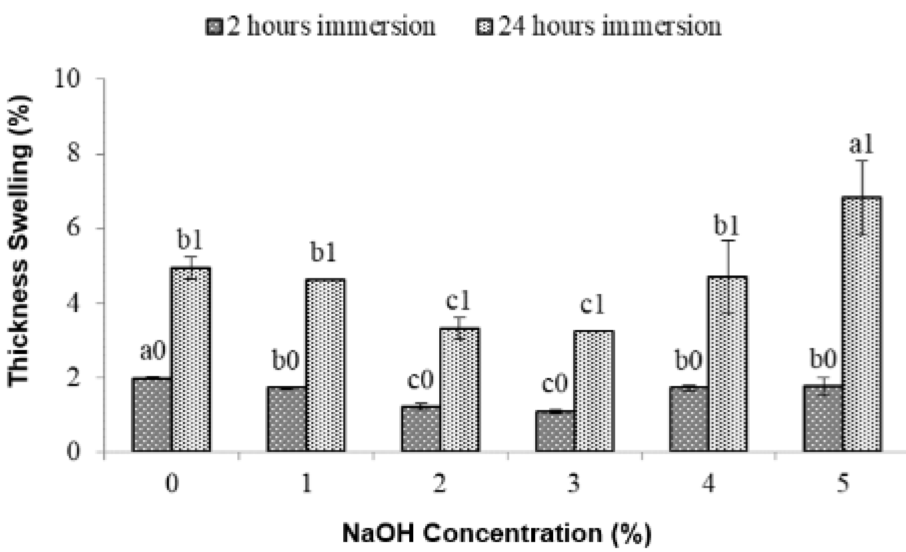

Fig. 3. Effect of NaOH concentration in the alkali washing treatment after steam treatment on TS of the BOSBs

The changes in WA and TS may be attributed to the chemical properties of the bamboo strands. Maulana *et al*. (2020) reported that bamboo strands treated with greater NaOH concentrations were lower in hemicellulose and lignin. The changes in the WA and TS values could be attributed to this factor (Fatrawana *et al*. 2019). Hemicellulose removal mainly caused the lower WA and TS up to 3% alkali concentration washing treatment. However, the greater WA and TS values of the BOSBs after alkali washing with NaOH at concentrations of 4% and 5% may be caused by the removal of hydrophobic components such as lignin (Cao *et al*. 2017).

Mechanical Properties

As shown in Fig. 4, the MOE values of the BOSBs with parallel- and perpendicular-to-face orientations were 1696 to 8511 MPa and 367 to 1633 MPa, respectively. The MOE values of both the parallel and perpendicular orientations increased with increasing alkali concentration but they decreased drastically when washed with the 4% NaOH solution. The results of the ANOVA ($\alpha = 0.05$) showed a very significant effect ($p < 0.01$) on the MOE values for both the parallel- and perpendicular-to-face orientations. The minimum MOE values of parallel and perpendicular boards permitted by the CSA 0437.0 (2011) standard (Grade O-2) are 5500 and 1500 MPa, respectively (SBA 2005). Therefore, the BOSBs washed with up to 3% NaOH solution satisfied this standard.

As shown in Fig. 5, the MOR values of the BOSBs with parallel- and perpendicular-to-face orientations were 32.4 to 62.3 MPa and 11.4 to 41.0 MPa, respectively. The MOR values of all the BOSBs met the CSA 0437.0 (2011) standard for Grade O-2 (SBA 2005). The results of the ANOVA ($\alpha = 0.05$) showed a very significant effect ($p < 0.01$) on the MOR for both the parallel- and perpendicular-to-face orientations of the BOSBs.

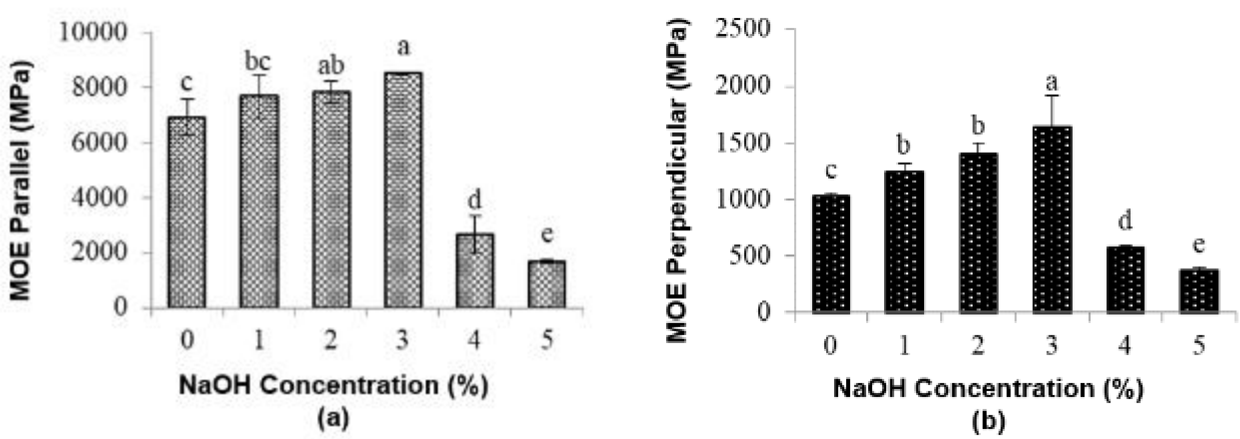

Fig. 4. Effect of NaOH concentration in alkali washing after steam treatment on the modulus of elasticity (MOE) values of (a) parallel- and (b) perpendicular-to-face orientations of the BOSBs

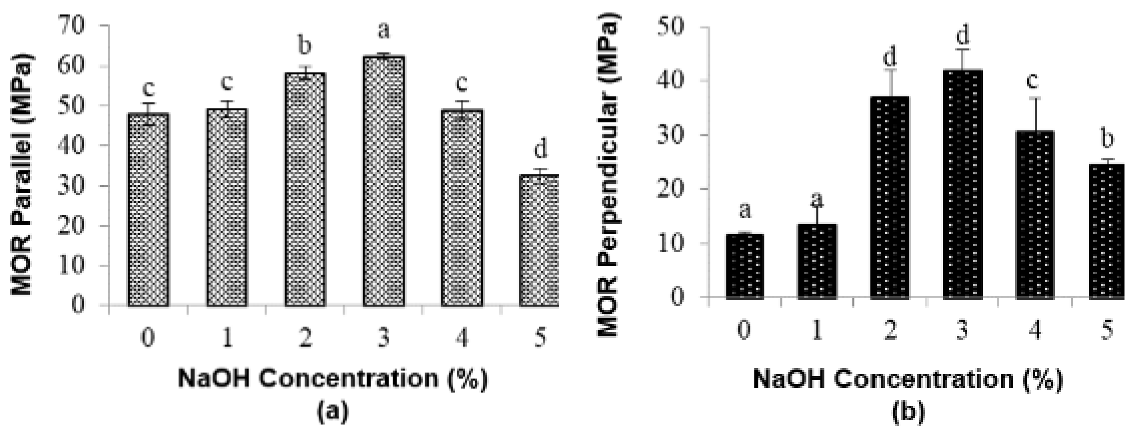

Fig. 5. Effect of NaOH concentration in alkali washing after steam treatment on the modulus of rupture (MOR) values of (a) parallel- and (b) perpendicular-to-face orientations of the BOSBs

The IB values of the BOSBs ranged from 0.03 to 0.49 MPa, as shown in Fig. 6. According to the CSA 0437.0 (2011) standard, the minimum IB value of OSBs for Grade O-2 is 0.345 MPa (SBA 2005). The IB values of the BOSBs increased with increasing alkali concentration until treatment with the 3% NaOH solution and surpassed the standard.

However, the IB values after alkali washing with NaOH solutions at concentrations of 4% or greater were very small. The ANOVA results showed that the alkali washing with 0% to 5% NaOH solutions had a significant effect ($p < 0.05$) on the IB values of the BOSBs.

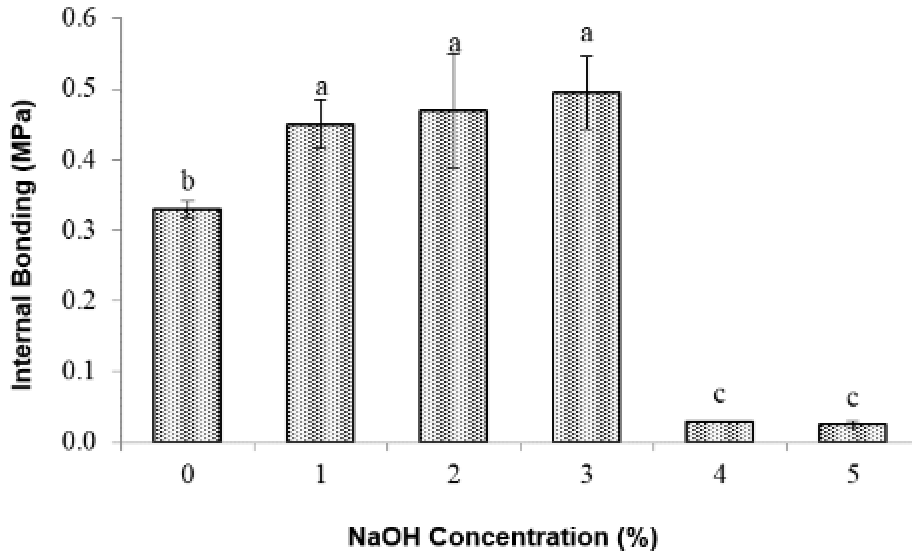

Fig. 6. Effect of NaOH concentration in the alkali washing treatment after steam treatment on the IB values of the BOSBs

In this study, the washing treatment with NaOH solutions of 1% to 3% increased the MOE, MOR, and IB values of the BOSBs. As reported previously (Maulana *et al*. 2020), washing treatments with higher NaOH solutions increase the pH value of the bamboo strands. The increased pH value of wood could increase pH value of phenol formaldehyde/wood curing system and lead to a decrease of the activation energy of phenol formaldehyde cure (He and Riedl 2004). Higher amounts of alkali also can decrease the gel time of phenol formaldehyde resin (Gardner and Eldner 1998). The removal of extractable substances and an appropriate pH condition for resin curing might be supported by the good bonding quality in OSB manufacturing. Pizzi and Stephanou (1993) reported that the phenol formaldehyde adhesive curing process at a pH greater than 9 was effective for these materials. A good curing process could lead to better IB and bending properties. In addition, the increased crystallinity of bamboo strands owing to alkaline treatment may contribute to the increase in board strength, including the MOE and MOR. The relative crystallinity and crystalline width in the Betung bamboo strands increased slightly with the treatment of steam and alkali washing with NaOH solutions of 1% to 3%, whereas washing with NaOH solutions of 4% and 5% tended to decrease the crystalline properties (Maulana *et al*. 2020). Higher crystallinity in the bamboo strands could improve the MOE and MOR values of the BOSBs. Furthermore, alkali washing at high concentrations may lead to the degradation of lignin and hemicellulose (Maulana *et al*. 2020). Such degradation can be a cause of the decreased OSB strength at high alkali concentrations. Moreover, the IB value is influenced by the surface conditions of the strands. The degraded products after stream treatment on the strand surfaces were reduced by the alkali washing treatment, resulting in smooth and clean surfaces (Maulana *et al*. 2020).

CONCLUSIONS

1. Alkali washing of the steam-treated bamboo strands significantly improved the physical and mechanical properties of the bamboo oriented strand boards (BOSBs), and the optimal concentration of NaOH solution was 3%.
2. The water absorption (WA) and thickness swelling (TS) values of the BOSBs decreased, and the modulus of elasticity (MOE), modulus of rupture (MOR), and internal bond (IB) values increased after alkali washing with NaOH solutions at concentrations of 1% to 3%.
3. The BOSBs manufactured from the bamboo strands treated with 3% NaOH solution surpassed the CSA 0437.0 (2011) (Grade O-2) standard for OSB panels.
4. An excessive use of NaOH could produce lower dimensional stability and poor mechanical properties.

ACKNOWLEDGMENTS

The authors sincerely acknowledge the Doctoral Programme for Outstanding Undergraduate Students (PMDSU) Research Grant (No. 4122/IT3.L1/PN/2020) and the Applied Research (PT) Grant (No. 4168/ IT3.L1/PN/2020 Pengembangan Hibrida Oriented Strand Board Baru dari Bambu dan Kayu Cepat Tumbuh Unggul untuk Bahan Konstruksi) from the Directorate of Higher Education (DIKTI), Ministry of Research, Technology, and Higher Education, Republic of Indonesia, for the financial support. This study was also supported by the Science and Technology Support Program through the National Research Foundation of Korea (NRF), funded by the Ministry of Science and ICT (MSIT) (NRF-2019K1A3A9A01000018), and the Basic Science Research Program through the NRF, funded by the Ministry of Education (No.2016R1D1A1B01008339 and No.2018R1A6A1A03025582). This study was also supported by 2018 Research Grant (PoINT) from Kangwon National University.

REFERENCES CITED

Adrin, Febrianto, F., and Sadiyo, S. (2013). "Properties of oriented strand board prepared from steam treated bamboo strands under various adhesive combinations," *Journal of Tropical Wood Science and Technology* 11(2), 109-119.

Bergmans, M. E. F., Beldman, G., Gruppen, H., and Voragen, A. G. J. (1996). "Optimisation of the selective extraction of (glucurono) arabinoxylans from wheat bran: use of barium and calcium hydroxide solution at elevated temperatures," *Journal of Cereal Science* 23(3), 235-245.

Cao, Y., Song, W., Yang, Z., Chen, Z., and Zhang, S. (2017). "The properties of particleboard made from alkaline-treated wheat straw and methylene diphenyl diisocyanate binder," *BioResources* 12(2), 3265-3276. DOI: 10.15376/biores.12.2.3265-3276

Chen, J. H., Xu, J. K., Huang, P. L., and Sun, R. C. (2016). "Effect of alkaline pretreatment on the preparation of regenerated lignocellulose fibers from bamboo

stem," *Cellulose* 23(4), 2727-2739.
CSA 0437 (2011). "Standards on OSB and waferboard," Canadian Standards Association, Toronto, Canada.
Fatrawana, A., Maulana, S., Nawawi, D. S., Sari, R. K., Hidayat, W., Park, S. H., Febrianto, F., Lee, S. H., and Kim, N. H. (2019). "Changes in chemical components of steam-treated Betung bamboo strands and their effects on the physical and mechanical properties of bamboo-oriented strand boards," *European Journal of Wood and Wood Products* 77(5), 731-739. DOI: 10.1007/s00107-019-01426-7
Febrianto, F., Jang, J.-H., Lee, S.-H., Santosa, I. A., Hidayat, W., Kwon, J.-H., and Kim, N.-H. (2015). "Effect of bamboo species and resin content on properties of oriented strand board prepared from steam-treated bamboo strands," *BioResources* 10(2), 2642-2655. DOI: 10.15376/biores.10.2.2642-2655
Febrianto, F., Purnamasari, I., Arinana, Gumilang, A., and Kim, N. H. (2013). "Steaming effect on natural durability of bamboo oriented strand board against termites and powder post beetle," *Journal of Tropical Wood Science and Technology* 11(2), 161-169.
Febrianto, F., Sahroni, Hidayat, W., Bakar, E. S., Kwon, G.-J., Kwon, J.-H., Hong, S.-I., and Kim, N.-H. (2012). "Properties of oriented strand board made from Betung bamboo (*Dendrocalamus asper* (Schultes.f) Backer ex Heyne)," *Wood Science and Technology* 46, 53-62. DOI: 10.1007/s00226-010-0385-8
Gardner, D. J., and Elder, T. J. (1998). "Surface activation treatment of wood and its effect on the gel time of phenol-formaldehyde resin," *Wood and Fiber Science* 20(3), 378-385.
He, G., and Riedl, B. (2004). "Curing kinetics of phenol formaldehyde resin and wood-resin interactions in the presence of wood substrates," *Wood Science and Technology*, 38(1), 69-81.
Iswanto, A. H., Febrianto, F., Wahyudi, I., Hwang, W. J., Lee, S. H., Kwon, J. H., Kwon, S. M., Kim, N. H., and Kondo, T. (2010). "Effect of pre-treatment techniques on physical, mechanical, and durability of oriented strand board made from sentang wood (*Melia excelsa*, Jack)," *J. Fac. Agric. Univ* 55(2), 371-377.
JIS A 5908 (2003). "Particleboards," Japanese Standards Association, Tokyo, Japan.
Kelly, M. W. (1977). *Critical Literature Review of Relationships between Processing Parameters and Physical Properties of Particleboard* (FPL-10), U. S. Department of Agriculture, Forest Products Laboratory, Madison, WI, USA.
Kuklewski, K. M., Blankenhorn, P. R., and Rishel, L. E. (1985). "Comparison of selected physical and mechanical properties of red maple (*Acer rubrum* L.) and aspen (*Populus grandidentata* Michx.) flakeboard," *Wood and Fiber Science* 17(1), 11-21.
Liese, W. (1987). "Research on bamboo," *Wood Science and Technology* 21(3), 189-209. DOI: 10.1007/BF00351391
Maloney, T. M. (1993). *Modern Particleboard & Dry-process Fiberboard Manufacturing*, Forest Products Society, Madison, WI, USA.
Maryanti, B., Sonief, A. A., and Wahyudi, S. (2011). "Pengaruh alkalisasi komposit serat kelapa-poliester terhadap kekuatan tarik [Effect of alkalization of coconut fiber-polyester composites on tensile strength]," *Jurnal Rekayasa Mesin* [*Journal of Mechanical Engineering*] 2(2), 123-129.
Maulana, M. I., Murda, R. A., Purusatama, B. D., Sari, R. K., Nawawi, D. S., Nikmatin, S., Hidayat, W., Lee, S. H., Febrianto, F., and Kim, N. H. (2020). "Effect of alkali-washing at different concentration on the chemical components of the steam treated

bamboo strands," *Journal of the Korean Wood Science and Technology* in press.
Maulana, M. I., Nawawi, D. S., Wistara, N. J., Sari, R. K., Nikmatin, S., Maulana, S., Park, S.-H., and Febrianto, F. (2018). "Change of chemical components content in Andong bamboo due to steam treatment," *Journal of Tropical Wood Science and Technology* 16(1), 83-92.
Maulana, S., Busyra, I., Fatrawana, A., Hidayat, W., Sari, R. K., Sumardi, I., Wistara, I. N. J., Lee, S. H., Kim, N. H., and Febrianto, F. (2017). "Effects of steam treatment on physical and mechanical properties of bamboo oriented strand board," *Journal of the Korean Wood Science and Technology* 45(6), 872-882. DOI: 10.5658/WOOD.2017.45.6.872
Maulana, S., Purusatama, B. D., Wistara, N. J., Sumardi, I., and Febrianto, F. (2016). "Effect of steam treatment on strand and shelling ratio on the physical and mechanical properties of bamboo oriented strand board," *Journal of Tropical Wood Science and Technology* 14(2), 136-143.
Murda, R. A., Nawawi, D. S., Maulana, S., Maulana, M. I., Park, S.-H., and Febrianto, F. (2018). "Chemical components changed in three bamboo species treated by steaming and washing processes," *Journal of Tropical Wood Science and Technology* 16(2), 102-114.
Pizzi, A. (ed.) (1983). *Wood Adhesives: Chemistry and Technology*, Marcel Dekker, New York, NY, USA.
Pizzi, A., and Stephanou, A. (1993). "On the chemistry, behavior, and cure acceleration of phenol-formaldehyde resins under very alkaline conditions," *Journal of Applied Polymer Science* 49(12), 2157-2170. DOI: 10.1002/app.1993.070491212
Rowell, R. M. (2004). "Chemical modification," in: *Encyclopedia of Forest Sciences*, J. Burley, J. Evans, and J. A. Youngquist (eds.), Elsevier, Oxford, UK, pp. 1269-1274. DOI: 10.1016/B0-12-145160-7/00053-3
SBA (2005). *OSB Performance by Design: Oriented Strand Board in Wood Frame Construction* (TM420), Structural Board Association, Ontario, Canada.
Zhang, S., Wang, W. C., Li, F. X., and Yu, J. Y. (2013). "Swelling and dissolution of cellulose in NaOH aqueous solvent systems," *Cellulose chemistry and technology*. 47(9-10), 671-679.

Article submitted: September 8, 2020; Peer review completed: October 4, 2020; Revised version received: December 8, 2020; Accepted: December 1, 2020; Published: December 16, 2020.
DOI: 10.15376/biores.16.1.987-996