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Changes in chemical components of steam-treated betung bamboo strands and their effects on the physical and mechanical properties of bamboo-oriented strand boards

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Abstract

The purpose of this study was to analyze the chemical component change in betung bamboo (*Dendrocalamus asper* (Schult. & Schult. F.) Backer ex K. Heyne) strands after different steam and washing treatments, and their influence on the physical and mechanical properties of bamboo-oriented strand boards (BOSB). Strands were prepared with three different treatments: (1) steam-only, (2) steam followed by washing with distilled water, and (3) steam followed by washing with 1% sodium hydroxide solution. The steaming process was performed at 126 °C for 1 h at a pressure of 0.14 MPa. Chemical components such as holocellulose, alpha-cellulose, lignin, and starch were analyzed. Phenol formaldehyde resin was used to manufacture BOSB, and the physical and mechanical properties were evaluated in the final products. Steam treatments resulted in changes in chemical components that affected the physical and mechanical properties of BOSB. These changes were mainly caused by the degradation of hemicellulose and extractives dissolved in hot water or 1% sodium hydroxide. These treatments increased the bonding between strands, resulting in higher dimensional stability and strength of BOSB. Considering all the performed experiments, the steam treatment followed by washing with 1% sodium hydroxide was the best treatment for manufacturing BOSB.

1 Introduction

Bamboo is a promising renewable material for the substitution of wood due to its versatile characteristics, such as fast growing and short rotation cycle, high physical and mechanical properties, and ease of process. Indonesia has a high biodiversity of bamboo species. Previous studies showed that about 160 bamboo species grow in Indonesia (Dransfield and Widjaya 1995; Widjaya et al. 2004). Unfortunately, most of them are categorized as lesser-known or lesser-used species. Bamboo exhibits appropriate characteristics as raw material for many products. These characteristics are related to its vascular bundles, chemical components, and chemical behavior during processing and utilization. Naturally, chemical components of bamboo are similar to wood, which is composed of cellulose (33.8−52.01%), hemicellulose (24.5−33.4%), lignin (24.84−32.65%), and small amounts of extractives (Kamthai and Puthson 2005; Nugroho et al. 2013; Wahab et al. 2013). Therefore, bamboo is a potential biomaterial for many products as a substitute material for timber, such as bio-composite (Anokye et al. 2016; Luo et al. 2014; Sharma et al. 2015; Verma and Chariar 2012; Yamashiro and Nishida 2015; Zhang et al. 2017; Zhao et al. 2010), pulp and paper (Ashaari et al. 2010; Yuan et al. 2017), and biomass energy (Asada et al. 2002; Wang et al. 2011; Yuan et al. 2017).

Recently, bamboo has been promoted as raw material for oriented strand board (OSB) products (Adrin et al. 2013; Febrianto et al. 2012, 2015; Maulana et al. 2017). Oriented strand boards prepared from bamboo were found to have better mechanical properties than wood (Febrianto

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et al. 2009, 2010, 2012; Iswanto et al. 2010). However, despite some acceptable properties, bamboo OSB exhibits several undesirable characteristics, such as low durability (Febrianto et al. 2013). Bamboo is more susceptible to biodegradation agents than common wood. It was suggested that the high levels of extractable polysaccharides in bamboo are responsible for such unexpected properties. Within these extractable substances, bamboo contains high starch content (Ashaari et al. 2010; Santhoshkumar and Bhat 2014) and extractive substances dissolved in 1% sodium hydroxide solution (Kamthai and Puthson 2005; Nugroho et al. 2013). The high extractable polysaccharides content in bamboo, such as starch and part of the hemicellulose, may also affect the low dimensional stability of bamboo and its products. These amorphous polysaccharides contain high levels of hydroxyl groups, which contribute to the high hygroscopic property of bamboo.

In wood production, thermal treatments are used to increase dimensional stability and improve durability. Heat and steam treatments at temperatures of 160−280 °C change the properties of wood due to changes in the chemical components of wood, specifically the degradation of polysaccharides and extractives (Cao et al. 2012; Cheng et al. 2016; Esteves and Pereira 2009; Esteves et al. 2013; Kucerova et al. 2016). A similar phenomenon was found with the heat treatment of bamboo. Steam treatment at 150−200 °C improved the dimensional stability, but the mechanical properties decreased (Yamashiro and Nishida 2015; Zhang et al. 2017; Zhao et al. 2010). It seems that high temperatures may degrade the cell wall components to some extent. After heat treatment at about 200 °C for 3 h, cellulose contents slightly decrease and a more important decrease is seen in hemicellulose contents (Yamashiro and Nishida 2015; Zhao et al. 2010). Hence, it is necessary to develop new treatments to process bamboo at lower temperature.

It was reported that some physical and mechanical properties of bamboo oriented strand boards (BOSB) increased by steam treatment at 126 °C (Adrin et al. 2013; Febrianto et al. 2015; Maulana et al. 2017). However, it was noted that, during the steam treatment, extractable substances were spread out and deposited on the surface of the treated strands. Furthermore, the acidity of strands increased due to the degradation of hemicellulose and extractives during the steam treatment. These conditions may physically and chemically affect the bonding ability of BOSB. In the present study, betung bamboo (*Dendrocalamus asper*) strands were subjected to steam treatment and washed with distilled water and a 1% sodium hydroxide solution. Finally, the changes in chemical components, produced by the application of different steam treatments, and their effects on the physical and mechanical properties of BOSB were evaluated.

2 Materials and methods

2.1 Materials

Betung bamboo was obtained from a 3−4 years-old bamboo plantation in Sukabumi, West Java, Indonesia. Bamboo culms without the internodes and the bark were converted into strands using sharp knives and scissors. The target length, width, and thickness of the strands were 70, 25, and 0.5 mm, respectively.

2.2 Methods

2.2.1 Steam treatment

Strands were steamed in an autoclave at 126 °C for 1 h under a pressure of 0.14 MPa. After the steam treatment, the strands were subjected to three different treatments, namely steam only, steam followed by washing with distilled water or with 1% sodium hydroxide solution. The untreated strands were also sampled as a comparison for the test result. Finally, the strands were first dried in air for a week and then in an oven at 60–80 °C for 3 days until reaching a moisture content of less than 5%.

2.2.2 Determination of chemical components and crystallinity

The contents of the chemical components in the bamboo strands as holocellulose, α-cellulose, lignin, and extractives were determined before and after the treatments. Holocellulose and α-cellulose were determined according to the Browning methods (Browning 1967). Lignin contents, which were expressed as Klason lignin and acid soluble lignin, were measured according to TAPPI 222 om-88 (TAPPI 2002a) and TAPPI UM 250 (TAPPI 2000), respectively. Cold and hot water-soluble extractives, ethanol–benzene soluble extractives, and 1% NaOH soluble extractives were determined according to TAPPI T-207 om-88 (TAPPI 1999), ASTM D1107-96 (ASTM 2013), and TAPPI T-212 om-2 (TAPPI 2002b), respectively. Starch content was determined according to SNI 01 2891-1992 (BSN 1992) and pH was determined according to SNI 06-6989.11-2004 (BSN 2004). Samples were tested three times for each parameter.

X-ray diffractometer (RINT TTR III, Rigaku Co. Ltd., Japan) was used to measure the crystallinity using CuKα radiation ($K = 0.15418$ nm) for the conditions of $2\theta = 10°–40°$ at a 1°/min scanning speed. The crystallinity index and average crystallite size were calculated on the basis of the methods by Segal et al. (1959) and Monshi et al. (2012), respectively.

2.2.3 Preparation of bamboo-oriented strand boards (BOSB)

The manufacturing of bamboo-oriented strand boards was similar to the procedure described by Maulana et al. (2017). Phenol formaldehyde, with solid content of 42% and resin content of 8%, was used as a binder. An additional 1% of wax was applied. Three-layers BOSB of (300 × 300 × 9) mm^3 (length × width × thickness) were made using a face-to-core-to-back layer ratio of 1:1:1. The targeted density of the boards was 0.7 g cm^{-3}. Then, the strands were hot pressed at 135 °C under a specific pressure of 2.5 MPa. The resulting BOSB were conditioned for 2 weeks under room temperature (25−30 °C) until reaching a constant weight.

2.2.4 Determination of the physical and mechanical properties of BOSB

Physical and mechanical properties of BOSB were evaluated according to the JIS A 5908:2003 standard (JSA 2003). The examined parameters were: density, moisture content (MC), water absorption (WA), thickness swelling (TS), modulus of rupture (MOR) and elasticity (MOE) both parallel and perpendicular to grain, and internal bonding strength. Samples were tested three times for each parameter.

2.2.5 Data analysis procedure

The research design used in this study was a simple randomized design with one factor, namely treatment variation consisting of four levels, namely untreated, steam, steam followed by washing with distilled water and steam followed by washing with 1% sodium hydroxide solution. Test results were then analyzed using analysis of variance. If there was a significant influence, they were analyzed further using Duncan multiple range test.

3 Results and discussion

3.1 Chemical components

Steam treatments mainly degraded the extractives and hemicellulose in betung bamboo. However, lignin was almost stable, except for the case of steam treatment followed by washing with 1% sodium hydroxide (Table 1). It was observed that part of the extractable substances degraded during the steam treatment and deposited on the surface of the bamboo strands, then being removed by washing treatments.

The hemicellulose content (30.72%) of the untreated bamboo decreased to 28.18, 27.53, and 26.63% by steam, steam followed by washing with distilled water, and steam followed by washing with 1% sodium hydroxides solution, respectively. Statistical analyses showed that steam treatments had a significant influence on hemicellulose content. Furthermore, Duncan's multiple range tests showed that the hemicellulose content from untreated betung bamboo strands was significantly different from treated strands. The hemicellulose content from betung bamboo strands treated only with steam treatment and betung bamboo strands treated with steam followed by washing with 1% sodium hydroxide statistically showed significantly different results. The hemicellulose content from strands treated with steam followed by washing with distilled water and strand treated with steam followed by washing with 1% sodium hydroxide

Table 1 Changes in chemical components of betung bamboo by steam treatment

Chemical component	Treatments			
	Untreated	Steam	Steam+ distillate water	Steam+ 1% NaOH
Holocellulose (%)	70.73 ± 0.77[a]	67.74 ± 0.51[ab]	67.38 ± 1.05[b]	67.49 ± 0.03[b]
Hemicellulose (%)	30.72 ± 0.80[a]	28.18 ± 0.02[b]	27.53 ± 0.25[bc]	26.63 ± 0.26[c]
Alpha-cellulose (%)	40.01 ± 0.03[a]	39.56 ± 0.49[a]	39.85 ± 0.81[a]	40.86 ± 0.23[a]
Klason lignin (%)	27.35 ± 0.33[a]	26.80 ± 0.07[a]	26.88 ± 0.09[a]	23.23 ± 3.43[b]
Acid-soluble lignin (%)	1.43 ± 0.035[a]	1.36 ± 0.002[b]	1.38 ± 0.034[ab]	1.49 ± 0.050[c]
Solubility in				
Hot water (%)	9.87 ± 0.196[a]	9.73 ± 0.448[ab]	9.28 ± 0.003[bc]	8.87 ± 0.729[c]
Cold water (%)	7.75 ± 0.19	6.91 ± 0.22	6.83 ± 1.84	6.8 ± 0.82
1% NaOH (%)	23.84 ± 0.10[a]	22.82 ± 0.27[b]	22.06 ± 0.66[b]	18.47 ± 0.66[c]
Ethanol–benzene (%)	5.72 ± 0.44[a]	5.75 ± 0.23[a]	4.72 ± 0.13[b]	4.49 ± 0.58[b]
Starch content (%)	25.22[a]	23.29[b]	22.6[c]	21.61[d]
pH	5.63	5.81	6.08	7.61

Superscript lower-case letters show Duncan multiple range test result. Different letters show differences between treatments according to Duncan multiple range test at 5% confidence interval treatment had no significant difference. Hemicellulose is the first structural compound to be thermally affected by heat treatments, even at low temperatures (Esteves and Pereira 2009). Previous research by Kucerova et al. (2016) showed that hemicellulose started to degrade at 100 °C and the degradation linearly increased with temperature. The degradation started by deacetylation and acetic acid release, which acts as a depolymerization catalyst increasing polysaccharides decomposition (Nuopponen et al. 2005). Hemicellulose is less durable to thermal decomposition because of its low molecular weight and branching structure (Fengel and Wegener 1984). D-xylose was degraded first, which indicates that xylan is an easily degraded group of hemicellulose. Lower hemicellulose content implies less free hydroxyl groups that can bind water. Therefore, the decomposition of hemicellulose provides better dimensional stability since the hygroscopicity of hemicellulose is higher than that of cellulose and lignin (Rahman et al. 2012).

The starch content of betung bamboo strands ranged from 21.61 to 25.22% (Table 1). Betung bamboo strands treated with steam followed by washing with 1% sodium hydroxide had the lowest starch content, while untreated betung bamboo strands had the highest value. Statistical analyses showed that the treatments had significant influence on the reduction of starch content in betung bamboo strands.

Low-temperature steam treatments did not affect cellulose because of its crystallinity (Esteves and Pereira 2009). The cellulose content remained constant in all treatments, with its relative content in relation to hemicellulose increasing from 1.30 to 1.54. The α-cellulose may contribute to the tensile strength of bamboo. The relative crystallinity of cellulose would increase along with the degradation of its amorphous part, resulting in a decreased accessibility of hydroxyl groups to water molecules (Bhuiyan and Hirai 2005; Boonstra and Tjeerdsma 2006; Wikberg and Maunu 2004). Table 2 shows the relative crystallinity of betung bamboo under different steam treatments. The relative crystallinity of betung bamboo increased with steam treatments, with betung bamboo treated only with steam showing the highest relative crystallinity. Betung bamboo with steam treatment followed by water washing and 1% NaOH washing showed slightly lower relative crystallinity than betung bamboo with steam-only treatment.

Table 2 Relative crystallinity of betung bamboo by steam treatment

Samples	Relative crystallinity (%)	Crystalline width (nm)
Betung steam	75.0 ± 3.0	3.2 ± 0.1
Betung steam + water	74.4 ± 2.2	3.4 ± 0.1
Betung steam + 1% NaOH	73.3 ± 4.3	3.4 ± 0.1

Klason lignin content of the untreated sample was 27.35%, decreasing to 26.80% with the steam-only treatment (Table 1). The highest removal of lignin was recorded in the steam followed by washing with 1% sodium hydroxide treatment. This may be due to the delignification of low molecular weight lignin by alkali. The acid-soluble lignin was not significantly changed by all the treatments. The formation of acid-soluble lignin during lignin Klason procedure was affected by lignin monomer composition (Matsushita et al. 2004, Nawawi et al. 2016, 2017a, b). Therefore, it was suggested that the chemical structure of lignin polymer was not changed significantly due to low delignification process during treatments.

Steam treatment with or without washing produced significantly decreased hemicellulose content in bamboo strands. The most degraded chemical constituents of bamboo by steam treatment were extractives, especially low molecular weight substances which were dissolved in hot water and 1% sodium hydroxide solution. The hot water and 1% sodium hydroxide soluble extractives contents decreased, respectively, 1.42% and 4.28% with steam, 5.98% and 7.79% with steam followed by washing with distilled water, and 10.13% and 22.53% with steam followed by washing with 1% sodium hydroxide treatments. The extractable substances dissolved in hot water were mainly starch, low molecular sugar, tannin, and gum, while the 1% sodium hydroxide solution dissolved low molecular polysaccharides and lignin (Fengel and Wegener 1984). In the same trend, the starch content of bamboo strands decreased 7.65, 10.39, and 14.31% with steam, steam followed by washing with distilled water, and steam followed by washing with 1% sodium hydroxide treatments, respectively. Steam treatments removed part of the extractable chemical components and washing treatments with distilled water or 1% sodium hydroxide were successful for the complete removal of degraded materials from the bamboo strands.

The extractable substances from bamboo at high temperature can originate not only from extractives in nature but also from degraded cell wall components (Esteves and Pereira 2009). Extractives such as fats and wax were no longer detected above 180 °C (Nuopponen et al. 2003). Esteves et al. (2008) stated that most of the original extractives disappear from wood with heat treatment. Basically, extractives move to the surface during the steam treatments and are completely removed with the washing treatments. This was shown by the lower extractives content in the samples that received washing treatments than in the samples that were not washed. The existence of extractives can affect the quality of adhesion of the finished product (Maloney 1993). Less extractives content would provide better conditions for the adhesion process.

3.2 Physical and mechanical properties of bamboo-oriented strand boards

The effects of the treatments on the bonding quality were evaluated to investigate the physical and mechanical properties of BOSB. To avoid the effect of density on the properties of the boards, the target density of boards was set to about 0.7 g cm^{-3}. Generally, the obtained density of BOSB met the target density, ranging from 0.71 to 0.72 g cm^{-3} and with the density between boards not significantly different (Fig. 1). In air-drying conditions, the water holding capacity of boards was different for different treatments. Although statistical analyses of the moisture content of BOSB showed relatively homogenous values, BOSB of treated bamboo strands had lower MC than untreated bamboo samples (Fig. 1). This is probably due to the lower hydroxyl groups content and better bonding quality of treated bamboo. Steam and washing treatments probably removed part of the hemicellulose and extractable carbohydrates, leading to the decreased hygroscopic properties of treated bamboo. Hemicellulose and extractable carbohydrates may contain high levels of hydroxyl groups. The better bonding quality of boards made from treated bamboo may also contribute to lower levels of hydroxyl groups and MC.

The water holding capacity and better bonding quality of treated BOSB were also indicated by the WA and TS of BOSB. Both parameters represented the dimensional stability of BOSB with values in the range of 26.13–43.56% and 7.99–9.82% for WA and TS, respectively (Fig. 2). Statistical analyses showed that the applied treatments had significant influences on WA and TS values. The lowest WA and TS values were obtained for BOSBs manufactured from treated bamboo strands with steam followed by washing with 1% sodium hydroxide solution. According to Table 1, the removed part of hemicellulose and extractives contents from the strands during steaming and washing with 1% sodium

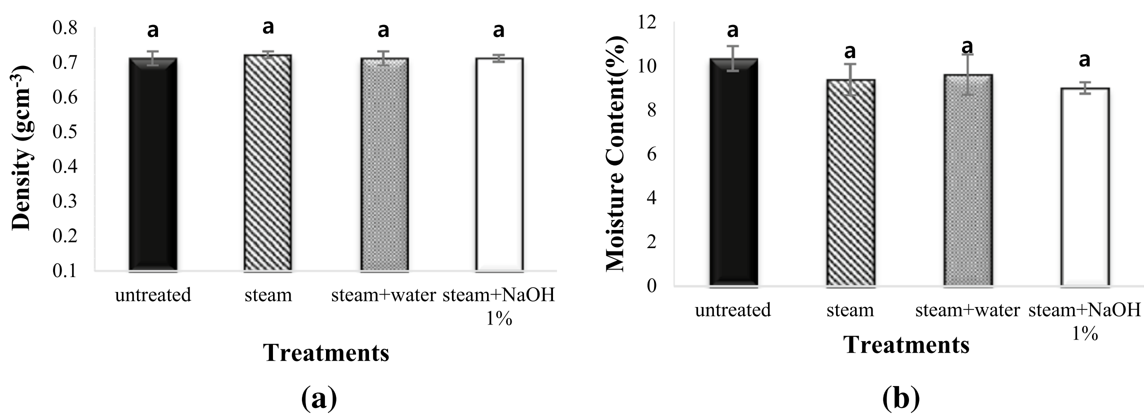

Fig. 1 Density (**a**) and moisture content (**b**) of BOSB under the different steam treatments. Different letters show significant differences between treatments according to Duncan multiple range test at 5% confidence interval; error bars show standard deviation of the data

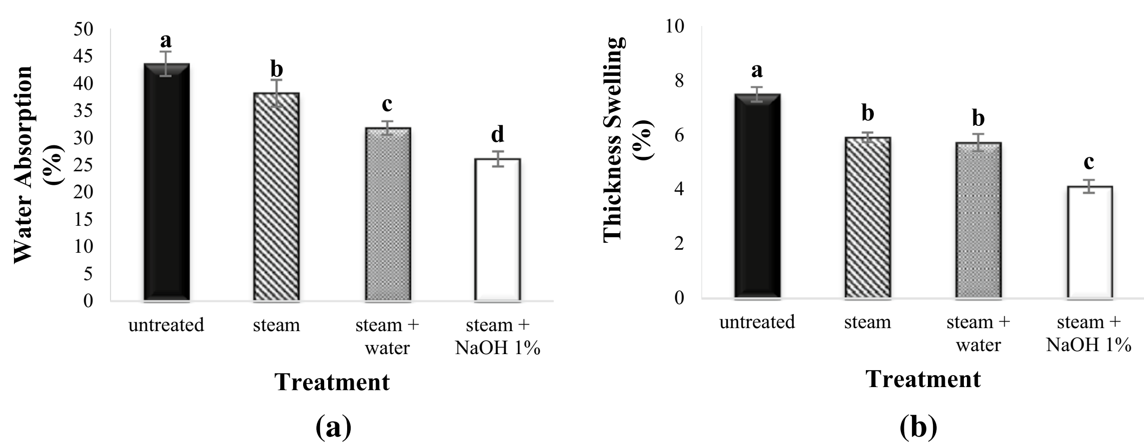

Fig. 2 Water absorption and thickness swelling of BOSB under the different steam treatments. Different letters show significant differences between treatments according to Duncan multiple range test at 5% confidence interval; error bars show standard deviation of the data

hydroxide solution may be responsible for the better dimensional stability of the boards. Extractives dissolved in hot water and 1% sodium hydroxide may be mainly low molecular carbohydrates with high content of hydroxyl groups (Fengel and Wegener 1984).

As shown in Fig. 3, MOE parallel to grain direction fulfilled CSA 0437 (Grade 0–1) standard in all BOSB, but only MOE perpendicular to the grain direction of BOSB manufactured from strand with steam treatment followed by washing with distilled water and 1% sodium hydroxide solution fulfilled CSA 0437 (Grade 0–1) (SBA 2004). Statistical analyses showed that the combination of steam and washing with distilled water or 1% sodium hydroxide solution increased the MOE of BOSB. The modulus of rupture (MOR), parallel and perpendicular, of all BOSB exceeded the minimum requirements of CSA 0437 (Grade 0–1) standard (SBA 2004). Steam treatment followed by washing with distilled water or 1% sodium hydroxide solution significantly increased the MOR of the boards (Fig. 4). The highest mechanical properties of BOSB were obtained from bamboo strands treated by steam followed by washing with 1% sodium hydroxide solution.

The quality of bonding can be predicted by internal bond (IB) which is defined as the tensile strength perpendicular to panel surfaces.

As shown in Fig. 5, IB strength of BOSB ranged from 0.39 to 0.53 MPa, being higher than the minimum requirement of CSA 0437 (Grade 0–1) standard (SBA 2004). Statistical analyses showed that all treatments significantly increased IB. Steam treatment followed by washing with 1% sodium hydroxide solution produced better bonding quality in BOSB than other treatments. The treatment

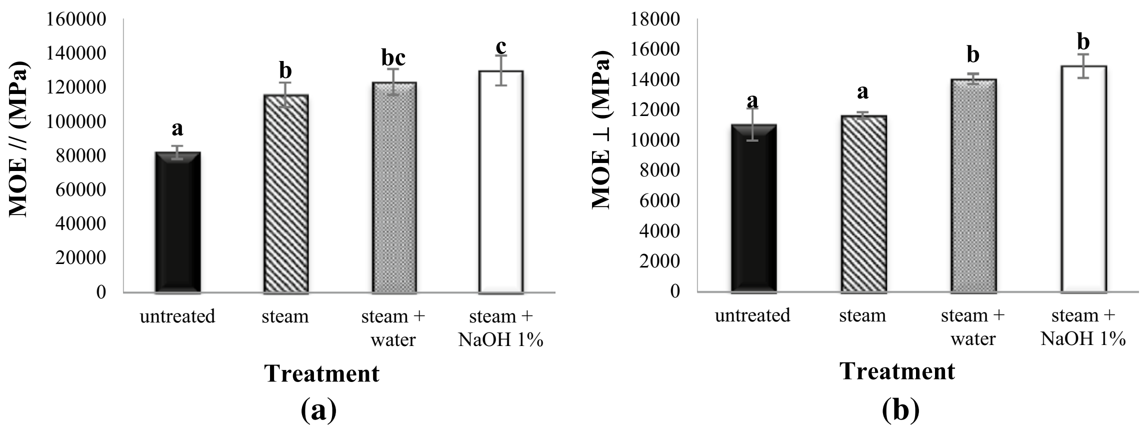

Fig. 3 Modulus of elasticity (MOE) in parallel (**a**) and perpendicular (**b**) direction to the grain, of BOSB under the different steam treatments. Different letters show significant differences between treatments according to Duncan multiple range test at 5% confidence interval; error bars show standard deviation of the data

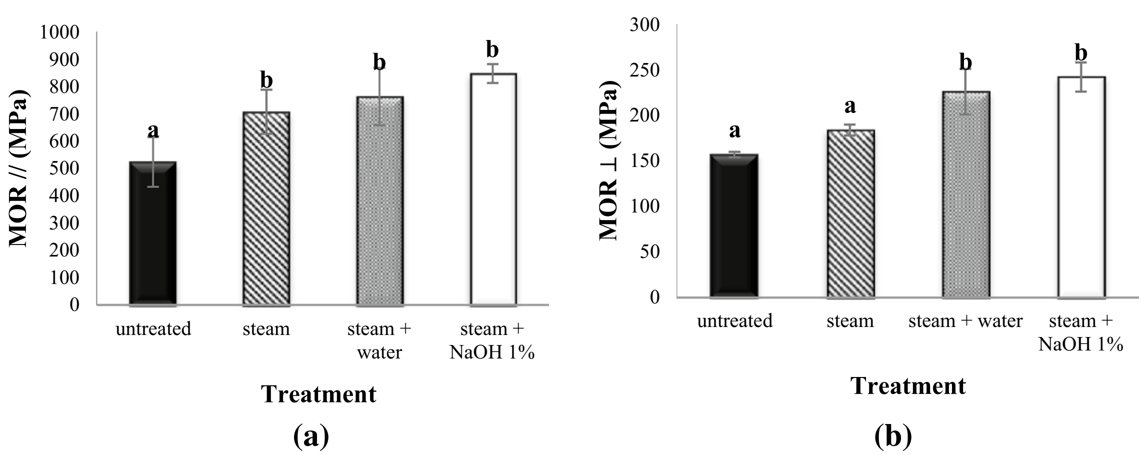

Fig. 4 Modulus of rupture (MOR) in parallel (**a**) and perpendicular (**b**) direction to the grain, of BOSB under the different steam treatments. Different letters show significant differences between treatments according to Duncan multiple range test at 5% confidence interval; error bars show standard deviation of the data

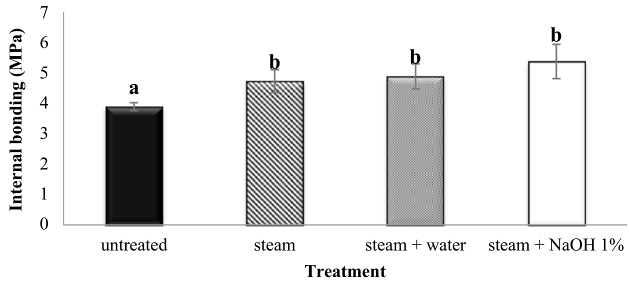

Fig. 5 Internal bond strength of BOSB under the different steam treatments. Different letters show significant differences between treatments according to Duncan multiple range test at 5% confidence interval; error bars show standard deviation of the data

created appropriate conditions for better bonding processes by removing part of the extractable substances from the strands, while also reducing acidity, making BOSB suitable for bonding with alkaline-based adhesives. The trend observed for IB in BOSB was in line with those observed for physical and mechanical properties.

The increasing physical and mechanical properties of treated BOSB were in agreement with the changes in chemical components caused by the treatments. This suggests that, basically, the degradation of hemicellulose and removal of extractives contents from the strands were the main reason for the better BOSB properties observed. Degradation of hemicellulose reduced the amorphous regions of materials, which caused increasing crystalline proportions and decreasing hygroscopic properties, leading to improvements in the mechanical properties and dimensional stability of the boards. The removal of extractives by the applied treatments may positively support the bonding process, allowing BOSB to obtain high physical and mechanical properties. pH also aids in the increase in the mechanical properties of BOSB. The pH tended to increase during treatments. Higher pH values give better adhesion to phenol–formaldehyde adhesives, which is normally cured at pH 11–12 or in base condition during the production of BOSB (Anwar et al. 2012). Sakuno and Moredo (1993) stated that the pH had no direct effect on bond strength and wood failure but influenced the adhesive curing process. For resin binders to cure properly, an optimum level of acidity must be established either on the surface or inside the substrate. The rate of crosslinking in most thermosetting adhesives is pH-dependent (Maloney 1993). The pH values in Table 1 show that betung bamboo treated by steam followed by washing with 1% sodium hydroxide solution had the highest pH value and produced better mechanical properties than untreated BOSB, BOSB treated by steam, and BOSB treated by steam followed by washing with distilled water. Higher pH value resulted in better adhesion process.

4 Conclusion

Steam treatments followed by washing with water or 1% sodium hydroxide solution changed the chemical components of bamboo strands, mainly decreasing the contents of hemicellulose and extractives. The steam treatment followed by washing processes increased the bonding ability of BOSB. Boards from steam-treated and washed bamboo strands showed higher physical and mechanical properties than steam-only and untreated samples. The washing processes after steam treatment increased the bonding ability of bamboo strands, resulting in improved physical and mechanical properties of BOSB compared to those of steam-only and untreated samples. The highest dimensional stability and strength of BOSB were obtained from strands treated with steam followed by washing with 1% sodium hydroxide solution, with all the values of physical and mechanical parameters satisfying the minimum requirements of the CSA 0437 (Grade 0–1) standard.

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