Static Bending and Compression Properties of Alkaline-Treated Densified Timber of *Paraserianthes falcataria*

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ABSTRACT Wood densification and alkaline pretreatment are well-known to enhance the mechanical properties and lignin-removal, respectively, especially those of low-density timber species. This study was aimed to determine the mechanical properties (static bending and compression) of untreated and alkaline-pretreated densified 3-layered *Paraserianthes falcataria* timbers. Pretreatment with 3%, 6% and 9% NaOH resulted in an increase up to 44% in mechanical static bending properties, where Modulus of Elasticity with 9% NaOH having the highest value in edge-wise bending, while 6% NaOH obtained the highest value of flat-wise bending. Both edge-wise and flat-wise bending showed slight increment in values for Modulus of Rupture between the concentrations. Compressive strength for compression parallel to the grain obtained by 0% NaOH (control) shows the highest value compared to other concentrations. Meanwhile, compression perpendicular to the grain of 9% NaOH enhanced for about 10% in compressive strength value compared to 0% NaOH.

KEYWORDS: Densification; alkaline pretreatment; low-density timber; mechanical properties; *Paraserianthes falcataria*.
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INTRODUCTION

Anatomically, wood is an anisotropic material with void structures. Their size of lumens and other components as cellulose, lignin and hemicellulose differs with wood species. Different wood modification concepts had been made and more resistant to destructive factors by environmental. However, the changes in wood properties depend on its characteristics (Bami & Mohebby, 2011). In order to improve the mechanical properties of low-density woods, wood densification method had been discovered in 1900s. Previous studies show various results as wood densification had been done using different wood species. According to Sandberg *et al.* (2017) mentioned in their findings that wood densification had been categorized into two, which are bulk densification and surface densification. Bulk densification referred to compression of cell wall structures increasing the total volume of the wood, while surface densification referred to compression of cell wall close to the surface of wood (Sandberg *et al.*, 2017; Kutnar *et al.*, 2015; Rautkari *et al.*, 2008).

Woods with low-density can be switched to high-density wood by densification, as it increased the mechanical properties and enhance the quality of woods (Kutnar & Sernek, 2007) by compressing of cell wall structure and porous lumens. First licensed densification methodology was in the year 1900, but the method was not continued as there are many attempts had been done between year 1930 to 1960 (Kollmann *et al.*, 1975). Raman & Liew (2020) used similar concentrations of NaOH for alkaline pretreatment for density test for alkaline pre-treated *P. falcataria* with sample dimensions of 300 mm X 50 mm X 8 mm. In this paper, 3-layered composite samples with different sizes were prepared according to standards for static bending and compression properties. The aim of this paper was to determine the mechanical properties of untreated and treated densified 3-layered *Paraserianthes falcataria* timbers by compressing the lamina to about 60% reduction compared to initial thickness. In this paper, low-density woods were modified by removing partial content of lignin from the cell wall structure by alkaline pretreatment using NaOH, before undergone densification to eliminate voids consist after lignin reduction. Commonly, polyurethane (PUR) and emulsion polymer isocyanate (EPI) used in glulam lamination depending on the condition of the product will be used in future (indoor or outdoor) (Petković *et al.*, 2019). However, Polyvinyl acetate (PVAc) was used in this study due to its environmental-friendliness compared to other adhesives and water-based adhesive. The benefits of using PVAc are low budget, easy application, non-poisonous, anti-fungal and bacteria attack resistant. PVAc can be applied using brushing, flowing, or spraying methods (Ebnesajjad, 2008; Pizzi, 2005). The results show increments in static bending and compression testing. The applications interest of this usually useful for construction materials such as beam and wall. Densified low-density woods can use as the alternative application as the high-density woods been used.

METHODOLOGY

Timber in the form of laminas from *Paraserianthes falcataria* (local name: Batai) were supplied by Sapulut Forest Development Sdn. Bhd. All the laminas with initial thickness of 20 mm, were prepared for alkaline pre-treatment using soda pulping method (pulp and paper technology) and sodium hydroxide (NaOH). For alkaline pretreatment, NaOH was diluted on weight basis (w/w) to produce 3%, 6% and 9% NaOH concentrations with 0% (untreated) as the control. The timbers were cooked with ratio liquid to wood of 10:1 for 30 minutes. Later, densification process was carried out on the untreated and treated test pieces where they were compressed using hot-press machine at 105°C and 6 MPa for 30 minutes with 8 mm stopper, followed by 10 minutes cooling process under pressure to 100°C or less, to achieve 8 mm thickness. This densification method was based on the hot-pressing mathematical model by Humphrey (1982), Humphrey and Bolton (1989), and Carvalho and Costa (1999). The 3-layered composites with parallel grain direction (also known as glulam), were produced with the lamination of densified laminas using polyvinyl acetate (PVAc) as the adhesive and pressure applied using clamps for 24 hours. Composites prepared for edge-wise bending and flat-wise bending test were referred to ASTM D198-21a (2021) with measurement of 300 mm x 50 mm x 24 mm and 300 mm x 24 mm x 50 mm for length, thickness and width respectively. Meanwhile, composites for compression parallel to the grain and compression perpendicular to the grain were prepared and conducted according to ASTM D143-21 (2021) and BS EN 408 (2010), sized to 200 mm x 24 mm x 50 mm and 150 mm x 24 mm x 50 mm for length or height, thickness, and width, respectively. Three laminas were arranged parallel to grain to produce 3-layered composites, i.e. glulam. Mechanical testing was done with static bending and compression to the grain. Types of wood failures occurred were referred to ASTM D143-21 (2021) as tabulated in Table 1 and Table 2. There were 7 replicates used for each concentration for all the tests.

RESULTS AND DISCUSSION

In this study, the mechanical properties of 3-layers composites using *P. falcataria* timbers were tested with static bending test (edge-wise and flat-wise) and compression test (parallel to the grain and perpendicular to the grain) after densified and treated timber with different concentration of NaOH together with the layered composites of densified and untreated timber as the control. The MOE and MOR for static bending and compressive strength for compression parallel to the grain and compression perpendicular to the grain of densified and treated with different concentrations NaOH and untreated *P. falcataria* timbers as the control were measured and results shown in Figure 1, Figure 2, and Figure 3.

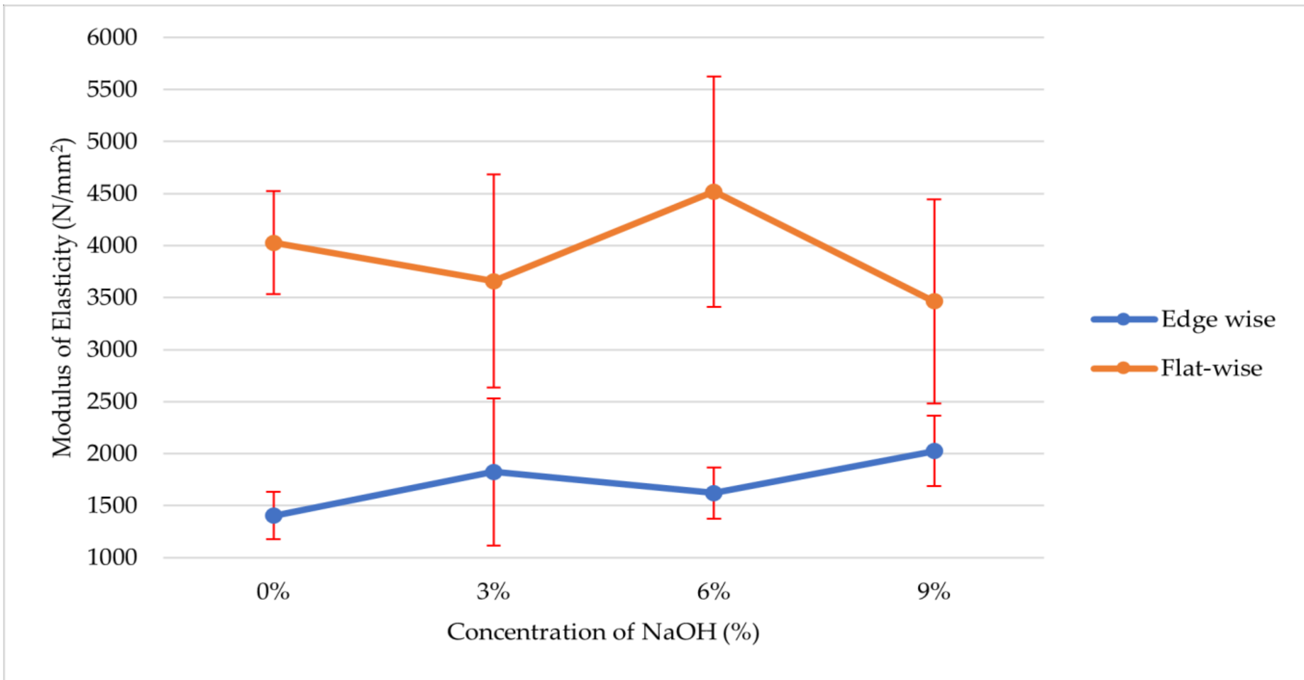

Figure 1. The mean values and standard deviation (±) of Modulus of Elasticity (MOE) for edge-wise bending and flat-wise bending of the densified and treated *P. falcataria* timbers on different concentrations NaOH (3, 6 and 9%) with densified and untreated *P. falcataria* timbers as the control (0%).

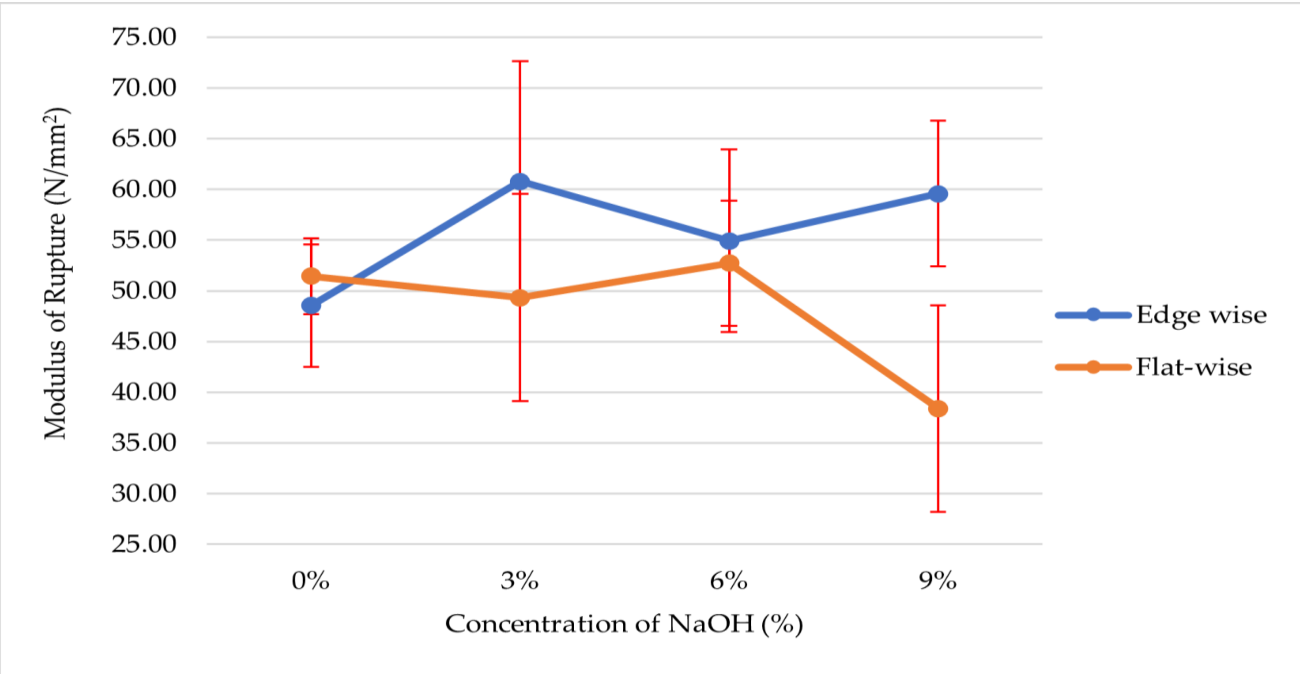

Figure 2. The mean values and standard deviation (±) of Modulus of Rupture (MOR) for edge-wise bending and flat-wise bending of the densified and treated *P. falcataria* timbers on different concentrations NaOH (3, 6 and 9%) with densified and untreated *P. falcataria* timbers as the control (0%).

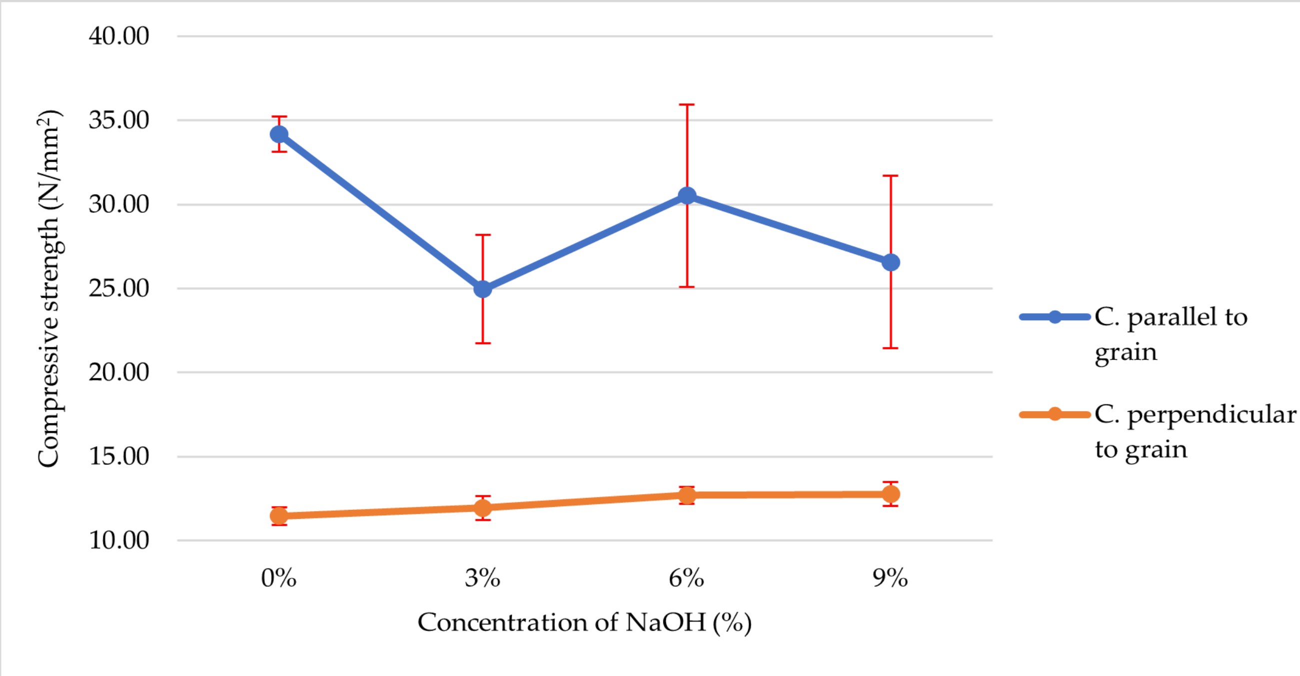

Figure 3. The mean values and standard deviation (±) of compressive strength for compression parallel to the grain and perpendicular to the grain of the densified and treated *P. falcataria* timbers on different concentrations NaOH (3, 6 and 9%) with densified and untreated *P. falcataria* timbers as the control (0%).

Figure 1 shows that edge-wise bending had obtained highest mean value of MOE in 9% NaOH with 2023.85±339.08 N/mm², and lowest by untreated (0% NaOH) timber with 1402.08±226.69 N/mm². In the flat-wise bending, the highest mean value of MOE was by 6% NaOH with 4516.86 ±1105.90 N/mm² and the lowest at 9% NaOH with 3462.98±981.86 N/mm². Meanwhile, Figure 2 for MOR, the edge-wise shows 3% NaOH treated timber has the highest mean value with 60.79±11.81 N/mm², while the untreated 0% NaOH has the lowest mean value of MOR with 51.43±3.75 N/mm². MOR for the flat-wise bending shows that concentration 6% NaOH has the highest mean value of bending strength with 52.71±6.19 N/mm² and concentration 9% NaOH has obtained the lowest mean value of MOR with 38.38±10.20 N/mm². High standard deviations shown in Figure 1 and Figure 2 were influenced by man-made products and natural wood properties, such as presence of knots, formation of earlywood and latewood, and content of extractives.

From the result, the MOE and MOR of edge-wise bending and flat-wise bending were affected by the alkaline pretreatment and densification, as alkaline pretreatment was done for the removal of partial lignin from the cell wall structure and densification was done to compress the cell wall to the maximum or desirable thickness. In this study, thickness reduction for about 60% was achieved resulting in the highest packed of microstructure which leads to higher strength (Raman & Liew, 2020). The stress increased during compressing of wood structure, through densification process, by eliminating the voids in structures after partial of lignin had been removed. According to Wolcott *et al.* (1989), the collapse of cells occurred depending on test conditions and the nature behavior of cell wall materials, such as by elastic distortion, plastic flexibility, or brittle suppressing. Adhesion and compatibility between wood components such as fibers and polymer had been increased after the lignin removed and cellulose reacted with NaOH, which resulting in higher MOE and MOR in treated test piece at the highest concentration NaOH in this study compared to untreated test piece (Islam *et al.*, 2012). However, it was the opposite for flat-wise bending, where the higher the NaOH concentration, the lower the mean values of MOE and MOR of flat-wise bending. This result indicated the MOE and MOR depended much on the direction of load applied to its grain and the wood properties during testing. According to ASTM D143-21 (2021), the categorization of wood failures was done by the form of fractures in surface. Wood failures that occurred after load applied to the test piece on edge-wise and flat-wise bending had been shown in Table 1. The failures seen were separated into "brash" and "fibrous", where brash signified sudden (abrupt) failure, while fibrous showed splinters. In this study, horizontal shear failure was mainly found in edge-wise bending, as in Table 1(a), while cross-grain tension and splintering tension followed by compression failure found in flat-wise bending in Table 1(b)(c).

Table 1. Comparison of the types of wood failure (ASTM D143-21, 2021) after static bending test, (a) edge-wise bending, (b)(c) flat-wise bending.

	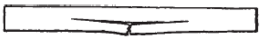	 
(a)Horizontal shear	(b) Cross-grain tension	(c) Splintering tension, followed by compression
		 

Table 2. Types of failure in compression (ASTM D143-21, 2021); (a) compression parallel to grain, (b) compression perpendicular to grain.

	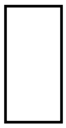
(a) Crushing	(b) No physical failure
	

Figure 3 shows that 0% NaOH (untreated) timber has the highest compressive strength for the compression parallel to the grain compared to the treated (3%, 6%, 9% NaOH) timbers, with 34.16±1.05 N/mm^2 and the highest concentration of NaOH has the higher compression perpendicular to the grain with 12.76±0.70 N/mm^2. According to Song *et al.* (2018), higher concentration NaOH leads to more reduction of lignin in natural timber which leads to higher density thus it was hard to densify a natural timber to highly packed timber. These may cause by the several number of replicates, but there were no huge differences between the values of compression perpendicular to the grain. Raman and Liew (2020) stated in their finding that wood with 9% NaOH has the highest density compared to other NaOH concentration (3% and 6%) and untreated woods (0% NaOH). As their results shows that untreated wood has very low density (not more than 400 kg/cm^3) and treated wood (3%, 6%, 9% NaOH) has improved about 587.2 kg/cm^3 to 909.2 kg/cm^3 after 7days observation. However, the changes in mechanical properties for densified woods depends on some factors such as wood species, treatment condition, pressing condition (such as temperature, pressure, cooling) and conditioning condition (Santos *et al.*, 2012; Islam *et al.*, 2014). Nairin (2006) had stated that compression properties were depending on its density, the early wood and late wood materials, ray volume and direction of load. However, Schrepfer and Schweingruber (1998) mentioned in their findings that earlywood regions were found easier to contort than latewood regions. The results of compression showed that the distortion shape differ according to its load direction. Compression perpendicular to the grain test showed no failures on test piece as when the load was applied, whereas the test piece become more compact and densely packed until it reduced in thickness compared to before the testing, as shown in Table 2 (b). Meanwhile, for compression parallel to the grain test, the type of failure was crushing, where the rupture is approximately horizontal, as shown in Table 2 (a).

CONCLUSIONS

Alkaline pretreatment and densification of timber influenced the performance of mechanical properties in *Paraserianthes falcataria*. However, anatomical structures of the wood need to be taken into account such as porosity, density, grain direction, and position of the timber used. From this study, the value of MOE for the edge-wise bending gets higher along with percentage NaOH, while the value of MOE for flat-wise bending increased until 6% NaOH and dropped in values when the concentration went higher. MOR for edge-wise bending shows increment after treated compared to untreated and MOR for flat-wise bending shows the values descending on higher NaOH concentration. Meanwhile compression parallel to the grain shows that the untreated timber has the higher value of compressive strength than treated timber and compression perpendicular to the grain shows increment with slight differences in values of compressive strength for untreated and treated timbers.

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