Effect of Impregnation with Diammonium Phosphate and Sodium Silicate on Some Physical and Mechanical Properties of Modified Laminated Veneer Lumber Made of Jabon Wood

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Laminated veneer lumber (LVL) and laminated veneer board (LVB) panels from jabon wood (*Neolamarckia cadamba*) were impregnated with fire retardation substances, namely diammonium phosphate (DAP) and sodium silicate (SS). Prior to testing, the boards were conditioned in relative humidity (RH) of 65% and a temperature of 25 °C. The moisture content (MC), bending strength tests in flat wise position, and bonding tests were conducted in accordance with the Japanese Agricultural Standard (JAS:2008). Density tests and hardness tests were conducted in accordance with ASTM D143 standard (2003) in 50 mm x 50 mm. Thickness-swell shrinkage tests were conducted in accordance with the standard BS EN 317:1993, and fire resistance was tested under PS 1-19 standard. The use of 20% DAP and SS solution on jabon wood using impregnation methods affected some of the properties of the panels, especially the moisture content, density, and bonding strength of LVL and LVB compared to the control panels. Both DAP and SS impregnation increased the density. The treatments showed promise for resisting fire, as well as increasing the moisture content and increasing the density compared to the control.

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INTRODUCTION

Wood is one of the most sustainable, aesthetically pleasing, and environmentally benign materials. The demand to use wood and wood-based products for application in both residential and non-residential building construction has been increasing over recent years. However, due to the inherent flammability of such products, they often contribute to unwanted fires, resulting in numerous injuries and fatalities. The use of wood is, therefore, limited by various safety requirements and regulations pertaining to its flammability and spread of fire characteristics. In order to improve the reaction to fire performance, timber products are commonly treated with fire retardants (Lowden and Hull 2013). Wood is undeniably the most useful and readily available natural raw material. However, the susceptibility of wood products to fire is one of the crucial challenges faced in the wood industry. The fire behaviour of wood is a very complex phenomenon due to the different constituents and their independent reactions to fire (Mensah *et al.* 2023). It has been found that the pure wood modifications are not entirely suitable for significantly improving the reaction to fire of wood. Therefore, combined strategies of wood modification and the use of fire-retardant chemicals has potential to provide higher protection (Popescu and Pfriem 2019).

Wood has a composition consisting of cellulose, hemicellulose, and lignin. Cellulose in wood that has a low water content will start to burn at a temperature of 300 °C, but hemicellulose will start to burn at a temperature of 150 to 200 °C. Lignin, which has a role in binding cellulose and hemicellulose, will decompose at a temperature of 220 to 250 °C and dehydrate at a temperature of 200 °C (Przystupa *et al.* 2020). The combustion mechanism starts when the temperature is at 105 °C, whereupon free water begins to evaporate from the wood. When the temperature is above 200 °C, emission gases will appear, resulting from exothermic reactions from burning of the wood. The wood will turn brown. At temperatures above 250 °C this process accelerates (Przystupa *et al.* 2020). When wood burns, it does not produce dangerous compounds but will produce a layer of char. This layer will prevent fire from entering deeper into the wood. So the wood burns more slowly until the char layer is damaged (Przystupa *et al*. 2020).

Laminated veneer lumber (LVL) is prepared by arranging veneers with parallel fiber directions and then gluing them together using adhesives to resemble solid wood (Ross 2010). One of the woods that can be used to make LVL is jabon wood. LVL is generally made from veneers of softwoods or low-density hardwoods with densities of 0.25 to 0.65 g/cm^3 (Sampoerna Kayoe 2023). To maintain dimensional stability, LVL panels are developed by adding multiple veneers with perpendicular fibers. The panel is called laminated veneer board (LVB) (Alamsyah *et al*. 2023). In the manufacturing industry, to meet market needs, there are some LVL modifications by changing some of the veneer layers to the transverse fiber direction.

With the reduction of timber production from natural forests, the timber industry began to switch to wood from cultivated forests (plantations) to maintain the availability of industrial raw materials. One type of plant suitable for cultivation is jabon (*Neolamacrkia cadamba*). Jabon is a fast-growing species. Jabon wood can be harvested when it reaches 5 to 6 years of age. With a relatively short life cycle compared to natural forest timber, jabon wood can be used as an alternative amid the decline of timber from natural forests (Sarjono *et al*. 2017).

As a wood derivative product, the burning nature of wood can be a drawback in LVL panels. LVL utilization is mostly in the construction field, either structural or non-structural. (Tsiulin 2020). When LVL is used as construction material such as floor, wall, or roof, then LVL panel must have good fire resistance (Ross 2010). In principle, that goal can be achieved by adding fire retardation materials.

Diammonium phosphate (DAP) and sodium silicate (SS) are compounds that can be used as fire retardants in wood. The presence of DAP will inhibit the growth of fire by forming charcoal on the burned wood so that it inhibits the spread of fire while SS inhibits it by the mechanism of ceramification in burned wood. The application of DAP and SS as a fire retardants material on wood can use the impregnation method or be used as a coating. (Hautamäki *et al*. 2020). In this study, the addition of DAP and SS by impregnation method was carried out. For comparison, the treatment was conducted on LVL and LVB panels. The objective of this study was to evaluate the effect of impregnation of DAP and SS on the physical and mechanical properties of modified laminated veneer lumber.

EXPERIMENTAL

Material Preparation

Jabon wood, having an age of 6 years, was obtained from community forests around Cibugel Village Sumedang, West Java, Indonesia. The wood, in the form of logs, was then peeled through rotary spindles at an industrial wood factory, namely PT Sumber Graha Sejahtera Tangerang Industry, with a thickness of 2.2 mm. Then the veneer was dried to a moisture content of 5%. Phenol formaldehyde (PF) was used as a base adhesive with the addition of filler (cassava flour) and accelerator. The addition of cassava flour is to reduce the use of adhesive base materials, thereby reducing production costs. The complete adhesive formulation used based on weight comparison is shown in Table 1.

Table 1. Composition of Adhesive Mixture Based on Weight Ratio

No	Adhesive Component	Specifications	Weight Comparison (g)	Weight Percentages (%)	Weight Application (g)
1	Resin Based	Phenol Formaldehyde	50	100	84
2	Filler	Tepung Lencana Merah (cassava flour)	5	10	8.4
3	Accelerator	H451 ($CaCO_3$)	4.5	9	7.56
Component Total			59.5	119	100

Note: Viscosities after mixing: 20 poises

The phenol formaldehyde (PF) used in this work is a commercial adhesive from an adhesive company, namely PT. Dover Chemical (product code: regular PF). It has a viscosity of 100 to 70 poise (at 30 °C) and a solid content of 41 to 43%. The molecular weight of phenolic resin was 2000 to 3000. Likewise, H451 (product code) is the accelerator of the active ingredient calcium carbonate ($CaCO_3$). Cassava flour is an industrial tapioca flour that functions as a filler with a particle size ranging from 50 to 80 mesh.

Table 2. Basic Properties of Jabon Wood Species

Density (g/cm³)*	MOE (N/mm²)**	MOR (N/mm²)**
0.29 to 0.56	4120	50

Sources: *Krisnawati *et al*. (2011); **Augustina *et al.* (2019)

Board Manufacturing

The veneer was impregnated at the retention level of 0.068 g/ cm^3 at 0.5 MPa for 25 min and then dried in a press at 95 °C. The wood was immersed in a solution of DAP and SS retarding substance with 20% of concentration. The LVL and LVB panels consisted of 9 layers of veneer with a target panel thickness of 18 cm. In LVL panels, all veneers had a long orientation while in LVB from 9 layers of veneers, the 2nd and 8th layers were inserted with cross type veneers (Table 3).

Table 3. Composition of Veneer Layers Structure of Board

Panel Type	Layer Number								
	1	2	3	4	5	6	7	8	9
LVL	//	//	//	//	//	//	//	//	//
LVB	//	⊥	//	//	//	//	//	⊥	//

Note: // = parallel; ⊥ = Cross section

The assembling process used phenol formaldehyde (PF) adhesive with a weight of 250 g/m^2, which was applied using a glue-spreader machine. The veneers were then put into a cold press with a pressure of 8 kgf/cm^2 for 1.8 min and then into a hot-press with a pressure of 8 kgf/cm^2 at 110 °C for 15 min. The panels were conditioned in a relative humidity (RH) of 65% and a temperature of 25 °C for 24 h, after which they were cut into their final dimensions.

Evaluation Tests

Prior to testing, the boards were conditioned at a relative humidity (RH) of 65% and a temperature of 25 °C. The moisture content (MC), bending strength tests in flat-wise position, and bonding tests were conducted in accordance with the Japanese Agricultural Standard (JAS:2008), density tests, and Janka hardness tests were conducted in accordance with ASTM D143 standard (2003) in 50 mm x 50 mm. Thickness-swell shrinkage tests were conducted in accordance with the standard BS EN 317:1993. The fire-resistant test was carried out with a sample measuring 40 x 40 cm and then firing a flame from a distance of 17 cm. The fire was positioned in the centre of the panel. The test was complete when smoke was visible from the opposite side of the surface of the panel during the burning period (Fig. 1). The fire-resistance test was carried out regarding the Voluntary Products Standard PS 1-19: 2019. Because of the lack of the LVB sample, the fire-resistant test was only carried out on LVL panel.

Fig. 1. Fire-resistant procedure

Statistical Analysis

This study used a two-factor completely randomized design. The first factor was the orientation of the veneer fiber direction, which consists of: 1). LVL with all veneers having parallel (long) fibers; 2). LVB. The second factor was the fire retardation treatment factor consisting of: 1). Control; 2). DAP impregnation; 3). SS impregnation calculated by analysis of Variant (ANOVA) using SPSS software. Tukey and Duncan tests were also applied to know more significantly different effects among the treatments.

RESULTS AND DISCUSSION

Moisture Content

The average air-dry moisture content of jabon solid wood is 15.4% (Widiyanto and Siarudin 2017), while the average of wood air-dry moisture content in Indonesia is 15% ranging from 12 to 18% (Ginting 2007). When compared to the solid wood, LVL (12.9%) and LVB (11.6%) panels have a lower moisture content. This can happen because during the making of LVL and LVB, the material passes through the press drying process. The JAS:2013 standard requires a plywood panel to have a moisture content below 14%. LVB has less moisture content compared to LVL. This could be an indication that LVB will be more resistant to swelling and shrinkage (Tenorio *et al*. 2011). In the DAP and SS impregnation treatments, both have higher moisture content compared to the control. Figure 2 shows that the DAP and SS impregnation treatments had moisture contents above the set standard. The indication of the cause of the high moisture content is due to the poor drying process after the impregnation process, which leaves a high enough moisture content. Another cause is that the moisture content is obtained from the adhesive that contains water. Another possibility is that DAP and SS are hygroscopic compounds that will absorb water in the environment. From the statistical test results, moisture contents were only influenced by impregnation treatment and not by differences in fibre direction. From the results of further tests (Tukey and Duncan), there was a significant difference (95% confidence level) between the control with DAP impregnation treatment and SS impregnation. Research conducted by Tomak *et al*. (2018) showed an increase in MC due to impregnation using sodium silicate. When impregnated, sodium silicate will fill the empty space and become a barrier for the water inside to escape into the air. This causes the water content of the panel to be high.

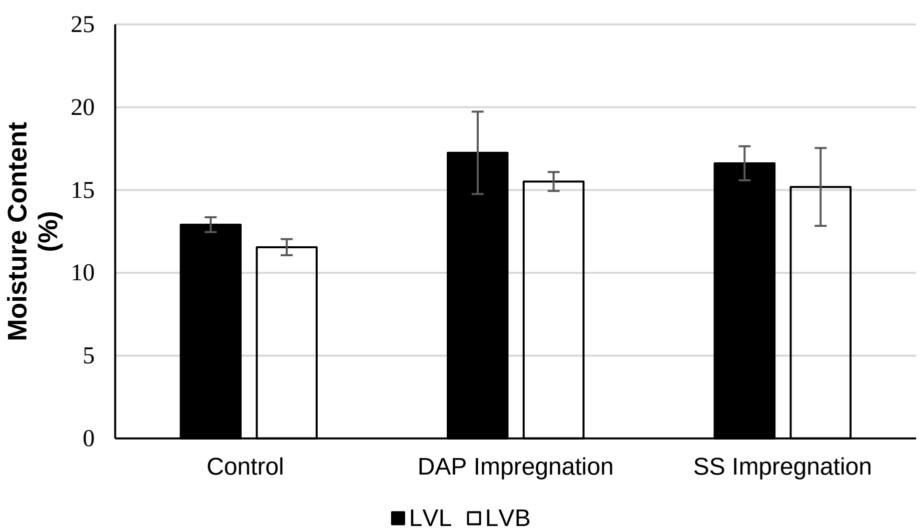

Fig. 2. Moisture content

Density

Density correlates with the mechanical strength of wood. In general, the higher the density, the better the mechanical properties (Augustina *et al.* 2019). The jabon solid wood has a density between 0.29 and 0.56 g/cm^3 according to the location of growth (Krisnawati *et al*. 2011). Research conducted by Widiyanto and Siarudin (2017) mentioned that jabon wood obtained from Garut has a specific gravity of 0.37 g/cm^3 in air-dry conditions. LVL and LVB have greater density values than solid (Fig. 3) wood from Widiyanto and Siarudin (2017). Both LVL and LVB density value is 0.44 g/cm^3. This is because LVL and LVB panels use the same type of wood. The density value is greater than the solid wood because LVL and LVB go through the process of compression and the addition of PF adhesive. From the statistical test results, density values were only influenced by impregnation treatment and not by differences in fibre direction. From the results of further tests (Tukey and Duncan), there was a significant difference (95% confidence level) between the control with DAP impregnation treatment and SS impregnation. According to Salca *et al.* (2020), the forging process can increase the density of wood. From the test results, the DAP and SS impregnation treatments resulted in a higher density than the control. In LVL panels, DAP impregnation increased the density by 13.4% and SS impregnation increased the density by 17.3%. This is in accordance with the research of Li *et al.* (2020), which states that impregnation can increase wood density. Research conducted by Bingbin *et al.* (2022) shows impregnation with sodium silicate can increase wood density when combined with the delignification process. From this combination, the increase in density can reach 30%. For the effect of across the preparation of veneer, LVL and LVB, there was no significant difference for all treatments.

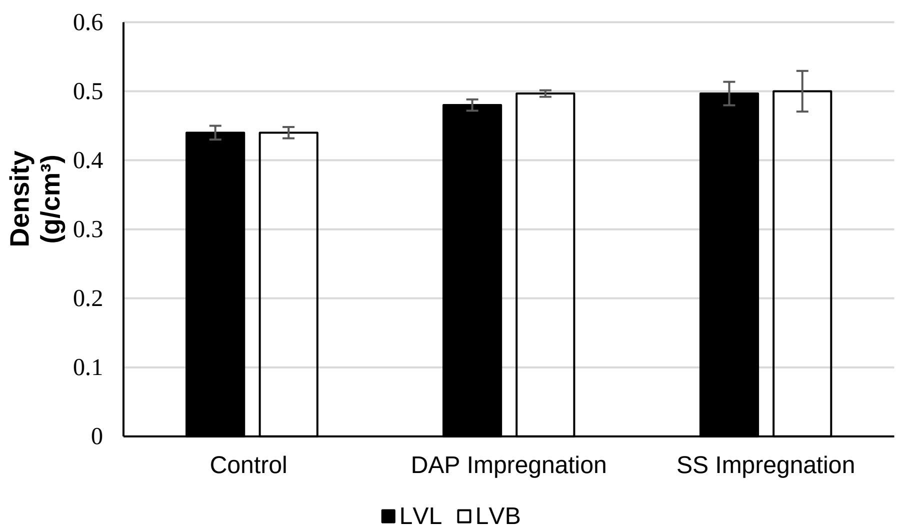

Fig. 3. Density

Thickness-swell Shrinkage

The shrinkage-deflection test indicates whether the shrinkage-deflection of wood has a difference between the length and width directions. As a result of being composed of veneers, the long orientation of the panel is the same as the longitudinal orientation of the solid wood, while for the width, it is the same as the tangential direction of the solid wood (Eckelman 2005). In Fig. 4, shrinkage in the length orientation was smaller than that in the width orientation. In the length shrinkage, the difference between LVL and LVB gave similar results. In the width shrinkage, there was a difference between LVL and LVB. For all treatments, LVB had a much smaller shrinkage percentage compared to LVL. DAP impregnation treatment resulted in a smaller shrinkage expansion compared to the control. The SS impregnation treatment gave a larger shrinkage expansion value than the control.

From the results of statistical tests, the swelling-length test was only influenced by the treatment (sig .023). In further tests (Tukey and Duncan), there was a significant difference between the control and DAP impregnation. The value of shrinkage expansion test in SS impregnation was greater than the control, which can be caused by the pH value of the SS solution used. The pH was very, which causes degradation in wood components and then opens up a lot of amorphous space so that water is easy to enter and increase swelling (Kuznetsov *et al*. 2021).

Sodium silicate that is impregnated will enter the cell wall (Mohebby and Hajialian 2022). In addition, sodium silicate also has low leaching resistance. This can be the explanation why there was an increase in the swelling test. Due to the long test, sodium silicate dissolves with water. If water evaporates, the sodium silicate will be left behind. On the other hand, sodium silicate is a water-absorbing compound, so there is some water that enters the wood and increases the swelling value. Another thing that can be considered is that SS is a strong base that can damage the chemical components of wood and make the crystalline area become amorphous. The area that is susceptible to swelling in the wood increases (Rafsanjani *et al*. 2014; Borůvka *et al*. 2016).

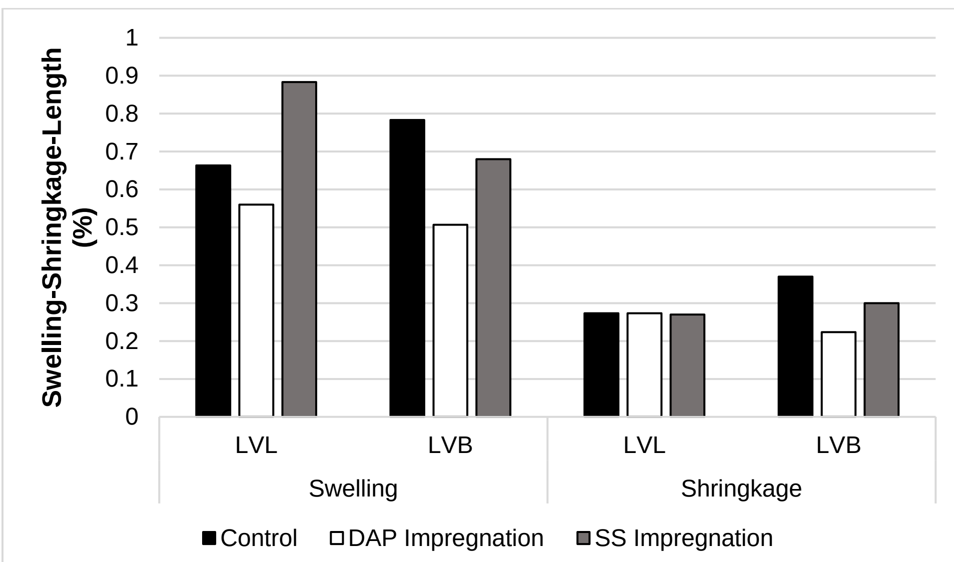

Fig. 4. Swell-shrinkage in length

LVL and LVB were noticeably different in the width direction (Fig. 5). LVB panels exhibited smaller swelling-shrinkage in the width direction compared to LVL. This is because LVB contains veneers with cross orientation (2nd and 8th order veneers) that restrain the shrinkage in the width direction of the panel. In the swelling-width test, the statistical test results showed that there was an effect of fiber direction and treatment. From the Tukey's further test, there was a significant difference between DAP impregnation with control and SS impregnation. In the Duncan's further test, the three treatments were considered to have significant differences. In the width direction of the panel, the cross veneer has the longitudinal fiber direction of the wood and the shrinkage properties of the wood in the longitudinal direction are very small so that the shrinkage is small (Prihatini *et al*. 2020). Whereas in LVL there are no veneers with cross orientation. All veneers have a long orientation; there is no restraint on the shrinkage in the width direction of the panel, which is entirely in the tangential direction of the fibers. The shrinkage in the tangential direction is greater than the shrinkage in the longitudinal fiber direction (Riki *et al*. 2019). This is also the reason why there was no difference between LVL and LVB in the panel length direction.

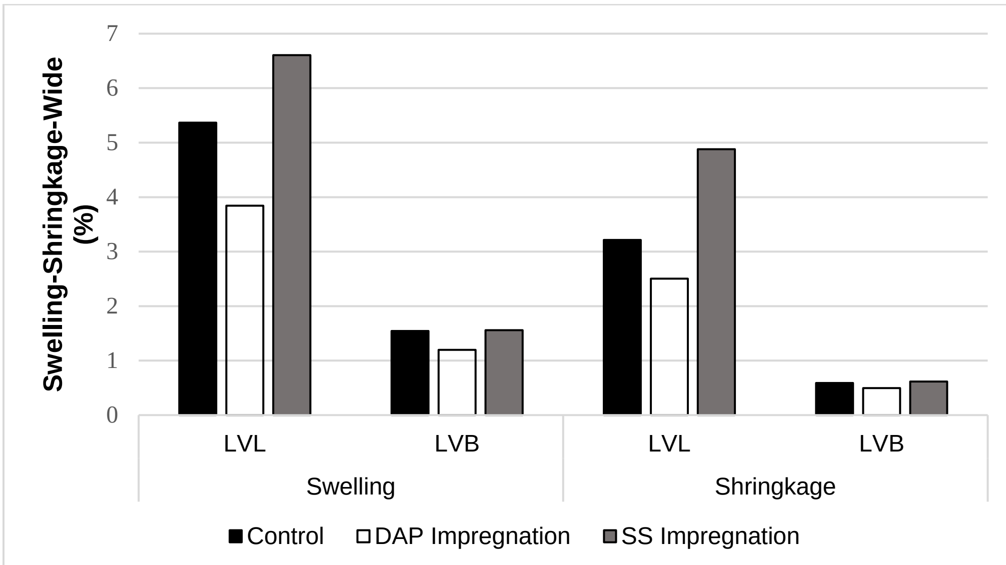

Fig. 5. Swell-shrinkage in width

Bending Strength

Bending strength testing produces two values, namely modulus of elasticity (MOE) and modulus of rupture (MOR) values (Figs. 6 and 7).

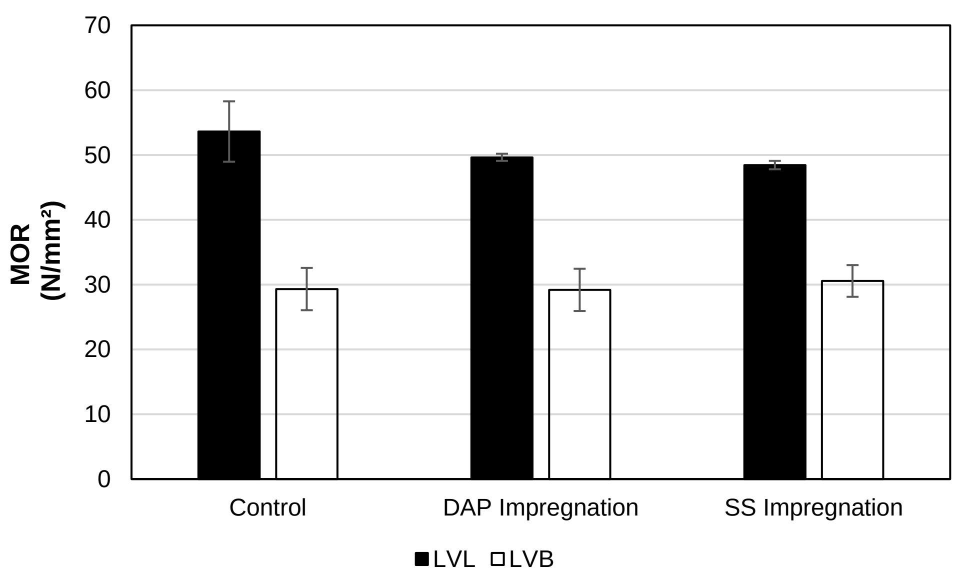

Fig. 6. Modulus of rupture (MOR)

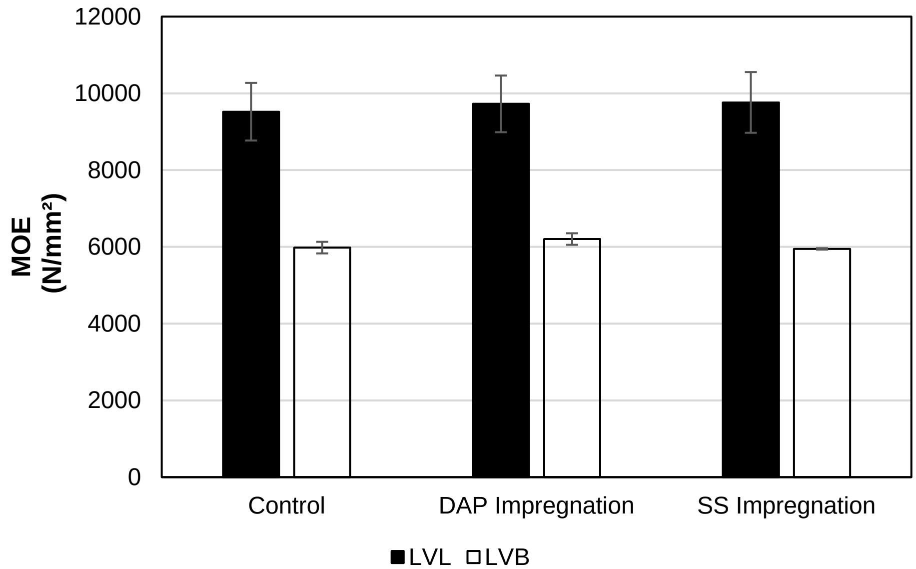

Fig. 7. Modulus of elasticity (MOE)

As a reference, jabon solid wood has an MOE value of 4120 N/mm^2 while its MOR value is 50 N/mm^2. In LVL and LVB panels, the MOE value was greater than solid wood. The MOR was smaller than solid wood. There was a difference between LVL and LVB, the MOE and MOR values of LVL were greater than LVB because LVL is composed of pieces that have parallel fibers. When tested with a four-point load, it is the longitudinal section that will receive the test load. In LVB, the 2^{nd} and 8^{th} veneers are installed in a direction perpendicular to the other veneers so that the load will hit the tangential direction of the two veneers. In LVL, all the fibers (9 layers) of the veneer were exposed to load in the longitudinal direction while in LVB, 7 veneers were affected in the longitudinal direction and 2 in the tangential direction. The longitudinal direction has much better strength compared to the tangential direction of the wood (Sun *et al*. 2022). Impregnation treatment did not give significant difference compared to the control in LVL panels. There was a difference between LVL and LVB. LVL exhibited greater MOE and MOR values compared to LVB. The MOE and MOR values of LVL were greater for all treatments than LVB. Impregnation treatment did not give significant difference compared to the control in LVL panels. DAP and SS impregnation treatments on LVB panels resulted in smaller MOE and MOR values than the control. This can happen because the SS solution has strong alkaline properties. Research conducted by Borůvka *et al*. (2016) showed that impregnation of compounds with high pH can cause degradation and mechanical damage. On the other hand, sodium silicate fills the lumen of the cell so that it can maintain its mechanical strength (Chen *et al*. 2020). This can explain why there was an increase in the MOE value of SS impregnation treatment for LVL panels. There was a difference between LVL and LVB. LVL had greater MOE and MOR values compared to LVB. The MOE and MOR values of LVL were greater for all treatments than LVB. From the statistical test results, the MOE and MOR tests were influenced by the fiber direction of the panel, while the treatment did not affect the MOE and MOR values.

Bonding Strength

Figure 8 shows that the bonding strength value of LVL panels was on average higher than the bonding strength of solid jabon wood (4.50 N/mm^2). The bonding strength value of LVB panels was lower than that of solid jabon wood except for LVB-control (LVB-control value 4.77 N/mm^2). There was a difference between LVL and LVB. LVB had a lower bonding value compared to LVL. From the statistical test results, the bonding test is influenced by fiber direction and impregnation treatment. In further tests (Tukey and Duncan), there were significant differences between the control treatment with DAP impregnation and SS impregnation.

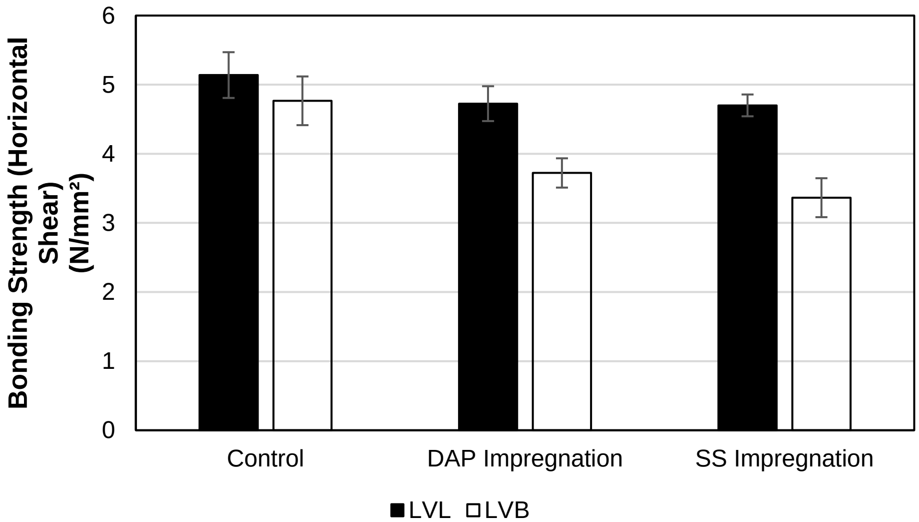

Fig. 8. Bonding strength

The difference in value between LVL and LVB can be attributed to the strength of the parallel fiber direction, which has better strength compared to the perpendicular one. In LVL all the veneers are parallel, while in LVB there are two veneers arranged perpendicularly so that the bonding value is smaller (Cristescu 2006). From the test results, the LVL-control panel has a bonding strength value of 5.14 N/mm^2. DAP impregnation treatment (4.73 N/mm^2) and SS impregnation (4.70 N/mm^2) gave an apparent decrease in the bonding value compared to the control, although the difference in value was not significant. A decrease in bonding value in the impregnation treatment is in accordance with previous research (Kawalerczyk *et al*. 2019). In their study, impregnation decreased the bonding value especially in veneers that had previously undergone an impregnation process. This may be due to the impregnated material blocking the adhesive from adhering to the veneer surface. Yan *et al*. (2023) researched wood impregnation with phosphate-based materials, when mixed with formaldehyde-based adhesives will reduce its shear strength. However, when comparing with other formaldehyde-based adhesives, PF adhesive is still better than UF (urea formaldehyde) adhesive.

Hardness

Figure 9 shows that there was no significant difference of hardness between LVL and LVB. Hardness was not affected by the difference in veneer arrangement based on the direction of fiber orientation. Factors affecting hardness include wood density. The denser the wood, the higher the hardness (Mania *et al*. 2020). Figure 8 shows that SS impregnation had the lowest hardness with 1850 N/mm^2 compared to the other treatments. DAP impregnation treatment resulted in a hardness value of 2380 N, which appeared to be greater than the control 2292.2 N/mm^2, but the difference in hardness value was not significant. Both DAP and SS coating treatments were not significantly different compared to the control hardness. In the hardness test conducted, impregnation treatment with SS resulted in a smaller value than the control. This can occur because sodium silicate which is alkaline (pH 13) makes the wood degraded (Borůvka *et al*. 2016). Another thing that can affect the results is the fact that the press drying temperature was too high. High pH and temperature can cause hydrolysis of cells and their cell walls (Saka and Tanno 1996). Although not significant, the increase in hardness value in DAP impregnation treatment can be caused by the increase in wood density. In contrast to SS, which has a high pH, DAP has a pH of 8, so it does not damage the wood structure. The increase in density increases the hardness of the wood (Budiman *et al*. 2020). From the statistical test results, the hardness test was influenced by the impregnation treatment with ($p = 0.026$). From the results of further tests (Tukey and Duncan), there was a significant difference between DAP impregnation treatment and SS impregnation. However, both treatments were not significantly different from the control.

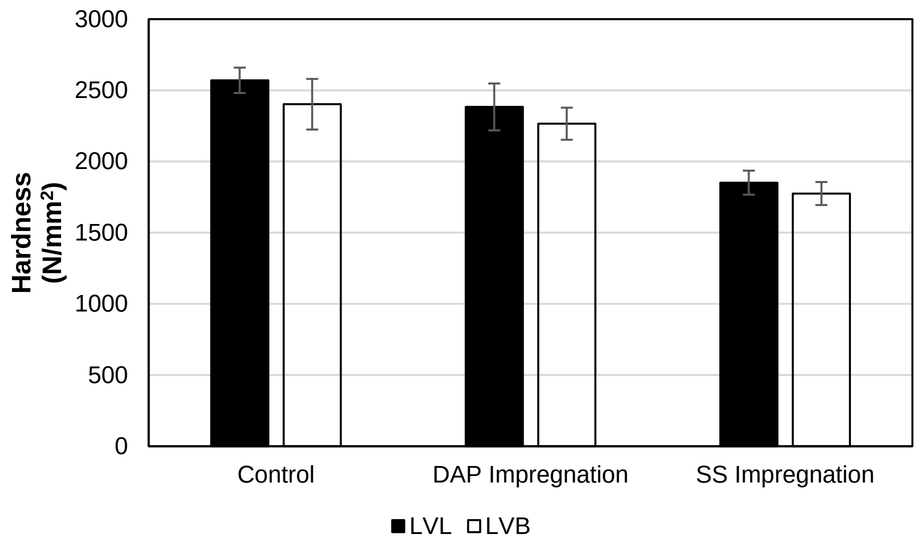

Fig. 9. Hardness

Fire Resistance

From the test results (Fig. 10), it was found that the control treatment had a burning time of 13 minutes, whereas DAP and SS impregnation treatments resulted in 26 and 25 minutes respectively.

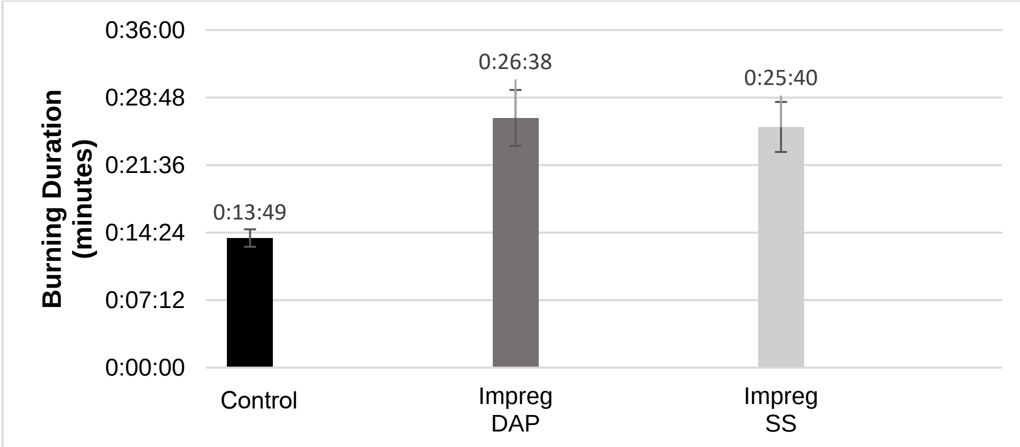

Fig. 10. Fire resistance

Both DAP and SS impregnations resulted in longer burning times compared to the control. Thus, in the burn test, impregnated wood had better fire resistance. DAP is a fire-retardant material with a mechanism to make charcoal faster so that combustion is suppressed. (Lowden and Hull 2013) The mechanism by which SS becomes a retardant material is by ceramification. Ceramification will prevent volatile gases from escaping in the pyrolysis process. The release of these volatile compounds will become additional fuel for the wood. So when this process is inhibited, the burning of wood will also be hampered (Lowden and Hull 2013). Additionally, silica-based retardants will create a layer made from accumulated silica from combustion residue. In the impregnation treatment, the DAP retardant material had a better value. Meanwhile, in the coating treatment, the SS retardant material showed a better resistance value than the DAP coating (Lowden and Hull 2013). All treatments had greater resistance to fire compared to the control. This is in accordance with research conducted by Hautamäki *et al*. (2020). The cited research stated that DAP retardant impregnation was indeed better than SS impregnation in inhibiting fire. The DAP compound has a pyrolysis mechanism that is more efficient in reducing heat. From the correlation test, there is a relationship between moisture content and burning time period. With an R^2 value of 0.84, it shows that the higher the moisture content, the longer the burning time. This is in accordance with research conducted by Bartlett *et al.* (2019). The results of their research show that wood with a higher moisture content is more difficult to burn because it requires higher energy. The energy used to burn is greater because it has to evaporate the water contained in the cells first. Conversely, if the moisture content is low, the cell cavity will be filled with air. This air can facilitate the burning. The implication is that the burning time will be longer if the moisture content of the wood is high. This is in accordance with the data obtained from the test results. It can be seen in Fig. 10 that the DAP impregnation treatment resulted in the longest burning time period compared to the control treatments. Apart from being a retardant, the impregnation treatment increases the moisture content of the panel, as can be seen in Fig. 1. Another thing that can influence the flammability of the panel is its density. From the results of statistical tests, the R^2 value is 0.71. This shows that the higher the density, the longer the burning time period, even though the correlation value is quite low. This phenomenon is in accordance with research conducted by Lowden and Hull (2013). From the results of their research, the denser the wood, the better its resistance to fire and vice versa. If seen from the data obtained in Fig. 2, DAP and SS impregnation increases the density. This could be one of the treatments that can resist fire, apart from being a retardant, then increasing the moisture content, and increasing the density compared to the control.

CONCLUSIONS

1. The use of 20% diammonium phosphate (DAP) and sodium silicate (SS) solutions on jabon wood using impregnation methods affected some of the properties of the panels, especially for the moisture content, density, and bonding strength of laminated veneer lumber (LVL) and laminated veneer board (LVB) compared to the control panels.
2. SS impregnation treatment reduced the hardness of panels, but it did not lead to significant differences compared to the control panels.
3. Other treatments (grain orientation of veneer layer) exhibited more influence on the modulus of elasticity (MOE) and modulus of rupture (MOR) of LVL and LVB.
4. Both DAP and SS impregnation increased the density. Both impregnants showed promise for repressing fire, as well as for increasing the moisture content and increasing the density compared to the control specimens.

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