Characteristics of LVB made of Gmelina Wood (*Gmelina arborea* Roxb.) with the Addition of Diammonium Phosphate and Sodium Silicate Fire Retardants

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Laminated veneer board (LVB) panel from gmelina wood is one form of developing processed wood products to improve the quality of laminated veneer lumber (LVL). The addition of fire-retardant materials is an important element that needs to be developed to increase the fire resistance properties of LVL and LVB panels. The fire-retardant materials used in this research were diammonium phosphate (DAP) and sodium silicate (SS) with a concentration of 20% each, using two different application methods, namely impregnation and coating. This research aimed to determine the effect of adding 20% DAP and 20% SS solutions on physical and mechanical characteristics, formaldehyde emissions, delamination percentage, and the burning time for LVB panels. Panel testing is carried out referring to the requirements of the ASTM D-143:2003 test standard for density, BS EN 317:1993 for swelling-shrinking, JIS A 1460 (2001) for formaldehyde emission, and JIS 701 (2008) for other parameters. Results from physical and mechanical tests showed that panels already met the standard. Formaldehyde emissions were less than 0.4.mg/L classified F**** which means the panel is safe and environmentally friendly. Percentages delamination already met the standard except for both SS impregnation and SS coating application methods. The longest burning time was achieved by the panel with added DAP impregnation.

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INTRODUCTION

Wood is a construction material that is popular with Indonesian people. The potential for supplies in relatively large quantities that are easy to obtain is a special attraction for the public. Apart from that, wood has high strength against tensile and shear forces, which makes it widely used as a construction element (Setiawan *et al*. 2014). The timber industry relies on the supply of wood from natural forests. However, the supply of wood raw materials from natural forests continues to decline, resulting in a significant shortage of wood raw materials (Iskandar and Supriadi 2017). According to Balfas (2010), the national wood deficit reaches more than 50 million m^3/year. This situation can be seen from the reduction in processed wood from various types of commercial wood or wood that is widely traded. Therefore, efforts to plant fast-growing wood species through the development of plantation forests, in the form of industrial plantation forests (HTI) and community forests, is one step to overcome this problem. It is hoped that the existence of wood from plantation forests will be able to replace the shortage of wood supply from natural forests. The types of fast-growing wood include mangium, sengon, jabon, rasamala, gmelina, and others (Iskandar and Supriadi 2017).

Gmelina (*Gmelina arborea* Roxb.), which is also known as "white teak," is a type of fast-growing wood. According to data from the Central Statistics Agency (2020), the amount of gmelina roundwood production in Indonesia in 2019 reached 65,616.75 m^3 and increased compared to the previous year. In 2018, the amount of gmelina roundwood production reached 52,488.01 m^3 (Central Statistics Agency 2019). This wood is widely used as building construction material, furniture, pulp, and so on. Gmelina wood stems have a yellowish white colour with fine grey fibrous bark. Gmelina wood is classified as durable class IV–V and strong class III, with an average density of between 0.42 to 0.61 g/cm^3. Most of the wood that comes from plantation forests has a small diameter. If this wood is processed directly, it will produce sawn boards or beams with small dimensions, so its use is limited. With these wood conditions, it is necessary to develop processed wood products to improve their quality and utilization, one of which is making laminated veneer lumber (LVL) (Iskandar and Supriadi 2017).

Laminated veneer lumber (LVL) and laminated veneer board (LVB) are processed wood products resulting from the development of woodworking technology. LVL is made from veneer obtained from wood logs that are peeled into thin sheets, then glued together using adhesive with the veneer arranged parallel to the grain. Meanwhile, in LVB there are several veneers arranged across the direction of the other veneer fibers (Alamsyah *et al.* 2023, 2024). These artificial boards are generally made as a replacement for sawn products, such as beams and boards. This is due to the advantages of artificial boards, which can be made with larger dimensions than solid wood, more uniform thickness, and have characteristics that are superior to solid wood (Iskandar and Supriadi 2017).

According to data from the Central Statistics Agency (2022), total plywood production in Indonesia has increased in 2021 to 4,445,664.17 m^3 compared to the previous year. The total plywood production in Indonesia in 2020 was 3,882,567.50 m^3 (Central Statistics Agency 2021). Meanwhile, in 2017, interest in processed wood products continued to increase from 6,000 m^3 to 7.55 million m^3 for plywood, LVL, veneer and sawn wood products (MEF 2018). LVL and LVB wood panels have the advantage of being able to replace solid wood while maintaining or even improving the structural properties of the wood (Haygreen and Bowyer 1996).

The use of LVL panels as a material for furniture and building construction elements means that combustion resistance will be an important element to consider. The development of fire-retardant-treated (FRT) for LVL and LVB panels is very important, considering the flammable nature of wood (Ross 2010). Diammonium phosphate (DAP) and sodium silicate (SS) are two fire retardant materials that are quite commonly used in society. The working mechanism of DAP is to form a char formation that can inhibit the spread of fire to the inside of the wood panel. The SS forms a charred layer that can inhibit the release of volatile gases, which otherwise would tend to speed up combustion (Hautamäki *et al*. 2020).

In this research, diammonium phosphate and sodium silicate were added as fire retardants to LVL wood panels and LVB from gmelina wood, either by impregnation or as coatings. The goal was to determine their effect on the characteristics of the panels, with attention to their burning times and burning rates.

EXPERIMENTAL

Tools and Materials

The tools used in this research were caddy, flame torch, glue spreader, impregnation machine, rotary cut machine, press dryer, and Universal Testing Machine (UTM). The materials used in this research were gmelina wood logs with a diameter of 30 cm and a height of 150 cm obtained from 12-year-old gmelina trees from Cibugel Village, Sumedang Regency, West Java. Other materials used were fire retardant materials in the form of diammonium phosphate (DAP) and sodium silicate (SS), Propan ™ Aqua Deck Lasur ADL 605 wood paint, phenol formaldehyde (PF) adhesive, and LPG gas.

Veneer Preparation

Wood veneer samples were obtained from wood logs that were peeled using a rotary cut machine and cut into veneer measuring 130 cm x 128 cm with a thickness of 2.2 mm. The wood veneer was dried in a press dryer until it reached 0% moisture content to prevent too high fluctuations in moisture content during sample shipping and storage. Wood veneer measuring 130 cm x 128 cm was cut into veneer measuring 120 cm x 40 cm.

Fire-Retardant Preparation

The fire-retardant materials used in this research were diammonium phosphate (DAP) and sodium silicate (SS). In its application, two different methods were used, namely impregnation on the veneer and coating which is mixed with the base coat in the finishing process. The concentration of fire-retardant material used for each treatment is 20% (Hautamäki *et al*. 2020).

Impregnation Treatment

The impregnation process was only carried out on veneer for panels that have been added with fire retardant material using the impregnation method. The impregnant solution is obtained from 20% fire retardant (DAP and SS) dissolved in water. The veneer is soaked in an impregnating solution and impregnated at a pressure of 0.5 MPa for 25 min. The veneer is then dried in a press-dryer until it reaches a water content of 0 to 8%.

Assembling Process

The target size of the wooden panels made was 120 cm x 40 cm x 1.8 cm. Veneer measuring 120 cm x 40 cm with a water content of 0 to 8% was arranged in 9 layers (9 ply), which were glued using phenol formaldehyde adhesive. The veneer surface was coated with an adhesive mixture of 25 g/m². In LVL wood panels, all the veneers were arranged parallel to the grain of the other veneers. The 2nd and 8th layer veneers were arranged perpendicular to the direction of the other veneer fibers on the LVB (Alamsyah *et al*. 2024) in the arrangement, as indicated in Table 1. Next, they were cold-pressed on a cold-press machine with a pressure of 8 kgf/cm² for 18 min. Then, the panels were hot-pressed in a hot-press machine with a pressure of 8 kgf/cm² for 15 min. The felted panels are then trimmed to cut off the edges that do not fit. Conditioning was carried out for 24 h at room temperature. Each panel was sanded to sand the rough surface of the panel and adjust the thickness of the panel.

Table 1. Composition of Veneer Layers Structure of Board

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

Note: // = parallel; ⊥ = perpendicular

Finishing Process

The material used as a coating for finishing wooden panels was Propan™ Aqua Deck Lasur ADL 605 paint as a base coat. For samples that were given additional fire-retardant material using the coating method, the base coat paint was mixed with the fire-retardant material. The composition of the coating mixture was 20% DAP/SS solution and Propan ™ Aqua Deck Lasur ADL 605 paint in a ratio of 40:60 (w/w). The coating material was applied using the spray method with a coating weight of 75 g/m².

Moisture Content

Wood moisture content testing refers to the JIS 701 (2008) standard. The test sample was made with a size of 5 cm x 5 cm. The test samples were weighed (initial weight) and then dried in an oven at 103+2 °C for 24 h until the weight was constant, at which point the weight was recorded (final weight). The wood moisture content was calculated by Eq. 1,

$$\boldsymbol{MC} = \frac{\boldsymbol{m_0 - m_1}}{\boldsymbol{m_1}} \times \mathbf{100\%} \tag{1}$$

where *MC* is the moisture content (%), m_0 is the initial weight (g), and m_1 is the oven dried weight (g).

Density

Wood density testing refers to the ASTM D-143 standard (2003). The test sample was made with a size of 5 cm x 5 cm. The test sample was weighed, and the volume was calculated by measuring the length, width and thickness using a caliper. The sample was dried in an oven at 103+2 °C for 24 h until the weight was constant. Wood density was calculated by the following equation,

$$\boldsymbol{\rho} = \frac{\boldsymbol{m}}{\boldsymbol{v}} \tag{2}$$

where ρ is the density (g/cm^3), m is the sample mass (g), and v is the sample volume (cm^3).

Swelling-Shrinkage

Swell-shrink testing refers to the BS EN 317 standard (1993). The test sample used in this test measured 5 cm x 5 cm. The dimensions of the test sample (length, width and thickness) were measured first, and the weight was calculated. The swelling-shrinkage test was carried out in several stages, namely oven for 24 h until it reached the dry weight of the furnace (bkt 1), soaking for 2, 24, 48, or 72 h, and drying again using the oven for 24 h until it reached the dry weight of the furnace (bkt 2). Dimension and weight measurements were carried out at each stage. The temperature used to dry the samples was 103.5 °C. Thickness expansion, length and width shrinkage were calculated by Eq. 3,

$$\boldsymbol{Ts} = \frac{\boldsymbol{t_2 - t_1}}{\boldsymbol{t_1}} \times \mathbf{100\%} \tag{3}$$

where T_s is the thickness Swelling (%), t_1 is the thickness of sample before soaking (mm), and t_2 is the thickness of sample after 24 h soaking (mm).

Veneer Weight Gain Percentage

The percentage of weight gain was calculated on the veneer after the impregnation process. The test sample used was a veneer measuring 10 cm x 10 cm. Samples were weighed before and after the impregnation process. The percentage of weight gain can be calculated using the following equation (Rahayu *et al*. 2020),

$$\boldsymbol{WPG} = \boldsymbol{m_0} - \boldsymbol{m_1} \times \mathbf{100}\% \qquad (4)$$

where WPG is the weight percent gain or percentage of weight gain (%), m_0 is the sample weight before impregnation (g), and m_1 is the sample weight after impregnation (g).

Mechanical Properties

Bending strength

Bending strength testing refers to the JIS 701 (2008) standard. The test sample was made with dimensions of 42 cm x 5 cm x 1.8 cm. Testing was carried out using a Universal Testing Machine (UTM) up to the elastic point limit of the test sample which is marked by the sample being broken or damaged. In this test, MOE and MOR values were obtained from the sample.

Bonding strength

Bonding strength testing refers to the JIS 701 (2008) standard. The test sample was made with dimensions of 20 cm x 1.8 cm x 1.8 cm. Testing was carried out on the front (face) and side (edge) using a Universal Testing Machine (UTM). Testing continued until the sample became damaged. In this test, the horizontal shear strength value of the sample was obtained.

Hardness

Hardness testing refers to the JIS 701 (2008) standard, using a test sample measuring 5 cm x 5 cm. The test was carried out using a Universal Testing Machine (UTM) with a load applied using an iron ball with a diameter of 10 mm until it penetrated the sample surface to a depth of half the diameter of the iron ball (5 mm).

Delamination Testing

Wood delamination testing refers to the JIS 701 (2008) standard. The test sample was made with dimensions of 7.5 cm x 7.5 cm. The test sample was weighed, then soaked in boiling water for 4 h. After that, the sample was drained and placed in an oven at 60 °C for 20 h until its original weight (100 to 110%) was reached. Then, the test sample was observed for layers on each side. The delamination ratio can be calculated using the following equation,

$$\boldsymbol{D} = \frac{\boldsymbol{a}}{\boldsymbol{b}} \times \mathbf{100}\% \qquad (5)$$

where D is the delamination (%), a is the total length of delamination on 4 sides (mm), and b is the total length of lines on 4 sides (mm).

Formaldehyde Emission Testing

Formaldehyde emission testing refers to the JIS A 1460 (2001) standard, and testing was conducted only on LVL panel samples. The test sample was made with dimensions of 15 cm x 5 cm. The tip of the test sample was dipped in liquid wax until the entire tip was covered, then left to sit until it hardened. In a desiccator, 20 mL of distilled water was placed in a plastic cup. The test sample was put into the desiccator and stored for 24 h at 20 °C. After that, 10 mL of the distilled water was taken and put into an Erlenmeyer flask containing 10 mL of acetyl-acetone ammonium acetate (a4). Then, the Erlenmeyer flask was covered and put in hot water for 10 min. Next, the mixture was tested using a UV-Vis spectrophotometer to obtain absorbance values. The absorbance values were then calculated and classified according to the classification based on the JIS A 1460 (2001) standard as in Table 2.

Table 2. Classification of Formaldehyde Emission (JIS A 1460 2001)

Classification	Avg. (mg/L)	Max. (mg/L)
F****	0.3	0.4
F***	0.5	0.7
F**	1.5	2.1
F*	5.0	7.0

Fire Resistance Testing

Testing for fire resistance was carried out using a burn test, which refers to the testing technique adopted from the VPS PS 1-19 standard. Testing was only carried out on LVL panel samples. The test sample was made with dimensions of 40 cm x 40 cm. Then, the sample was placed on a support at a distance of 17 cm from the fire source with a flame burst temperature ranging from 1100 to 1250 °C. In the test sample, fire was fired with a focus on the center of the panel. During the test, the burn time was calculated until smoke appeared on the back surface of the test sample.

Fig. 1. Fire resistance test procedure (Alamsyah *et al*. 2024)

Research Analysis

Test result data were analyzed using a 2-factor Completely Randomized Design (CRD) with 3 replications. The factors used were (1) variations in the orientation of the veneer fibers, in the form of LVL (the orientation of the veneer fibers arranged parallel) and LVB (the orientation of the 2^{nd} and 8^{th} veneer fibers arranged perpendicular to the direction of the other veneer fibers), as well as (2) treatment with the addition of fire retardant materials (contact or without the addition of fire retardant materials, DAP impregnation, SS impregnation, DAP coating, and SS coating).

RESULTS AND DISCUSSION

Physical Properties

Moisture content

Moisture content testing shows the percentage of the amount of water contained in the panel board to the weight of the panel board in kiln dry or oven dry conditions (Supriadi *et al*. 2020). The moisture content value of each treatment was then compared with the moisture content requirements for panel boards according to the JAS:2008 standard, so that it can be seen whether the panel met the standards or not.

Figure 2 shows a graph of the results of moisture content testing on LVL and LVB wood panels for each treatment. Based on the research results, the moisture content value of the gmelina panel board samples showed values ranging between 10.94% and 13.24%. The lowest moisture content was found in the LVL-control wood panel samples, while the highest one was found in the DAP-impregnated LVB wood panel samples. However, all samples of panel board in this study met the JAS:2008 standard for LVL which requires a water content value of <14%.

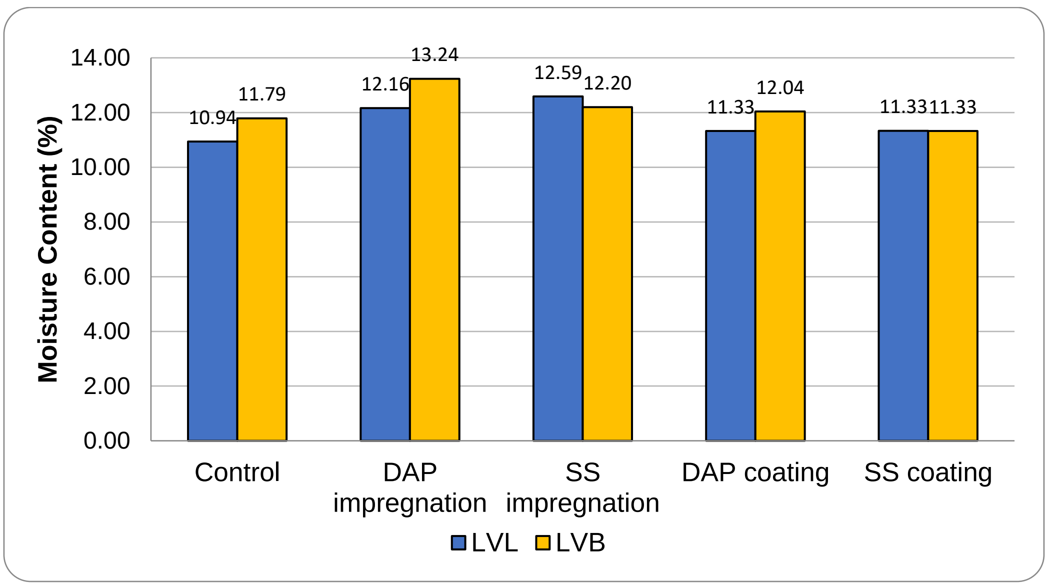


Fig. 2. Average moisture content of LVL and LVB

The results of the statistical analysis test showed that the orientation of the veneer fibers was not significantly different from the percentage of moisture content of the panel board. Meanwhile, for each treatment the results showed no significant difference in the percentage of moisture content of the panel boards. This is because the orientation of the veneer fibers has a more significant effect on the mechanical and structural properties of the wood panel. Research by Shukla and Kamdem (2008) shows that the physical properties of LVL panels made from two different hardwood species are influenced by the physical properties of the solid wood species, but they are not influenced by the fiber orientation of the panels made.

The varying moisture content values of panel board can be caused by varying initial moisture content of the veneer. The variation in moisture content values is thought to occur due to the influence of temperature and humidity around the veneer storage area. This is caused by the hygroscopic nature of wood, which can release and attract water content (moisture) in response to changes in temperature and humidity in the surrounding air (Bahanawan *et al*. 2020). In conditions of high air humidity during storage, wood veneers will absorb water content (moisture) from the surrounding environment. According to Haygreen and Bowyer (1996), the type of wood can also influence the water content of panel boards. The type of wood that has a high density value, the higher the moisture content (Arsad 2011; Setiawan *et al*. 2014).

Another factor that influences the variation in the percentage of moisture content of wood panels is the imperfect drying process, especially for veneer resulting from the drying process after impregnation. The principle of the impregnation method is to replace the water molecules contained in the cell walls with impregnating material molecules (Haygreen and Bowyer 1996). In this research, the impregnating material used was a mixture of fire retardant materials in the form of DAP and SS, with water as the solvent. This impregnation treatment can make the veneer wet again, so that if the drying process is less than perfect, a fairly high moisture content will remain in the veneer. Therefore, when covered with adhesive and arranged into one wooden panel, the adhesive will fill the empty cavities and harden. The ability of panel board to absorb and release water will be reduced, so that when the glued veneer is not completely dry (moisture content > 8%), the water content will be locked and it is possible that the resulting panel board product will have a fairly high moisture content (moisture content close to 14%).

The weight of the layer can also affect the moisture content of the panel board. The moisture content of panel boards will tend to increase as the weight of the whitewash used increases. This is caused by an increase in the specific gravity of wood (Arsad 2011; Setiawan *et al*. 2014; Supriadi *et al*. 2020).

Density

Wood density testing shows the amount of material contained in the wood cell walls, including other substances that play a role in the strength properties of wood, so that the density value of the panel board has an influence on the strength of the resulting panel board. Density testing was carried out to determine whether the artificial boards studied had low, medium, or high density (Supriadi *et al*. 2020). Density is one of the properties of wood which can indicate strength and other mechanical properties. The higher the density of the wood, the higher the mechanical properties of the wood.

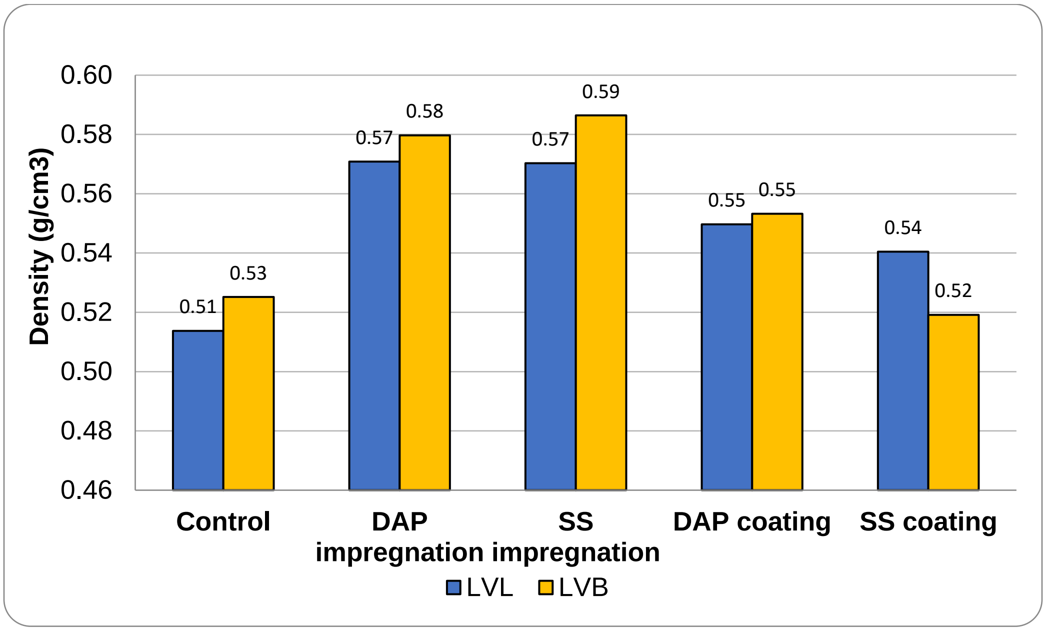


Fig. 3. Average density of LVL and LVB

Figure 3 shows a graph of the density test results on LVL and LVB wood panels for each treatment. The research results showed that the density value of gmelina imitation board ranged between 0.51 and 0.59 g/cm³. The lowest wood density value was found in the LVL-control wood panel sample, while the highest density was found in the SS-impregnated LVB wood panel sample. The density after becoming an artificial board shows a higher value compared to the density of the wood. The density of gmelina wood at a water content of 12% with a thickness of 5 to 7 cm is 0.49 g/cm³ (Gérard *et al*. 2017).

The results of the statistical analysis test showed that the orientation of the veneer fibers was not significantly different from the density value of the panel board. Meanwhile, each treatment showed a significantly different value to the density value of the panel board. Based on the research results, it was found that the density value in the treatment of applying fire retardant material with impregnation was greater than that of coating, and the lowest value was found in the control. This is in accordance with research by Li *et al*. (2020), who stated that the increased veneer density was caused by the wood cell cavities being filled with oligomers of fire-retardant materials in the form of DAP and SS. In this research, the impregnation process carried out on Chinese pine wood using 20% (w/w) sodium silicate can increase the density value of the wood with a density increase ratio of 53.44 ± 1.59%.

Tenorio *et al*. (2011) showed an increase in the density value after becoming an artificial board with a density value for LVL of 0.523 g/cm³ and for plywood (LVB) of 0.516 g/cm³. The increase in the density value of the panel board is influenced by the presence of an adhesive layer that fills the empty cavities and compaction occurs when pressing the panel board (Supriadi *et al*. 2020). By using the same raw materials and the same manufacturing conditions, the difference in fiber orientation of LVL and LVB panels was not significantly different in terms of density values. The factors that influence the value of wood density include the type of wood (wood density), the amount of compression pressure during the compression process, the number of constituent layers, adhesive content, and other additional materials (Kelly 1977).

Swelling-Shrinkage

Panel boards are composed of several layers of veneer that are glued together with adhesive and subjected to compression until they are formed into a panel. The long orientation direction of the wood panel is the tangential orientation direction of the solid wood. The width orientation direction of the wood panel is the radial orientation direction of the solid wood.

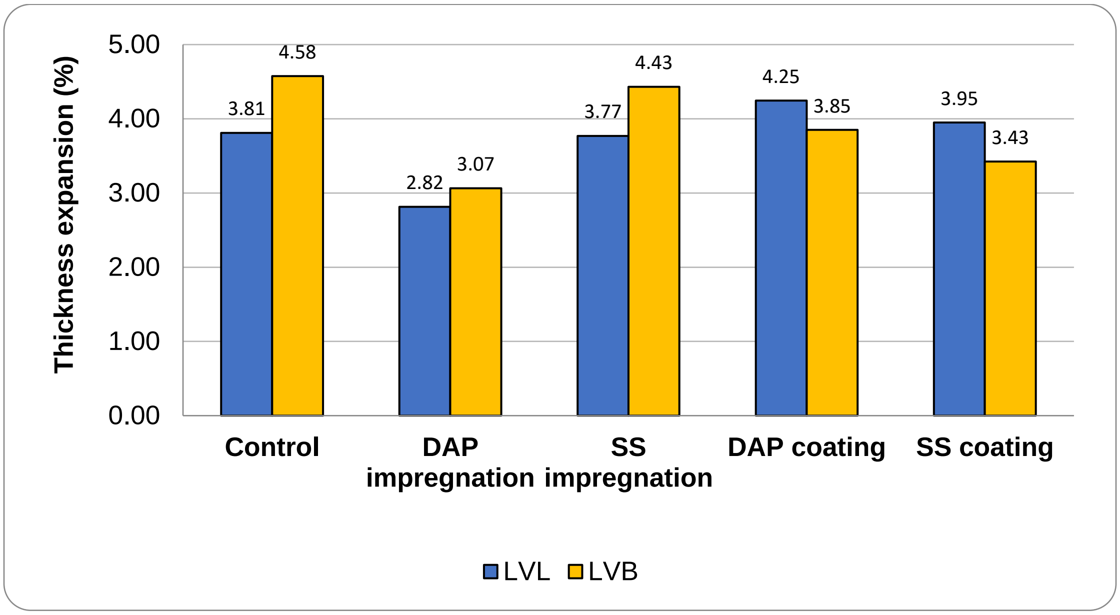


Fig. 4. Average thickness expansion of LVL and LVB

Figures 4 through 6 show the test results for thickness expansion, length shrinkage, and width shrinkage of gmelina panel board samples in all treatments. Based on the test results, it was found that the thickness expansion value tended to be higher for LVB panels than LVL (Fig. 4). The results of this study were similar to those of Tenorio *et al*. (2011), which showed that the percentage of thickness expansion of LVB wood panel samples from gmelina wood (2.09%) is greater than that of LVL wood panel samples (1.76%).

Based on the results of statistical analysis, the orientation of the veneer fibers was significantly different from the percentage of shrinkage in the length of the wood panel. Figure 5 shows the results of the test for shrinkage of the length of the wood panels in all treatments. The length loss value tended to be higher for LVB panels than LVL.

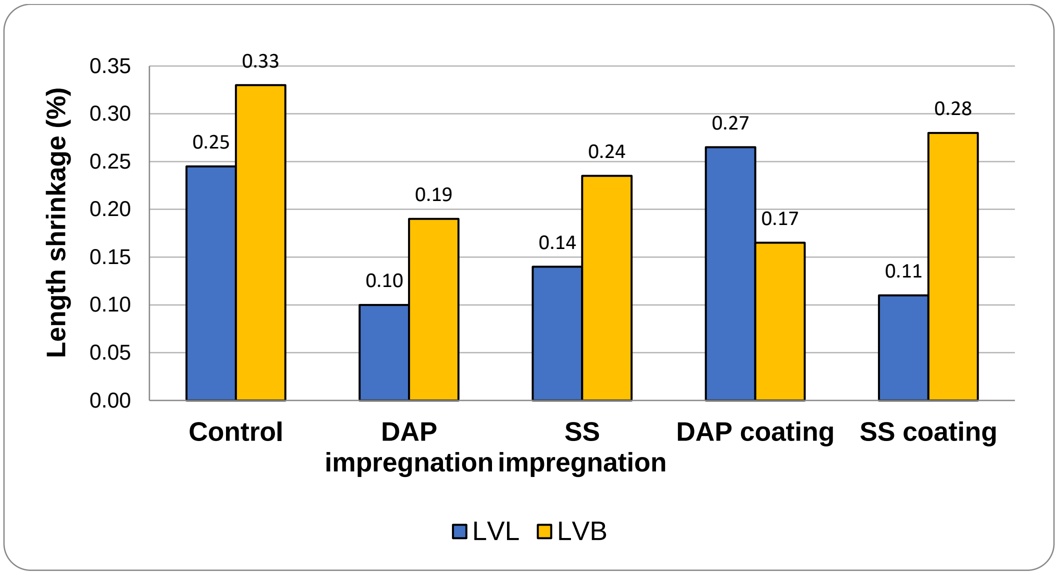


Fig. 5. Average length shrinkage of LVL and LVB

Figure 6 shows the results of the test for shrinkage of the width of the wood panels in all treatments. Based on the test results, it was found that the width loss value tended to be higher for LVL panels than LVB. This is because in LVL panels all the veneers were arranged parallel to the direction of the grain, or like the tangential direction of solid wood.

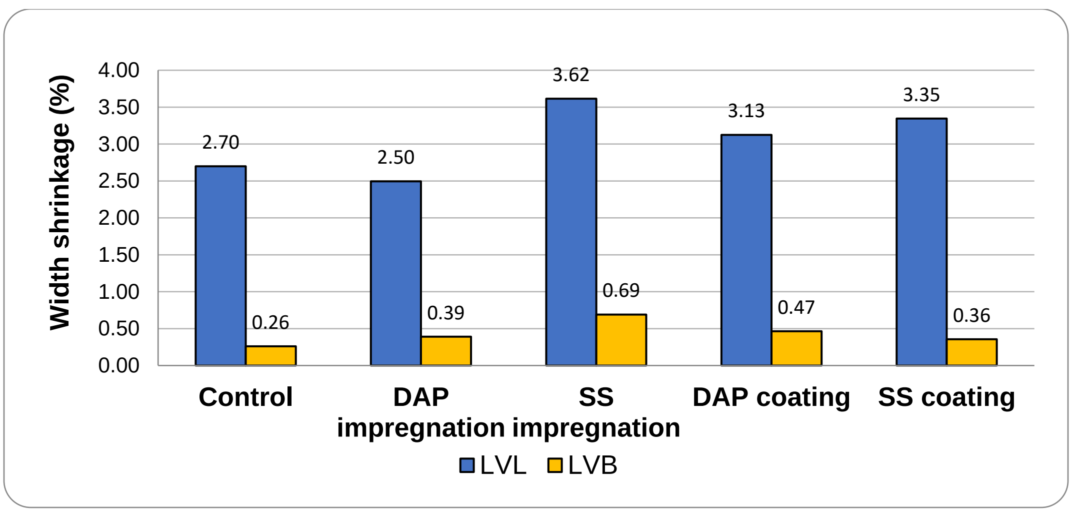


Fig. 6. Average width shrinkage of LVL and LVB

Meanwhile, in the tangential direction wood had greater swelling-shrinkage properties compared to the longitudinal direction (Riki *et al*. 2019). In LVB panels the direction was arranged perpendicular to the direction of the other veneer fibers, thus providing the ability to resist shrinkage in the direction of the panel width. The direction of the grain in the width dimension of the panel was the direction of the longitudinal grain of the solid wood, where wood has low swelling-shrinkage properties in the longitudinal direction (Prihatini *et al*. 2020). Therefore, the percentage of shrinkage in the width dimension for LVL was higher than for LVB panels.

Based on the method of applying the fire-retardant material, the percentage of thickness expansion, width shrinkage, and length shrinkage in wood panel samples tends to be higher when treated using sodium silicate (SS). This can be caused by the characteristic of SS which is a strong base, causing degradation of the chemical components of the wood which results in the formation of amorphous areas. Therefore, wood will bind more easily with water and cause thick expansion (Kuznetsov *et al*. 2021).

Weight Percent Gain (WPG)

Weight percent gain or weight gain percentage shows the percentage of weight gain that occurs in a product after being treated. In this research, WPG described the percentage of weight gain in veneer after being impregnated using fire retardant materials in the form of diammonium phosphate (DAP) and sodium silicate (SS). Based on the research results, it was found that the percentage of increase in veneer weight in the impregnation treatment with DAP and SS respectively was 8.90% and 9.79%. The percentage increase in weight of gmelina veneer in the impregnation treatment using SS retardant material was greater than in the impregnation treatment using DAP. According to Ding *et al*. (2008), wood porosity and density can affect the impregnated rate of wood. Impregnated rate will increase along with high wood porosity and low wood density. This is because wood with low density has more empty cavities available, so it can increase the impregnated rate which makes it easier for DAP and SS molecules to enter the wood (Sukartana and Balfas 2008). Gmelina wood has a density of 0.49 g/cm³ (Gérard *et al*. 2017), with a fairly small to fairly large pore diameter and a small frequency. Apart from that, gmelina wood has a high tylosis content. Tylosis is a bubble-like structure that originates from the protoplasm of parenchyma cells that fill the vessel cells near the paired nodes (Mompewa *et al*. 2019). The high content of tylosis and other deposits in the cell cavities can inhibit the rate of water movement in the wood (wood is difficult to dry) and can prevent the entry of impregnating materials into the wood (Wahyudi 2013). Therefore, with the small pore diameter and low frequency, as well as the high tylosis content, the percentage of weight gain after impregnation of gmelina wood veneer is not that large.

Mechanical Properties

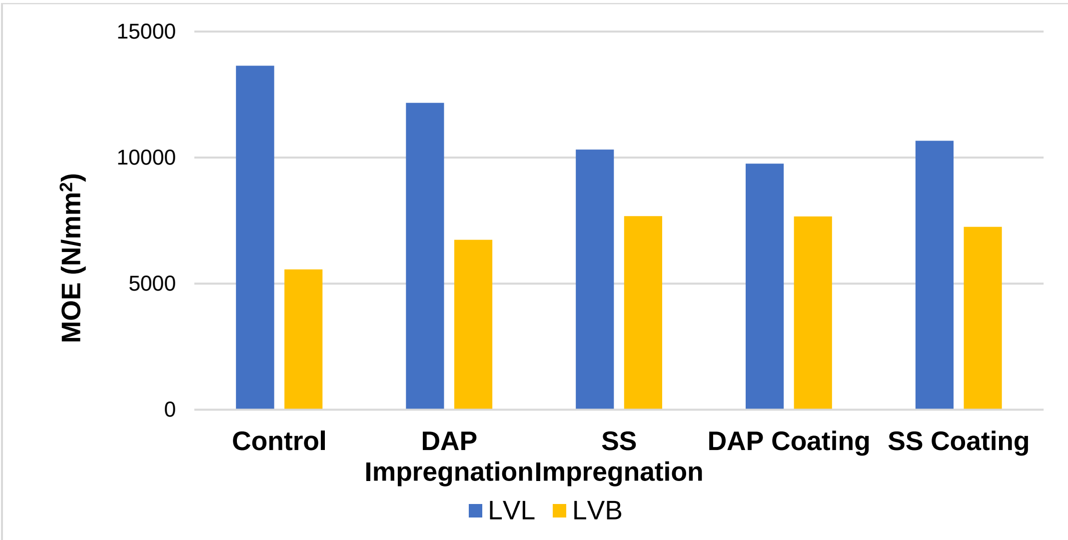
The mechanical properties of artificial boards can be defined as their ability to withstand external loads (Supriadi *et al*. 2020). Mechanical properties testing consists of bending strength, bonding strength, and hardness. The mechanical properties data for LVL and LVB panels are shown in Tabel 3 and Figs. 7, 8 and 9.

Table 3. Average Value of Mechanical Properties Test

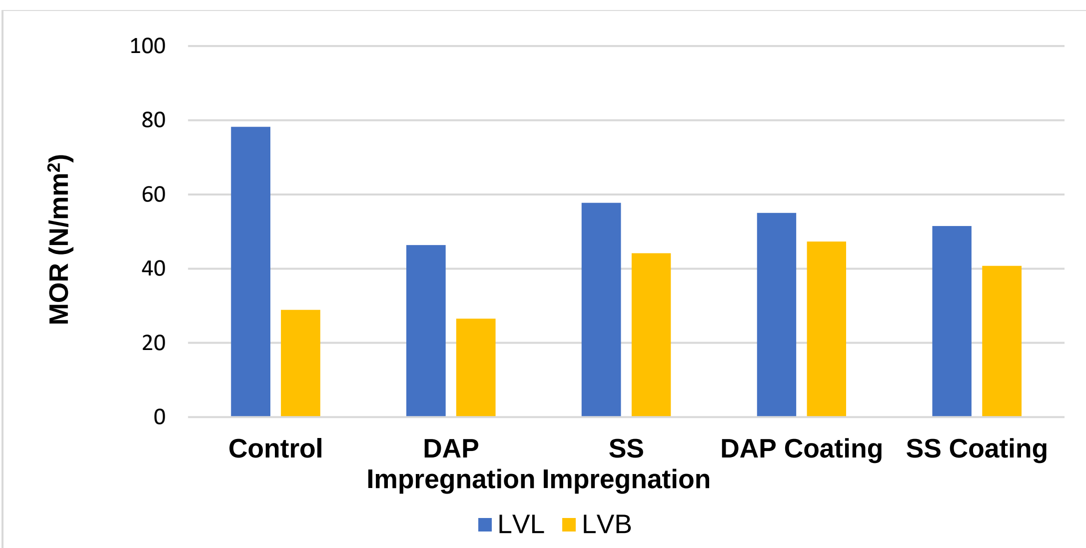
Retardant application	Bending (N/mm^2)				Horizontal Shear Strength (N/mm^2)		Hardness (N)	
	MOE		MOR					
	LVL	LVB	LVL	LVB	LVL	LVB	LVL	LVB
Control	13646.15	5567.66	78.23	28.98	3388.29	3542.22	6.65	4.30
DAP impregnation	12171.10	6740.16	46.35	26.53	4057.62	3516.60	6.69	4.04
SS impregnation	10319.41	7679.20	57.75	44.16	2895.71	3708.01	6.04	5.71
DAP coating	9762.60	7664.42	55.03	47.33	3291.99	3801.96	5.90	5.43
SS coating	10666.75	7256.71	51.50	40.77	3918.56	3106.06	7.09	5.92

Bending Strength

Bending strength testing was carried out to measure the MOE and MOR values of LVL and LVB wood panel samples from all treatments (Fig. 7). Based on the results of statistical analysis, it was found that the orientation of the veneer fibers was significantly different from the MOE and MOR values of wood panels. This can be seen from the average MOE value in the LVL panel sample which tended to be higher than the LVB panel sample as shown in Table 4. The same thing also happened in the MOR test, where the average MOR value in the LVL panel sample was higher than LVB panel samples. This is because LVL has a higher strength in the longitudinal direction than LVB.



MOE **(a)**



MOR **(b)**

Fig. 7. MOE (a) and MOR (b) values

In LVL wood panels, the veneer arrangement is made parallel with all grain directions parallel. Meanwhile, in LVB wood panels, the 2nd and 8th layers of veneer are arranged with the fiber orientation perpendicular to the direction of the other veneer fibers. Veneer with a parallel grain direction (long) is the longitudinal direction of the solid wood, while veneer with a perpendicular direction (cross) is the tangential direction of its solid wood. This bending test was carried out at four points where the load will be supported in the longitudinal section. According to Sun *et al*. (2022), the strength of the longitudinal direction of wood is greater than the tangential direction. Therefore, the bending test showed that LVL wood panels were better than LVB wood panels.

Bonding Strength

Bonding strength testing was carried out to measure the horizontal shear of LVL and LVB wood panel samples from all treatments (Fig 8). Based on the results of statistical analysis, it was found that the grain orientation of wood veneer in the panels has a significant effect on the horizontal shear strength value of the wood panels. The research results shown in Table 4 show the horizontal shear strength values for LVL and LVB wood panel samples from all treatments. Based on the test results graph, it was found that the LVL wood panel samples had higher strength values compared to the LVB wood panel samples in all treatments. The strength of LVL panels is caused by the parallel arrangement of veneers, making LVL wood panels have higher structural strength than LVB wood panels (Tenorio *et al*. 2011).

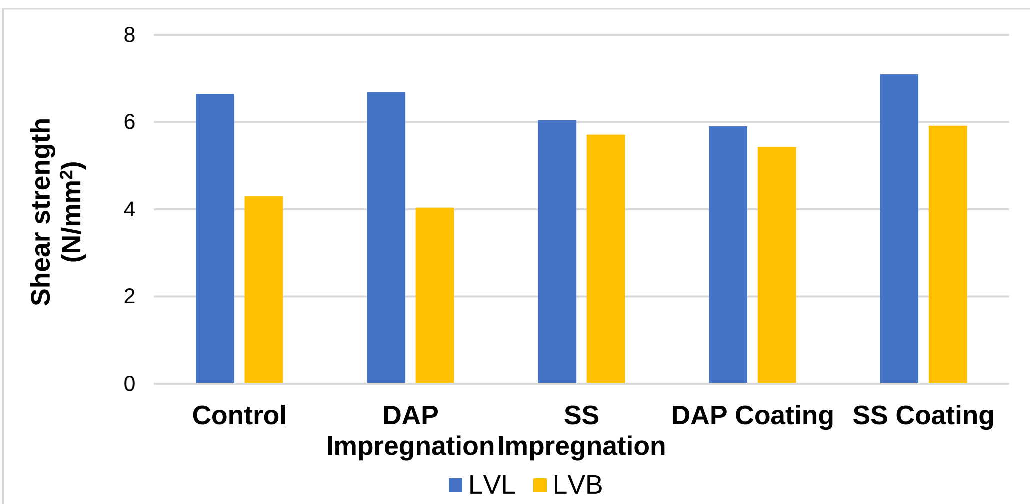


Fig. 8. Horizontal shear strength

Based on the method of application of the fire-retardant material, impregnation treatment tends to have a lower value than coating treatment. This is in accordance with research by Kawalerczyk *et al*. (2019), who stated that impregnation treatment can reduce the bonding value, especially in veneers that receive impregnation treatment. Apart from that, adhesives are also related to the shear strength of LVL and LVB wood panels. According to Yan *et al*. (2023), the bonding value of a wood panel can be influenced by the type of adhesive used. However, in this study PF adhesive was used which has good quality as an adhesive and does not cause a large decrease in bonding value when compared to other types of formaldehyde adhesives.

Hardness

The results of statistical analysis showed that the orientation of the fiber direction and the application treatment of the fire-retardant material were not significantly different to the panel hardness value. The lowest hardness value was found in the SS-impregnated LVL wood panel sample (Fig. 9). This is due to the characteristics of sodium silicate which is alkaline and capable of degrading the chemical components of wood, so that the strength of the wood is reduced (Borůvka *et al*. 2016). Meanwhile, the highest hardness value was found in the DAP-impregnated LVL wood panel samples. In contrast to the properties of sodium silicate, diammonium phosphate is not classified as a strong base with a pH of 8. Therefore, DAP does not have properties that can degrade the chemical components of wood, so increasing the density value of DAP-impregnated LVL wood panels can increase the hardness value of the wood panels (Budiman *et al*. 2020).

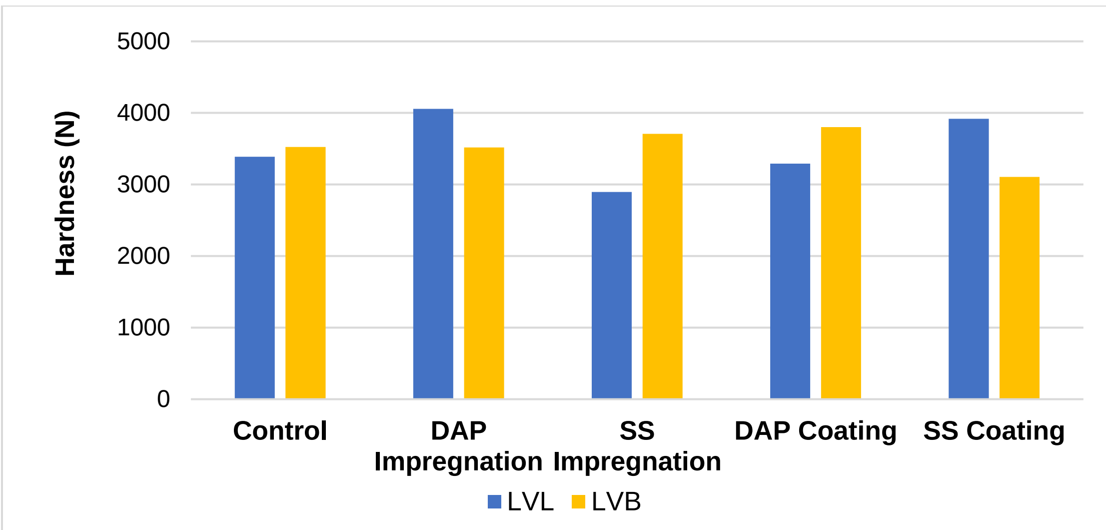


Fig. 9. Hardness values

Delamination

The results of the delamination percentage test on the gmelina imitation board panels are shown in Fig 10. Delamination in this panel board sample could be caused by the adhesive curing process in the middle of the veneer layer being difficult to achieve.

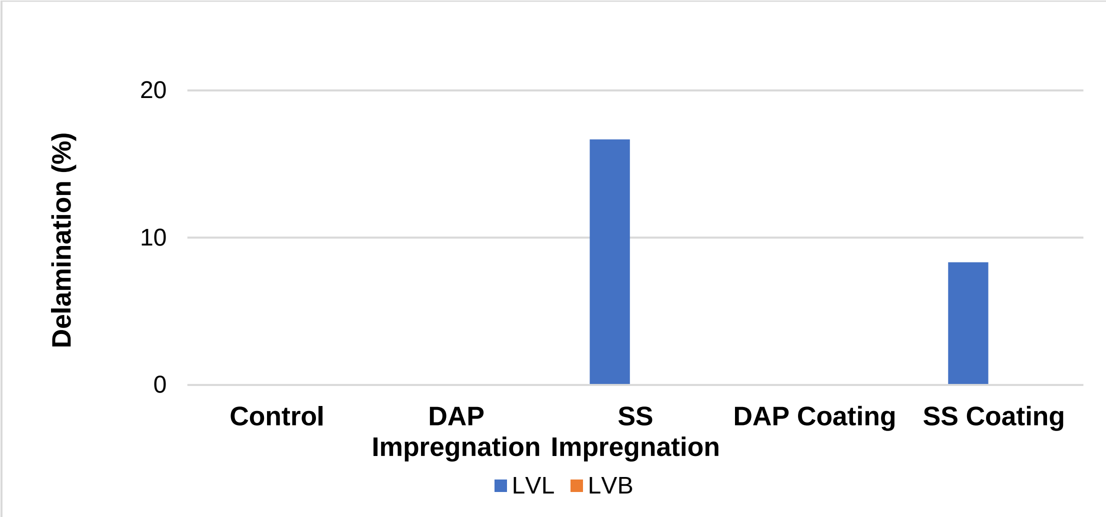


Fig. 10. Percentage of delamination

Based on the test results, it was found that the percentage of passing the delamination test on LVL panels with SS-impregnation and SS-coating treatment was 16.67% and 8.33% with a delamination percentage of 0% on other wood panel samples. Based on the JAS:200 standard for LVL panels, the standard percentage of passing the test is <10%, so that LVL panels with SS-impregnation treatment are declared not to have passed the delamination test with a large delamination percentage reaching 16.67%. By contrast, no delamination occured in LVB panels. According to Ekawati (1968), factors that influence the delamination value of artificial boards include the shear plane, type of adhesive, and their interactions. Delamination in this panel board panel sample could be caused by the adhesive curing process in the middle of the veneer layer being difficult to achieve due to the large number of layers, resulting in less than optimal interaction between the adhesive and the veneer surface (Iskandar and Supriadi 2017).

Formaldehyde Emissions

The formaldehyde emission test results from the LVL panel are in Table 5. The table lists the average value and maximum value of the amount of formaldehyde emissions in the gmelina LVL panel. Based on the test results, it was found that all LVL panels from gmelina wood in each treatment were included in the F**** classification. The results obtained were in accordance with the JIS A 1460 (2001) standard for LVL with the average and maximum values respectively, namely 0.3 and 0.4 mg/L, so that all LVL panels are judged to be safe to use. This good formaldehyde emission test result was obtained because the type of adhesive used in making wood panels uses phenol formaldehyde (PF) adhesive, which has a low formaldehyde emission level (Liang *et al*. 2021).

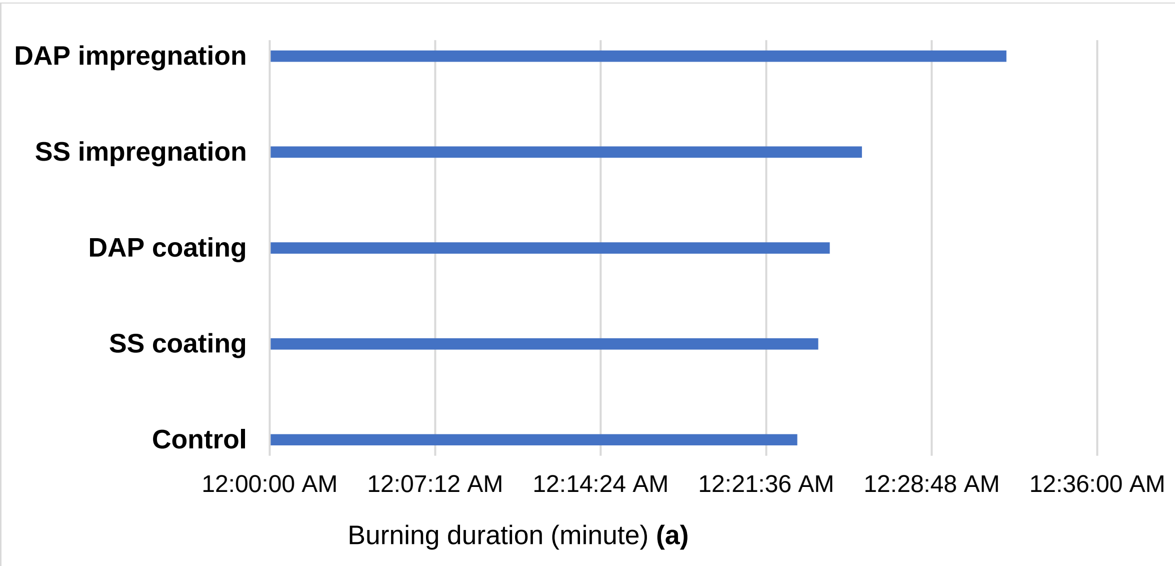
Table 4. Formaldehyde Emission of LVL

Treatment	Average Value (mg/L)	Maximum Value (mg/L)	Classification
Control	0.3	0.4	F****
DAP impregnation	0.1	0.1	F****
SS impregnation	0.3	0.3	F****
DAP coating	0.3	0.3	F****
SS coating	0.3	0.3	F****

The DAP impregnation panel sample had a lower formaldehyde emission value than the control panel sample. This is attributed to the nature of DAP, which produces ammonia and N-H groups on the veneer surface that react and help reduce formaldehyde emissions (Demir *et al*. 2017). Based on statistical tests, the orientation of the fibers in the panel board was not significantly different from the amount of formaldehyde emissions. Therefore, formaldehyde emission testing was only carried out on LVL panel samples.

Fire Resistance

The combustion test results obtained in this study were the average burning time and burning rate of the samples. Based on the results of statistical analysis, it was found that the DAP impregnation treatment gave significantly different results to the burning time. Figures 11 (a and b) shows a graph of the burning time for each treatment. Based on the research results, it was found that the addition of fire-retardant material can increase the burning time and reduce the burning rate of wood panels, when compared with control samples. The order of burning time up to the longest time in sequence is control (22 min 57 seconds), SS coating (23 min 52 seconds), DAP coating (24 min 22 seconds), SS impregnation (25 min 46 seconds), and DAP impregnation (32 min 3 seconds). The burning rate were 0.81 min, 0.77 min, 0.78 min, 0.72 min, and 0.59 min for control, SS coating, DAP coating, SS impregnation and DAP impregnation respectively.



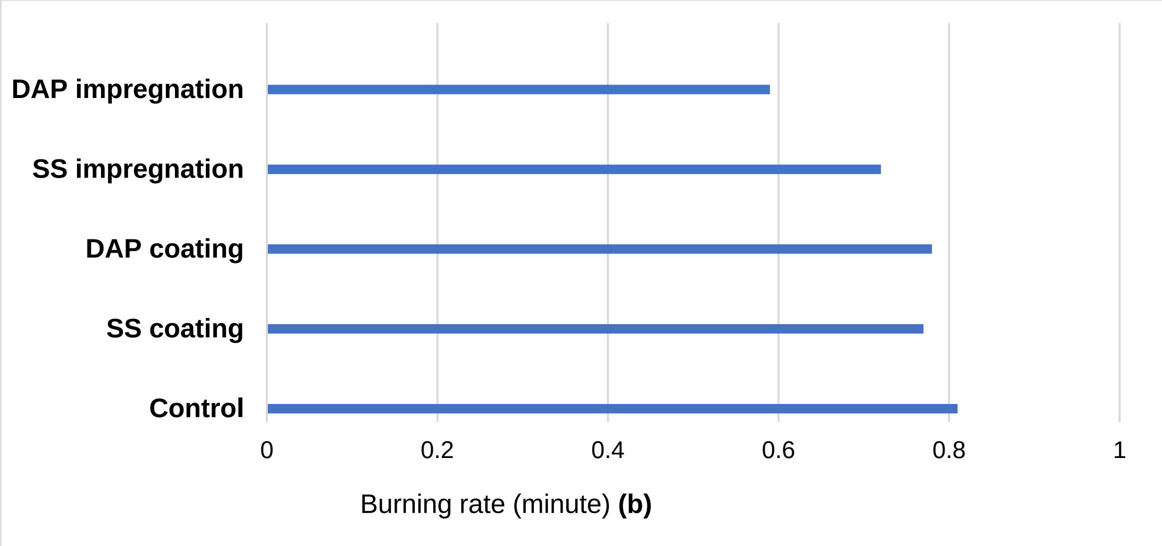


Fig. 11. Burning duration (a) and burning rate (b)

Based on the method of applying the flame-retardant material, samples with the impregnation method were found to have a longer burning time than samples with the coating method, which is in accordance with of Lowden and Hull (2013). The longer burning time is attributed to the fact that the application of the impregnation method can insert fire retardant material into the wood cell cavities, so that the fire-retardant material is more evenly distributed over each layer of veneer in the wood panel. The durability of wooden panels using the coating method is no better than the impregnation method because the application of the fire-retardant material acts as a 'coating' and is only found on the surface of the panel. However, the application of fire-retardant materials using the coating method can also prevent the release of flammable vapours and oxygen access (Lowden and Hull 2013).

Based on the flame-retardant material applied, samples using DAP have a longer burning time compared to samples using SS. This is due to the characteristics of DAP, which has a working mechanism as a fire-retardant material by decomposing into ammonia and phosphoric acid and forming char (Lowden and Hull 2013). The ammonia and phosphoric acid formed will react and can remove flammable volatile gases. Meanwhile, the char forms a layer that can prevent fire from spreading and entering the inside of the wood, thereby extending the burning time (Przystupa *et al*. 2020). The working principle of SS as a fire-retardant material is to undergo ceramicization, which means forming a layer of silica resulting from the combustion residue, which can inhibit the release of volatile compounds so that wood burning will be hampered (Lowden and Hull 2013). The results of this study are in accordance with Hautamäki *et al*. (2020) and Alamsyah *et al*. (2024), which showed that wood panels impregnated using DAP have longer burning resistance compared to impregnation treated using SS.

CONCLUSIONS

1. The addition of 20% diammonium phosphate (DAP) and 20% sodium silicate (SS) solutions can improve several physical properties of laminated veneer lumber (LVL)

and laminated veneer board (LVB) panels from gmelina wood, such as moisture content and density for each treatment. The addition of 20% SS solution was able to increase the percentage of thickness expansion. In terms of mechanical properties, the addition of 20% DAP and 20% SS solutions did not significantly differ in terms of mechanical properties. However, the addition of 20% SS solution resulted in a decrease in hardness in LVL panels from gmelina wood.

2. In the formaldehyde emission test, the addition of 20% DAP solution to the impregnation treatment was able to reduce the amount of formaldehyde emissions due to the production of ammonia and N-H groups produced on the veneer surface, which could react and help reduce formaldehyde emissions.
3. The effect of adding 20% DAP and 20% SS solutions was found to be significantly different on the burning time of LVL gmelina wood panels. The DAP impregnation treatment gave the best fire resistance test results with a burning time of 32 min 2 seconds. Meanwhile, the best treatment using SS as fire retardant was the impregnation treatment with a burning time of up to 25 min 46 seconds.

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Conflict of Interest

The authors state no conflict of interest.

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