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PERFORMANCE OF GLUED LAMINATED TIMBER (GLULAM) MADE FROM KELEMPAYAN WOOD WITH DIFFERENT LAMINA ASSEMBLY PATTERNS AND ADHESIVE SPREAD RATES

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Abstract: *This study investigates the impact of adhesive spread rates and lamina assembly patterns on the physical and mechanical properties of glue laminated lumber (glulam) manufactured from Kelempayan wood (Neolamarckia cadamba (Roxb.) Bosser). For this purpose, lab-scale 3-ply homogenous glulams were manufactured using low-MOE, average-MOE, and high-MOE laminas, and 3-ply mixed glulams of low-high-low-MOE and high-low-high-MOE lamina, with an adhesive spread rate of 100 g/m^2 applied on both sides of the lamina. A 3-ply homogenous glulam was also manufactured using the average-MOE lamina with an adhesive spread rate of 200 g/m^2. The physical and mechanical properties of the glulam, including moisture content, density, modulus of rupture (MOR), and modulus of elasticity (MOE), were examined and compared to the Japanese Industrial Standards (JAS) for glulam. The results found that the adhesive spread rates did not have a significant effect on the physical and mechanical properties of the glulam. However, the lamina assembly patterns had a significant impact on the mechanical properties of the glulam. The highest MOR and MOE were observed in the homogenous glulam manufactured from the high-MOE laminas, followed by the mixed glulam manufactured from the high-low-high-MOE laminas. These assembly patterns meet the MOR and MOE requirements specified in the 3-ply homogeneous structural grade glulam standard, indicating that Kelempayan wood can be a feasible option for glulam production.*

Key words: *Kelempayan, glulam, lamina, assembly pattern, adhesive spread rate.*

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1. Introduction

Glulam comprises many layers of solid wood lumber called lamina bonded with a high-strength adhesive to create a single structural wood-based material [16, 17]. Glulam comes in various sizes with a customized fabrication to suit almost any building style, such as vaulted roofs, domes, and even bridges with huge curved or arching members [14]. Moreover, structural glulam is engineered to be free of defective knots, eliminating sloping grains around the laminas and thus increasing strength [10], [13]. Therefore, glulam meets the need for modern architecture with an emphasis on environmental sustainability.

It is well known that the strength of each lamina is essential to ensure the structural performance of the glulam. For instance, the Japanese Agricultural Standard (JAS) for glulam required the modulus of elasticity (MOE) of the lamina to be above 6,000 MPa [8]. Therefore, not all wood species could be used as raw materials for lamina production, especially the species with a higher growth rate that generally have a relatively lower density, thus affecting the mechanical properties of the wood [2].

In addition, it was reported that the lamina assembly pattern in the glulam could influence its mechanical properties. According to a recent study, utilizing a lower-grade lamina on the compressive surface of the glulam can result in a decrease in bending stiffness, despite its advantages in postponing the initial cracking [5]. Another study assessed the feasibility of Sugi lumber with an exceptionally low MOE in glulam manufacturing. It was noted that the creep performance of the glulam made with an extremely low MOE at its inner layer had no significant differences compared to that made with a higher MOE at its inner layer [1.

Moreover, selecting adhesive types is crucial in achieving high-quality durable bonds in a wood-to-wood joint. It was reported that phenol resorcinol formaldehyde, melamine urea formaldehyde, and polyurethane adhesives exhibited exceptionally strong bonds which effectively resisted the hygrothermal stresses and qualified for structural uses [3], [15]. It was also reported that an insufficient adhesive spread rate resulted in a thin, starved glue line and could decrease cohesion strength. Therefore, a sufficient quantity of adhesive applied during glulam manufacturing is imperative to guarantee optimal bonding quality. A previous study revealed that increasing the spread rate of polyvinyl acetate adhesive led to better performance when the spread rate was increased with acceptable performance to the moisture cycle [9], [15].

On the other hand, in reducing pressure on the natural forest, the Malaysian government conducted a huge campaign for establishing forest plantations using some native fast-growing species, including Kelempayan (*Neolamarckia cadamba* (Roxb.) Bosser) [6], [12]. Kelempayan wood has an air-dry density of 0.29 to 0.47 g/cm^3, is classified as a light hardwood, and is widely used as raw material for plywood, pulp, and paper production [11]. As the density of the wood is relatively low, investigation of whether Kelempayan wood can meet the required standards, and thus be used for glulam manufacturing is essential. For this purpose, this preliminary study was carried out to explore the potential of using Kelempayan wood as a raw material for glulam manufacturing. The main objective was to examine how the physical and mechanical properties of the glulam are affected by different lamina assembly patterns and adhesive spread rates.

2. Materials and Methods

2.1. Materials

For this study, a Kelempayan log with a diameter of 200 mm and length of 1000 mm from a local sawmill in Kelantan, Malaysia, was used as raw material for lamina production. In addition, a PVAc-based adhesive was used as the binder for glulam manufacturing. The log was cut into 20-mm thick boards, which were then further processed into lamina with dimensions of 500 lengths, 50 widths, and 6 mm thickness. A total of 59 laminae were used in this study. After drying, the average moisture content of the laminas was 11.5%, with an average density of 0.47 g/cm^3.

2.2. Lamina Grading

Lamina grading was conducted based on their average modulus of elasticity *(MOE)* and standard deviation (*SD*) and sorted into high-MOE (MOE_h), average-MOE (MOE_{ave}), and low-MOE (MOE_l) laminas. The high-MOE lamina has $MOE_h > MOE + SD$. The average-MOE lamina has $MOE - SD << MOE_{ave} << MOE + SD$, while the low-MOE lamina has $MOE_l < MOE - SD$. Accordingly, the modulus of elasticity (*MOE*) of each lamina was determined usingthe Instron-type universal tester (*UTM*). A load was applied to the lamina at 1 mm/min loading speed until a 5 mm deflection was attained over an effective span of 400 mm.

2.3. Glulam Production

The adhesive was applied to both sides of the lamina at a spread rate of 100 g/m^2 to manufacture the lab-scale 3-ply glulam. Three types of homogeneous glulam were produced using the low-, average-, and high-MOE lamina. In addition, two types of mixed glulam composed of different grades of the lamina in the surfaces and inner layers of the glulam were produced, as shown in Figure 1. In this study, a spread rate of 200 g/m^2 was also employed to manufacture homogenous glulam using the average-MOE lamina for the examination of the effect of adhesive spread rates on the properties of the glulam. The clamping system was employed to compress the glulam at room temperature for 24 hours.

2.4. Evaluation of Properties

The physical and mechanical properties of glulam, including moisture content, density, modulus of rupture (*MOR*), and modulus of elasticity (*MOE*), were examined with each test replicated three times. The results were then compared to the JAS for glue-laminated timber. The moisture content examination was conducted using the oven-dry method. The sample was dried in an oven at 103°C for 24 hours, and the moisture content was calculated using the following equation (1):

$$MC\left[\%\right] = \frac{m_1 - m_0}{m_0} \cdot 100 \qquad (1)$$

where:

MC is moisture content, m_1 and m_0 are the initial mass and the mass of the samples after oven-drying, respectively. The density was obtained by measuring the mass and dimensions of the sample and calculating the ratio of mass to volume.

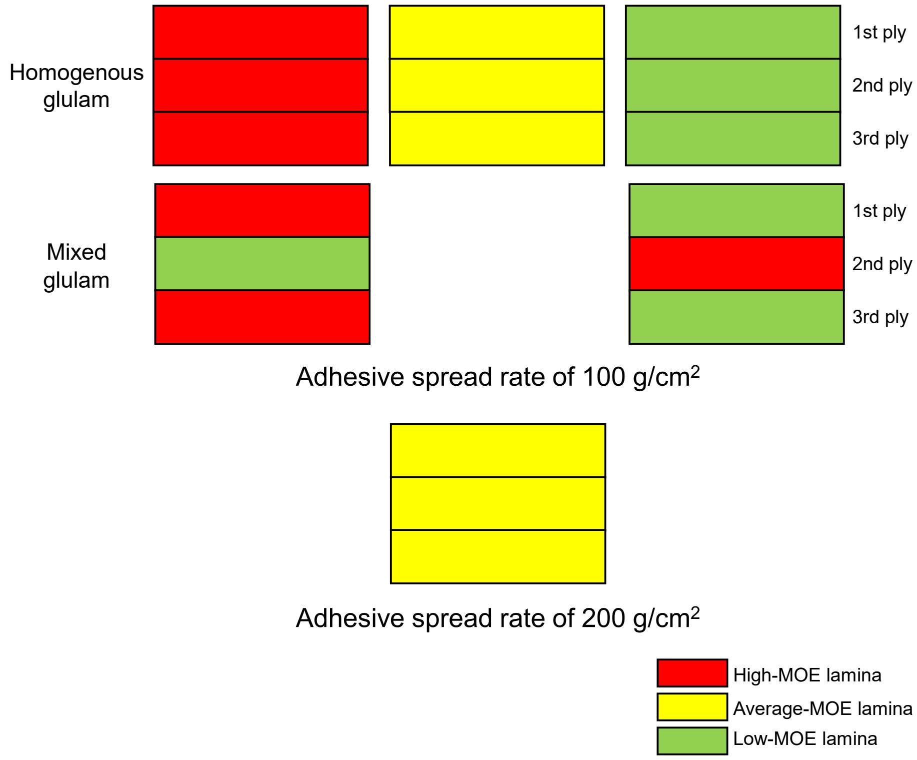

Fig. 1. *The lamina assembly patterns used for glulam manufacturing in this study*

On the other hand, the MOR and MOE were determined using a three-point bending test on a universal testing machine (*UTM*) with 10 mm/min loading speed until the sample broke. The MOR and MOE were then calculated using the following equations (2) and (3):

$$MOR = \frac{3 \cdot P \cdot L}{2 \cdot b \cdot h^2} \quad (2)$$

$$MOE = \frac{P_1 \cdot L^3}{4 \cdot d_1 \cdot b \cdot h^3} \quad (3)$$

where:

P is the maximum load;
L – the span;
b and *h* – the width and thickness of the sample;
P_1 and P_2 – the load and deflection at the proportional limit, respectively.

3. Results and Discussions

3.1. Lamina Grading

Figure 2 shows a load of each lamina plotted against its deflection. The figure confirmed that a lamina with a higher *MOE* exhibits a greater load at any deflection point than a lower *MOE*. It is well known that the properties of wood are influenced by its radial and longitudinal positions in the tree [4]. Thus, the *MOE* of the wood derived from a single log can exhibit substantial variations. For example, the wood located close to the pith typically has a lower *MOE* due to juvenile wood compared to the wood found near the bark, which is produced by a more matured cambium [18]. A similar trend was observed at the base of the tree compared to the top. Furthermore, the strength of the wood is also impacted by the wood defects, including knotting and sloping grain orientation.

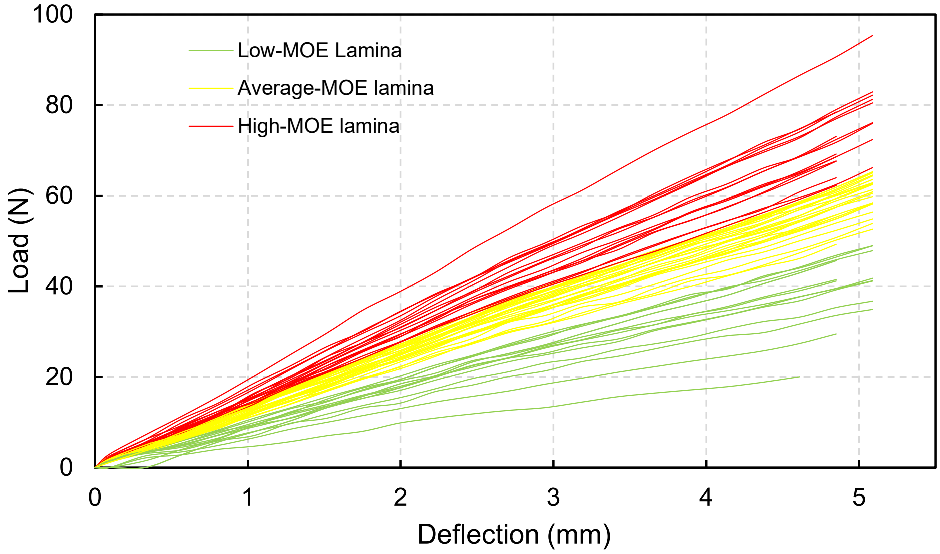

Fig. 2. *The load and deflection of each lamina*

Based on the grading results, the lamina was sorted into the high- and low-*MOE* when its *MOE* exceeded 8,573 and was below 6,947 MPa, respectively. The results were much higher than Rubber wood lamina, which reported that the high- and low-*MOE* lamina were above 5,871 and below 2,103 MPa, respectively [7].The findings indicate that most of the lamina satisfies the standard requirement of more than 6,000 MPa, meaning that Kelempayan wood holds significant potential as a raw material for glulam manufacturing. Furthermore, as illustrated in Figure 3, the number of laminas was depicted following their *MOE*. The results revealed that the number of the average-*MOE* lamina was 26, whereas the high-*MOE* and low-*MOE* laminas were 17 and 16, respectively.

3.2. The Effect of Adhesive Spread Rates on Density and Moisture Content

The average density and moisture content of homogenous glulam manufactured from the average-*MOE* lamina with different adhesive spread rates of 100 and 200 g/m^{2}are shown in Figure 4.

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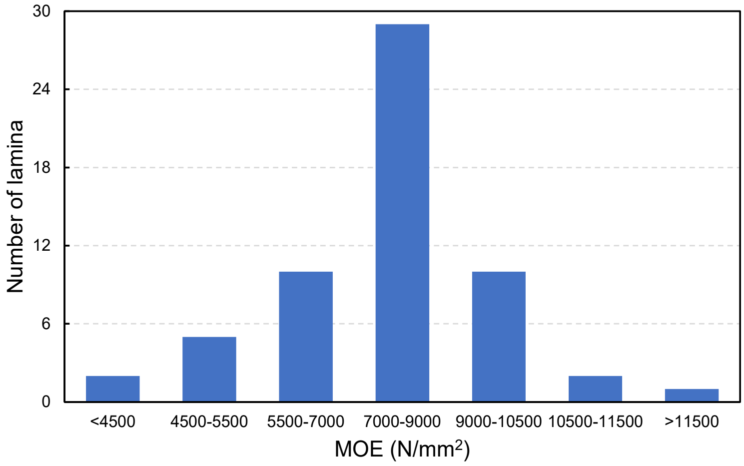

Fig. 3. *The number of lamina based on its MOE*

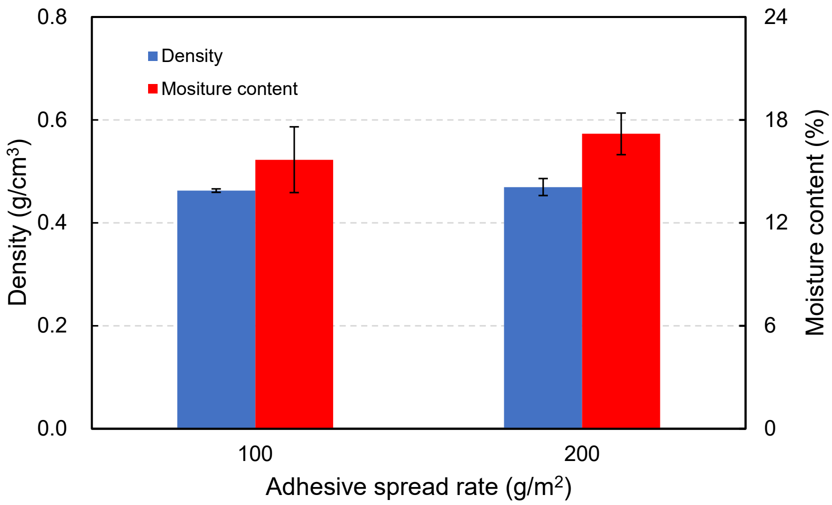

Fig. 4. *The effect of adhesive spread rates on the density and moisture content of the glulam*

The average density and moisture content was 0.46 g/cm^{3}and 15.7%, and 0.47 g/cm^3 and 17.2% for the glulam manufactured with an adhesive spread rate of 100 and 200 g/m^2, respectively. The glulam manufactured with a greater adhesive amount typically exhibits a greater density and moisture content. However, the results, particularly the density, did not show a noticeable confirmation of this consensus, probably due to the variation in the density and moisture content of the individual lamina composed of the glulam. In addition, the analysis of variance (ANOVA) showed that the adhesive spread rates did not significantly affect the density and moisture content of the glulam.

Furthermore, to comply with the standard requirement, the moisture content of the glulam must not exceed 15%. The findings imply that an alternative adhesive with a lower moisture content should be employed in glulam manufacturing.

3.3. The Effect of Lamina Assembly Patterns on Density and Moisture Content

The average density and moisture content of the glulam manufactured using different lamina assembly patterns are illustrated in Figure 5. The average density was 0.45, 0.46, 0.49, 0.45, and 0.46 g/cm^3 for the homogenous low-MOE, homogenous average-*MOE*, homogenous high-*MOE*, mixed low-high-low-*MOE*, and mixed high-low-high-MOE glulams, respectively. According to the results, the density of the glulam is influenced by the lamina assembly patterns. Although glulam produced from higher *MOE* materials typically exhibits higher density, ANOVA indicated that the lamina assembly patterns had no significant impact on the density of the glulam.

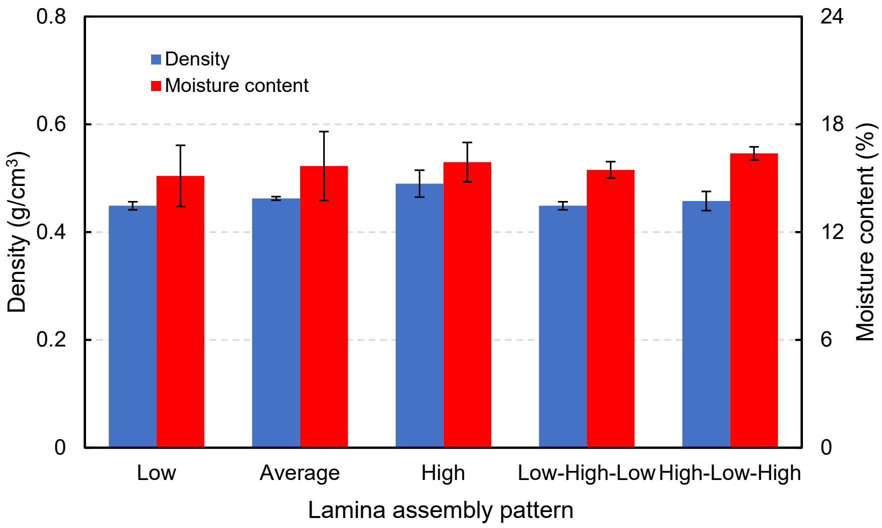

Fig. 5. *The effect of lamina assembly patterns on the density and moisture content of the glulam*

On the other hand, the average moisture content was 15.1, 15.7, 15.9, 15.5, and 16.4% for the homogenous low-*MOE*, homogenous average-*MOE*, homogenous high-*MOE*, mixed low-high-low-*MOE*, and mixed high-low-high-*MOE* glulams, respectively. The findings revealed that the homogenous glulam manufactured using the low-*MOE* lamina had the lowest moisture content, whereas that manufactured using the high-*MOE* lamina had the highest moisture content. The reason for this result remains unclear; nonetheless, ANOVA indicated that the difference was not statistically significant. Furthermore, the results showed that none of the glulam manufactured in this study met the standard requirement of less than 15%.

3.4. The Effect of Adhesive Spread Rates on Bending Properties

The average *MOR* and *MOE* of the homogenous glulam manufactured from the average-*MOE* lamina with different adhesive spread rates of 100 and 200 g/m^2 are illustrated in Figure 6. The average *MOR* and *MOE* of the glulam manufactured with the adhesive spread rates of 100 and 200 g/m^2 were 60.19 and 4,734, and 61.03 and 5,094 MPa, respectively. The findings suggest that the glulam manufactured with a greater adhesiveamount tends to exhibit higher *MOR* and *MOE*. A similar tendency was found in glulam produced from Rubberwood lamina [7]. This is because an increased amount of adhesive leads to more extensive physical and chemical bonding between the lamina and the adhesive, thereby enhancing the bending properties of the glulam. However, the *MOE* of the glulam was determined to be much lower than the *MOE* of the individual lamina. This finding is likely attributed to a weaker bonding strength among the lamina than the strength of the individual lamina, highlighting the necessity of employing a different type of adhesive with a superior bonding strength. ANOVA demonstrated that the impact of adhesive spread rates on the bending properties was insignificant. The previous study also found a similar result, mentioning that the adhesive spread rate did not significantly affect the bond strength [19]. Furthermore, followingthe standard requirement, the *MOR* and *MOE* of homogenous grade 3-ply structural grade glulam (E55-F225) must exceed 22.5 and 5,500 MPa, respectively. The findings indicated that the *MOR* of the glulams manufactured in this study met the requirement, while the *MOE* did not.

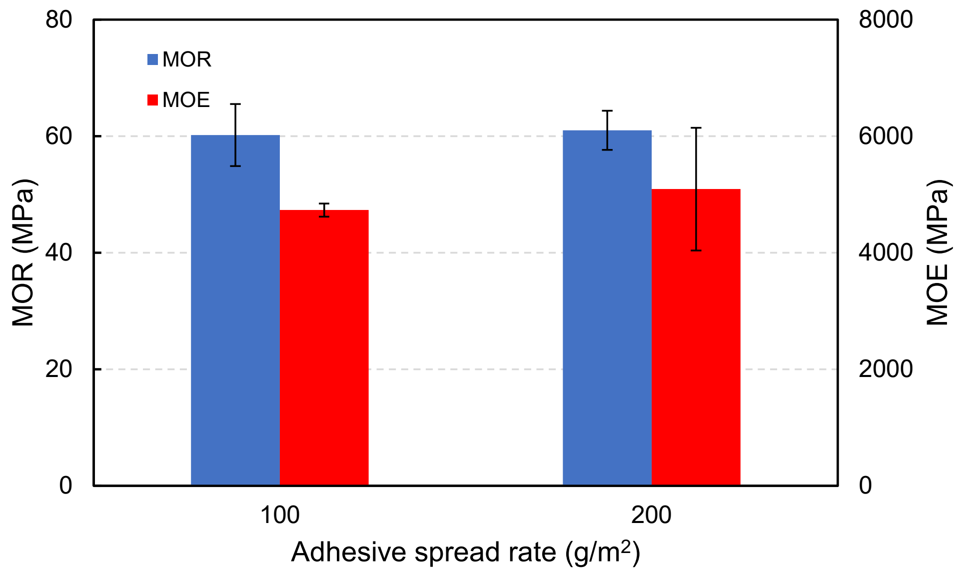

Fig. 6. *The effect of adhesive spread rates on the MOR and MOE of the glulam*

3.5. Effect of Lamina Assembly Patterns on Bending Properties

The average *MOR* and *MOE* of the glulam manufactured using different assembly patternsare illustrated in Figure 7. According to the figure, thehomogenous glulam manufactured from the high-*MOE* lamina had the highest average *MOR* and *MOE*, which were 65.25 and 5,675 MPa, respectively. This was followed by the mixed glulam manufactured from the high-low-high-MOE lamina, while the homogenous glulam manufactured from the low-*MOE* lamina had the lowest average of *MOR* and *MOE*, which were 33.41 and 4,302 MPa, respectively.

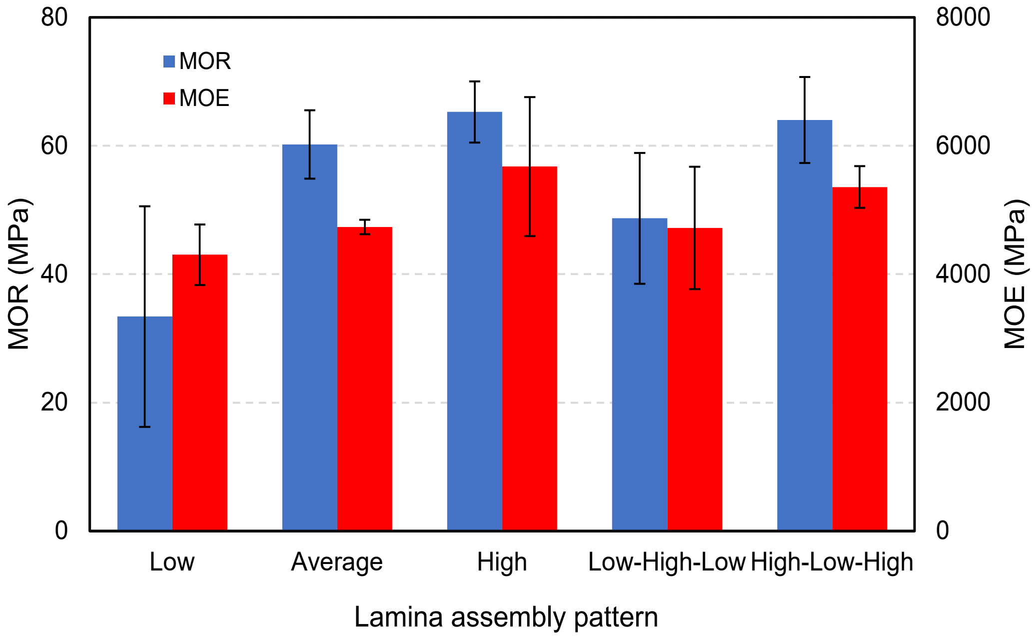

Fig. 7. *The effect of lamina assembly patterns on the MOR and MOE of the glulam*

The findings demonstrate that the *MOR* of all the glulam satisfied the standard requirement. However, for the *MOE*, all the glulam, except for the homogenous high-*MOE* glulam and the mixed high-low-high-*MOE* glulam failed to meet the standard requirement. The findings suggest that the lamina assembly pattern impacts the bending performance of the glulam. Specifically, the glulam composed of the high-*MOE* laminas on both the top and bottom surfaces demonstrated greater *MOR* and *MOE* thanthe other lamina assembly patterns.It is well known that during the bending test, the top surface of the glulam undergoes compression while the bottom surface experiences tension, with the neutral axis in the middle representing the area with zero stress. Therefore, incorporating the high-*MOE* lamina on both the top and lower surfaces of the glulam could enhance its load resistance. On the other hand, placing the high-*MOE* lamina in the middle of the mixed low-high-low-*MOE* glulam did not significantly increase its *MOR*, as this region falls within the zero-stress zone of the glulam.In addition, the previous finding specifically mentioned that the behavior of the bottom surface lamina exhibited the most influence on the strength and stiffness of the glulam rather than the middle lamina [5].

4. Conclusions

This study investigated the feasibility of using Kelempayan wood for glulam manufacturing and examined the impact of different adhesive spread rates and lamina assembly patterns on the physical and mechanical properties of the glulam. The results found that the adhesive spread rates did not have a significant effect on the physical and mechanical properties of the glulam. However, the lamina assembly patterns had a significant impact on the mechanical properties of the glulam. The highest *MOR* and *MOE* were observed in the homogenous glulam manufactured from the high-*MOE* lamina, followed by the mixed glulam manufactured from the high-low-high-MOE laminas. These assembly patterns meet the *MOR* and *MOE* requirements specified in the 3-ply homogeneous structural grade glulam standard, indicating that Kelempayan wood can be a feasible option for glulam production.

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