

Influence of Various Adhesives on Properties of Betung Bamboo Laminated Boards

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Bamboo can be engineered for laminate boards and other sustainable construction material. The adhesive type is expected to affect the laminated board's quality. This study analyzed the physical (density, moisture content, and delamination) and mechanical (bending and shear strength) properties of betung (*Dendrocalamus asper*) bamboo laminated boards prepared using various adhesives. The most favorable adhesive for enhancing betung bamboo laminated boards was determined. The bamboo lamina was arranged into boards (3 layers) measuring 30 x 15 x 1.5 cm each in length, width, and thickness. The laminated board was glued using isocyanate, epoxy, and polyvinyl acetate (PVAc) adhesives using the double glue spread technique. The laminated board was tested for its physical and mechanical properties, following the JAS 234:2003 standard. Betung bamboo laminated board with isocyanate, epoxy, and PVAc adhesives had densities ranging from 0.89 g/cm³ to 0.95 g/cm³, moisture contents of 7.64% to 24.37%, delamination ranges from 0% to 100%, modulus of elasticities from 109,000 to 178,000 kg/cm², modulus of rupture values range from 709 to 1,570 kg/cm², and shear strength values of 25.0 to 60.0 kg/cm². Isocyanate adhesive was found to have the best quality in physical tests, while epoxy adhesive achieved the best quality in mechanical tests of laminated boards.

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INTRODUCTION

Bamboo is considered to be a versatile non-timber forest product with the highest production volume in Indonesia (Wardana *et al.* 2022). Indonesia's bamboo production in 2021 was around 231,93 tons and had increased to 258,76 tons in 2022 (BPS 2022). This is a significant increase, showing that people are switching from wood to bamboo. This phenomenon reduces damage to primary rainforests, such as deforestation caused by forest burning, forest encroachment, land clearing, and illegal logging (Wahyuni and Suranto 2021). Consequently, this switching can reduce forest damage owing to the advantage of the fast-growing potential of bamboo.

Bamboo has a high diversity and very abundant resources. This abundance consists of 1642 bamboo species worldwide, with 172 species found in Indonesia (Vinsensia *et al.* 2020). Bamboo has various advantages, including being easy and cheap to find compared to wood, besides being easy to cultivate. It only takes one year to grow sufficiently to be harvested. The is a very short time compared to wood, which requires ten years. Bamboo also has advantages such as practical quality and does not require high technology. Apart from that, bamboo also has weaknesses, including being easily broken because it has cavities which can cause the swelling/shrinking due to temperature or moisture content, the need for insect repellent as it is susceptible to being eaten by moths, and the fact that the material is less resistant to direct weather changes such as exposure to sunlight and rain (Yuuwono 2016).

People have widely used bamboo for a long time. These uses include making household properties, places for pets, house walls, decorations, fences, food, medicinal ingredients, and firewood (Dian *et al.* 2014). The waste is modified as a standard mixture of designing paving blocks (Rizky Fauzi *et al.* 2018) and making briquettes (Junaidi 2015). In addition, bamboo (betung) can be used for building materials (Priyanto and Yasin 2019; Kapita and Mulya 2021), medicinal plants (Febrianti *et al.* 2022), processed food (Sunardi *et al.* 2018; Cahaya *et al.* 2020), furniture (Widyorini *et al.* 2016), and household appliances (Partasasmita *et al.* 2017). Bamboo can also be used for laminate boards. Laminated bamboo has the potential to be developed. Bamboo that has been laminated is much stronger than wood and can be used as the main structure (Belatrix *et al.* 2022). Belatrix *et al.* (2022) reported that laminated boards had a modulus of elasticity of 14,900 MPa and a modulus of rupture of 96.8 MPa.

The raw material and adhesive type can affect the laminate board's quality. Previous study reported that betung bamboo has a higher potential to be used as raw material for laminated boards compared to other species (Hartono *et al.* 2022). This is because betung bamboo has a higher density and compressive strength. Meanwhile, the type of formaldehyde-free adhesive, such as isocyanate, epoxy, and polyvinyl acetate (PVAc), affects the quality of the laminate board (Agustina *et al.* 2015; Kamal *et al.* 2017). Formaldehyde-free adhesive was prioritized in this study, with the goal of covering broader research and evaluating less commonly used adhesives. Furthermore, this work presents the possibility of using these three adhesives for future applications. These three adhesives reflect three different characteristics of adhesives. However, the study about formaldehyde-containing adhesives has raised many concerns about formaldehyde emissions. The urethane group is formed from the reaction between isocyanate groups and hydroxyl groups (Gama *et al.* 2018). However, the present study considered an isocyanate adhesive. A previous study reported that laminated wood (glulam) bonded with isocyanate and epoxy has good physical and mechanical properties (Hadi *et al.* 2021; Wijaya *et al.* 2023). In addition, PVAc adhesives are commonly used in the wood industry for general assembly applications, film overlay and high-pressure lamination, edge gluing, wood veneer, and edge bonding (Iždinský *et al.* 2021).

Additionally, the use of boric acid in this study serves as a preliminary treatment and functions as a preservative for bamboo lamina. It is well known that bamboo is susceptible to attack by powder post beetle organisms and fungi. The boric acid acts as a preservative for bamboo lamina, as well as increasing dimensional stability, mechanical strength, and wettability. The improved wettability may improve the bamboo lamina's bonding quality by making it easier for the adhesive to distribute (Yusof *et al.* 2023). Therefore, this study analyzed the effect of the type of adhesive on the quality of laminated

boards from betung bamboo. This research aimed to analyze the physical and mechanical properties of betung bamboo laminated boards on various adhesives. Apart from that, this research also aims to obtain optimal results for the type of adhesive used to improve the quality of betung bamboo laminated boards.

EXPERIMENTAL

Raw Material Preparation

The materials used in this study were betung bamboo (*Dendrocalamus asper*), isocyanate adhesive, epoxy adhesive, PVAc adhesive, boric acid, and water. The base of the bamboo was cut into lamina of 30 cm long, 2 cm wide, and 0.5 cm thick. Then, the lamina was placed in an oven at 60 °C for 48 h. The bamboo laminae were placed in a soaking container comprising a boric acid solution with a concentration of 3% for 24 h. After that, the soaked lamina was placed in an oven at 60 °C for 48 h for boric acid to fixation.

Laminated Board Manufacturing

The bamboo lamina was arranged into boards (3 layers) with a length of 30 cm, a width of 15 cm, and a thickness of 1.5 cm. Then, the boards were glued using isocyanate, epoxy, and PVAc adhesives using the double glue spread technique. These three commercially available adhesive types were applied directly, without the need for additional other materials. The glue spread level of the isocyanate adhesive (85:15) used was 280 g/m² (Hadi *et al.* 2021), the glue spread level of the epoxy adhesive (1:1) used was 120 g/m² (Darmawan *et al.* 2021), and the glue spread level of the PVAc adhesive was 280 g/m². After gluing on the laminate board, it was cold pressed using clamps on all sides at room temperature for 24 h. After pressing, the boards were conditioned at room temperature for ten days.

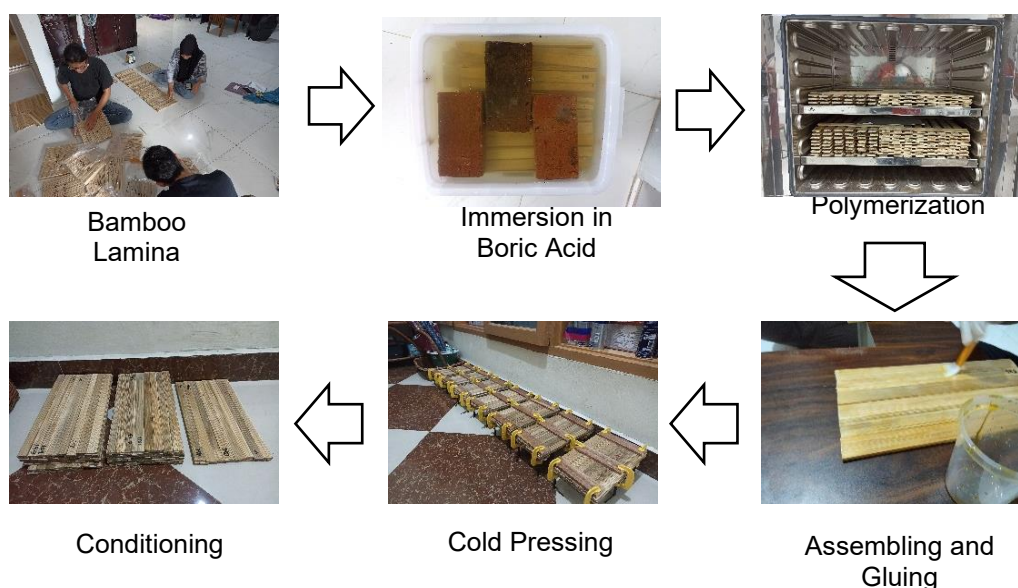


Fig. 1. Manufacturing bamboo laminated board

Testing of Bamboo Laminated Board

The laminated board was tested for its physical and mechanical properties, following the JAS 234 (2003) standard. Physical property testing includes density, moisture content, and delamination. Meanwhile, mechanical property testing included bending and shear strength evaluations.

Field Emission Scanning Electron Microscope (FE-SEM)

The FE-SEM analysis was carried out to determine the laminated board's glue line and bonding qualities. The laminated board was cut into cross sections of approximately 0.05 cm and then arranged into the sample grids using carbon tape, and then sputter coated with gold-palladium (mini sputter coater, Quorum). It was analyzed using the FE-SEM technique (FE-SEM Thermo Scientific – Quattro S) on the 50 $\times$ and 500 $\times$ magnifications with an accelerating voltage of 10.00 kV.

RESULTS AND DISCUSSION

Physical Properties of Laminate Boards

The density values of laminated boards are shown in Fig. 2. The values ranged from 0.89 to 0.95 g/cm³. The highest density value of 0.95 g/cm³ was found in the laminated boards with PVAc adhesive. The lowest density value of 0.89 g/cm³ was found in the isocyanate adhesive. It was statistically demonstrated that there was no significant difference in the density of betung laminated boards with three different adhesives. The analysis of variance data indicated that the adhesive type did not significantly affect density. A high density of laminated board with PVAc adhesives may be influenced by the solid content of the adhesive gluing process. The factors that affect the difference in density values include the solid content of the adhesive gluing process (Putra *et al.* 2022). Betung laminated board density ranged from 0.89 g/cm³ to 0.95 g/cm³. This value was higher than the betung laminated board in the previous study (Trisatya *et al.* 2022), which had density values ranging from 0.613 to 0.625 g/cm³.

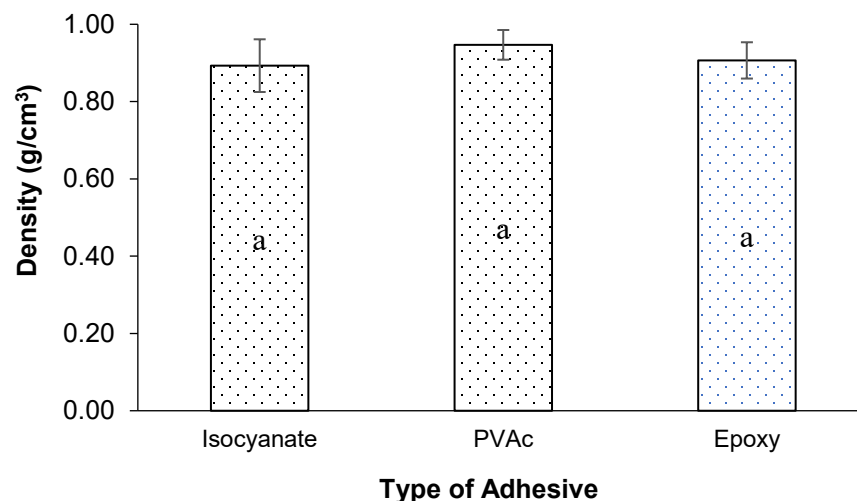


Fig. 2. Density values of laminated boards. The same letter (a) indicates no significant difference in statistical analysis.

The value of the moisture content of the laminate board can be seen in Fig. 3, ranging from 7.64% to 9.07%. The lowest moisture content value of 7.64% was found in the treatment with an isocyanate adhesive, and the highest moisture content value of 9.07% was found in the treatment with an epoxy adhesive type. Based on statistical analysis, the moisture content results were not much different between the adhesives. Based on JAS 234:2003, the permissible moisture content conditions cannot exceed 15%. Therefore, the moisture content of laminated boards in this study, bonded with isocyanate, epoxy, and PVAc adhesive, met the standard. According to Wulandari *et al.* (2022), there is an inverse relationship between the amount of moisture content in wood and the strength of the wood, where the higher the moisture content, the lower the strength of the wood. A high moisture content in wood can prevent the adhesive liquid from sticking, so a high moisture content in wood will reduce the effect of gluing and increase the absorption of wood, which weakens the adhesive bonding. Based on Fig. 3, the moisture content that met the standard was around 7.64% to 8.50%. This value is relatively smaller than the betung bamboo laminated board in the research of Wulandari *et al.* (2021), where the moisture content values ranged from 13.5% to 13.9%.

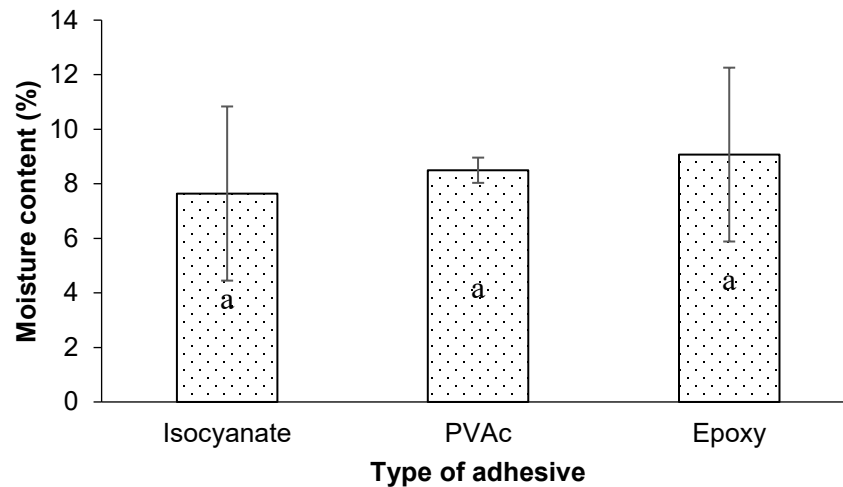


Fig. 3. Moisture contents of laminated boards. Letters a and b indicate significant differences in statistical analysis.

The delamination values of laminated boards can be seen in Fig. 4, which ranged from 0% to 100%. The lowest delamination value was found in the treatment with the isocyanate adhesive type of 0%, and the highest was found in the treatment with the PVAc adhesive type of 100%. Figure 4 shows the various delamination results for the three types of adhesives. The standard JAS 234:2003 requires a maximum delamination of 4%. Therefore, the laminate boards that did not meet standard requirements were those treated using PVAc adhesive and epoxy adhesive. The only delamination value that met the standard was isocyanate adhesive, which had a value of 0%. The delamination test in this study was conducted through the boiling test specimen in water (100 °C) for 4 h (Hadi *et al.* 2021). The utilization of this temperature potentially caused the delamination in the cases of the epoxy and PVAc adhesives. The PVAc adhesive achieved high strength, but it became soft and stretchy when exposed to high temperatures. Hanif and Rozalina (2020) stated that the weakness of PVAc adhesive is its high sensitivity, so it is unsuitable for outdoor placement. The strength of the bonding can weaken when exposed to heat and

humidity, and its adhesive properties remain inadequate, which can result in damage. In addition, epoxy adhesives, while known for their high strength and durability, exhibit several disadvantages when exposed to elevated or fluctuating temperatures. One of the primary concerns is their relatively limited thermal stability (Ahmadi 2019).

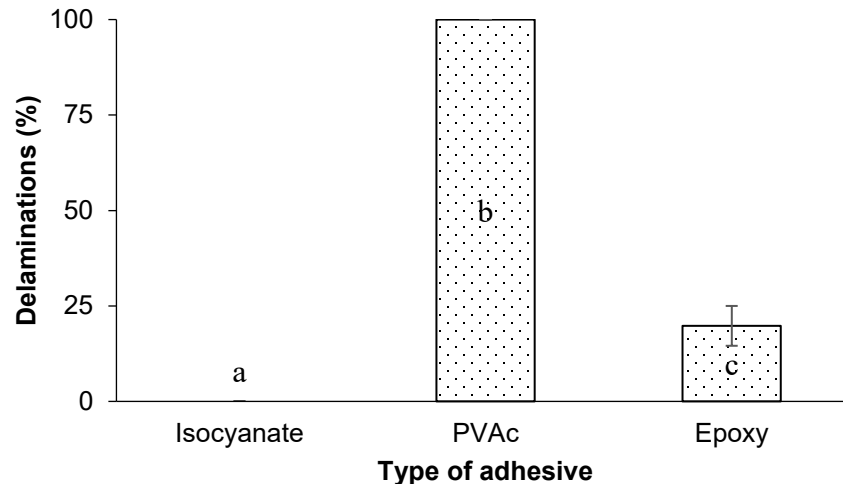


Fig. 4. Delamination values of laminate board. Letters of a, b, and c indicate significant differences in statistical analysis

The delamination in this study was found to occur within the adhesive. Delamination of adhesive refers to the separation or failure at the interface between an adhesive and one or more of the bonded substrates, or within the adhesive layer itself. This phenomenon is a critical concern in structural bonding, composites, laminates, and coatings, as it compromises the mechanical integrity and longevity of bonded systems (Shang *et al.* 2019). From the analysis of variance data, it can be seen that the type of adhesive had a significant effect. Duncan's test results further showed that the PVAc adhesive type had the highest delamination compared to isocyanate and epoxy adhesive types.

Mechanical Properties of Laminate Board

The modulus of elasticity (MOE) results for laminated boards are shown in Fig. 5. The lowest MOE value of 109,000 kg/cm² was found in the treatment with the isocyanate adhesive type. In contrast, the highest modulus of elasticity value was found in the treatment with the epoxy adhesive type of 178,000 kg/cm². Based on Fig. 5, the treatments using isocyanate and PVAc adhesives were almost uniform but inversely proportional to those of epoxy adhesive. Epoxy adhesives have a high effect on increasing the value of the MOE of laminated boards. All three types of adhesives met the JAS 234:2003 standard, where the minimum value of MOE is 75,000 kg/cm². Therefore, isocyanate, PVAc, and epoxy adhesives on betung laminated boards can be used as structural raw materials.

The MOE values in Fig. 5 ranged from 109,000 to 178,000 kg/cm². This range is very different from the characteristics of betung bamboo glulam in the study by Putra *et al.* (2022), where the MOE value ranged from 210,000 to 926,000 kg/cm². Meanwhile, this value was also very different from particleboard made from sorghum dregs (Iswanto *et al.* 2018), which ranged from 17,200 to 20,700 kg/cm². The analysis of variance data found that the three types of adhesives had a significant effect. Duncan's test results further showed that the epoxy adhesive had a higher value than the other two types of adhesives.

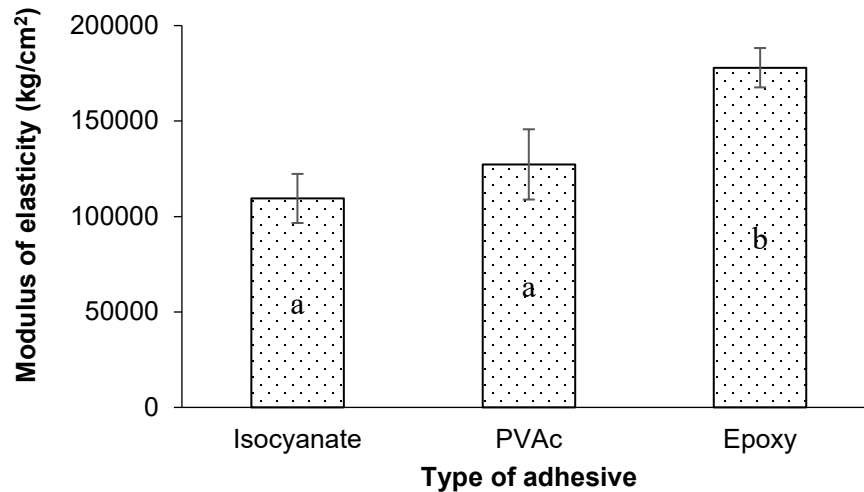


Fig. 5. MOE of laminate board. Letters of a and b indicate significant differences in statistical analysis

The value of the modulus of rupture (MOR) of the laminated board can be seen in Fig. 6. It ranged from 709 to 1,570 kg/cm². The lowest MOR value was found in the treatment with isocyanate adhesive (709 kg/cm²). In contrast, the highest MOR value of 1,570 kg/cm² was found in the treatment with epoxy adhesive. Figure 6 shows that the MOR value increases in the three different treatments. These three adhesives achieved values that met the standard requirements of JAS 234:2003, where the minimum value is 300 kg/cm². From these results, it can be concluded that different adhesives provide different MOR levels. Belatrix (2022) stated that the type of bamboo used, the direction of placement of the laminate lamina, the type of adhesive used, the amount of adhesive applied, variations in the thickness of the lamina, and the arrangement of the layers placed could influence the average values of bending strength and MOR of the laminate boards.

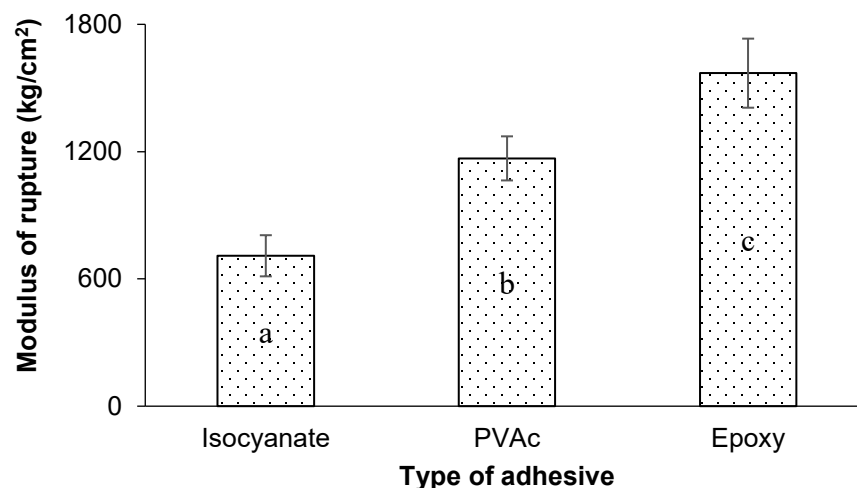


Fig. 6. MOR of laminate board. Letters of a, b, and c indicate significant differences in statistical analysis

The MOR values ranged from 709 to 1570 kg/cm². The highest value has results that were not much different, while the lowest value had a value that was far from the laminated

bamboo floor in Putra *et al.* (2022), where the MOR values ranged from 87.3 kg/cm² to 1,260 kg/cm². Meanwhile, this value is higher than fiberboard in the study of Nuryawan *et al.* (2018), which ranges from 25 to 111 kg/cm². The analysis of variance showed that the three types of adhesives had a significant effect. Duncan's test results obtained a higher epoxy adhesive value than the other two adhesives.

The shear strength values of laminated boards can be seen in Fig. 7, ranging from 25.0 to 60.0 kg/cm². The lowest shear strength value of 25.0 kg/cm² was found in the treatment with isocyanate adhesive type, while the highest shear strength was found in the treatment with epoxy adhesive type of 60.0 kg/cm². The application of different adhesives had an impact on the level of shear strength of betung laminated boards. However, of the three types of adhesives, only epoxy adhesive met the requirements of the JAS 234:2003 standard, where the shear strength value is >54 kg/cm². The shear strength values in Fig. 7 ranged from 25.0 to 60.0 kg/cm². This range is lower than betung bamboo lamination using PVAc or UF adhesive in Loiwtu (2018) research, which ranged from 70.8 to 78.6 kg/cm². The data analysis of variance shows that the three types of adhesives had a significant effect. Duncan's further test results showed that the epoxy adhesive had the highest shear strength value compared to the isocyanate adhesive and PVAc adhesive.

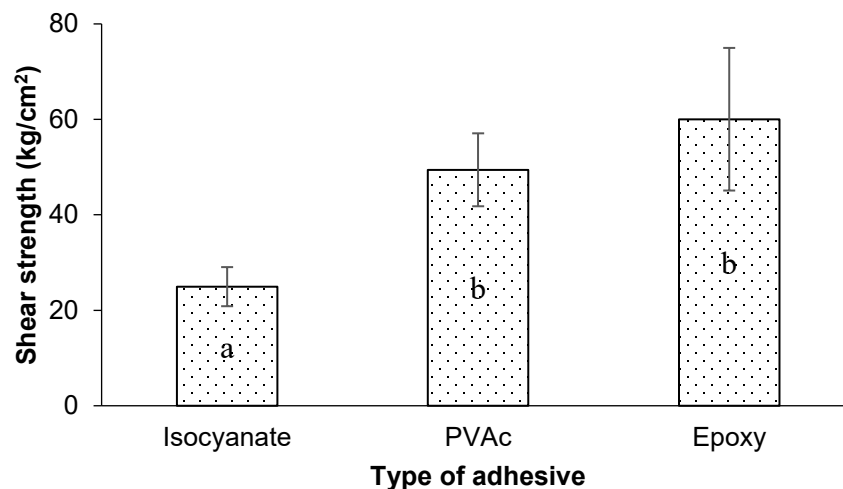
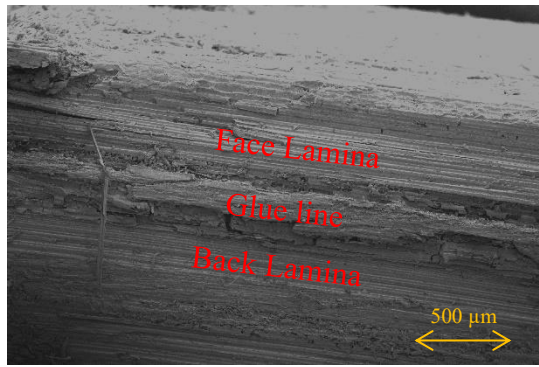


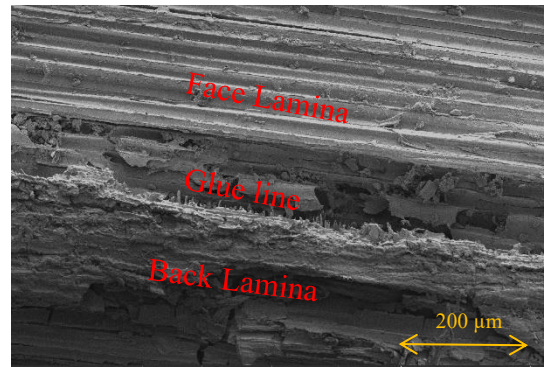
Fig. 7. Shear strengths of laminate board. Letters of a and b indicate significant differences in statistical analysis

FE-SEM Analysis

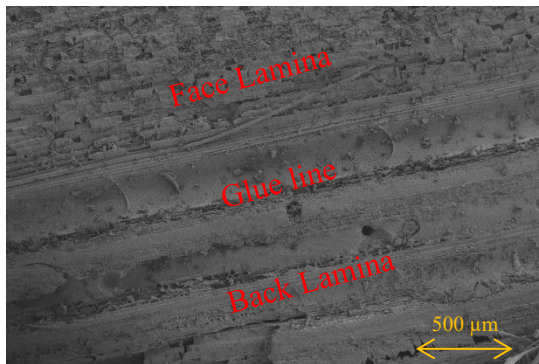
Figure 8 shows the results of the morphological analysis using the FE-SEM. The glue lines formed in the bamboo laminated board were analyzed, as well as the face and back lamina (Fig. 8), which gave the product good adhesion. In addition, Fig. 8 reveals that the laminated board bonded with epoxy adhesive had a uniform, dense, and compact glue line compared to the others. Therefore, the mechanical properties of the laminated board bonded with epoxy adhesive were higher than those of others. Irregular and porous glue lines were represented by glue lines on PVAc and isocyanate adhesive. A previous study reported the quality of glue line affected the quality of the panel composite (Ando and Sato 2009).



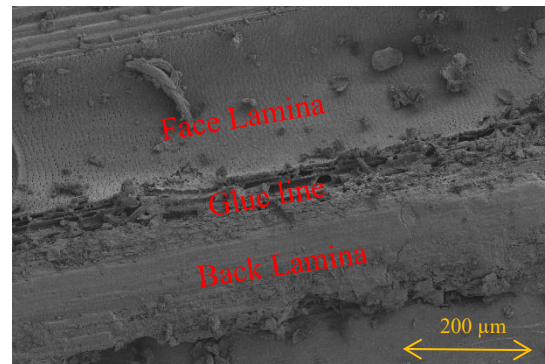
a. Bamboo laminated board bonded with PVAc; 150× magnification



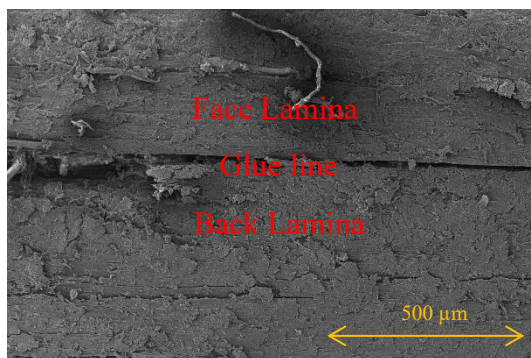
b. bamboo laminated board bonded with PVAc, 500× magnification



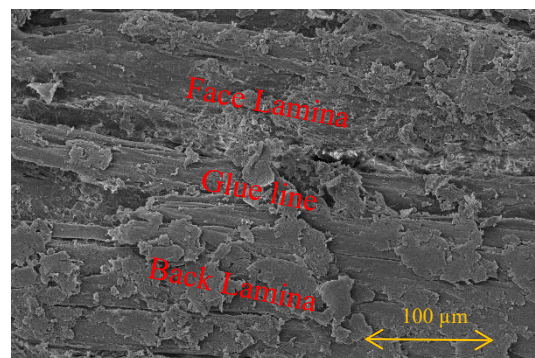
c. Bamboo laminated board bonded with epoxy; 150× magnification



d. Bamboo laminated board bonded with epoxy; 500× magnification



e. Bamboo laminated board bonded with isocyanate; 150× magnification



f. bamboo laminated board bonded with isocyanate; 500× magnification

Fig. 8. FE-SEM analysis of bamboo laminated board

CONCLUSIONS

1. Betung bamboo laminated board with isocyanate, epoxy, and polyvinyl acetate (PVAc) adhesives exhibited density values ranging from 0.89 to 0.95 g/cm³, moisture content value 7.64% to 24.37%, delamination of 0% to 100%, modulus of elasticities of

109,000 to 178,000 kg/cm², modulus of rupture values ranging from 709 to 1,570 kg/cm², and shear strength values of 25.0 to 60.0 kg/cm².

2. Isocyanate adhesive displayed the best quality in the physical test of laminated boards, especially related to the low moisture content and no delamination after soaking in water for 24 hours.
3. Epoxy adhesive achieved the best quality in mechanical tests of laminated boards in all parameters, namely modulus of elasticity, modulus of rupture, and shear strength. This was followed by PVAc and isocyanate adhesive.
4. PVAc adhesive demonstrated inferior adhesive performance and is only suitable for usage in dry conditions due to its significant delamination after soaking.
5. Dense and compact glue lines contribute positively to the strength of the laminate board.

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