Physical and mechanical properties of impregnated polystyrene jabon (Anthocephalus cadamba) glulam

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Abstract. Jabon (Anthocephalus cadamba) laminas were impregnated with polystyrene and reached 21.2% polymer loading. The laminas were manufactured for three-layer glued laminated timber (glulam) using isocyanate glue with glue spread 280 g/m² and cold-press process. For comparison purposes, untreated glulam as control and also solid wood were prepared. The physical-mechanical properties were evaluated according to the Japanese Agricultural Standard (JAS) 234-2003. The results showed that the color of glulam was not different from polystyrene glulam. The density of polystyrene glulam was higher than untreated glulam and solid wood, but the moisture content was lower than the other. The product kinds of solid wood, untreated glulam, and polystyrene glulam did not affect shear strength and modulus of rupture (MOR), while the modulus of elasticity (MOE) of untreated glulam and hardness of polystyrene glulam were the highest values and the other products were not different one each other. Both kinds of glulam fulfilled the Japanese standard in terms of moisture content, MOR, and delamination in hot water, but MOE and shear strength did not. Regarding its advantages, polystyrene glulam could be further developed using a higher wood density.

1. Introduction
Jabon (Anthocephalus cadamba) is one tree species which intensively planted in Indonesian plantation forests. Wood becomes popular recently for raw material of the wood industry, especially plywood manufacturing. The wood had white to light yellow in colour, specific gravity 0.29-0.56, Indonesian strength class III-IV, MOE 42.900 kg/cm², MOR 516 kg/cm², and shear strength 36.6 kg/cm²[1].

Wood from young trees had inferior characteristics in terms of physical-mechanical properties, and also susceptible attacked by bio-deterioration agents [2,3,4,5,6,7]. The timber is mostly small-diameter logs with a diameter of about 20 cm. The small diameter logs could be ignored if the timber is manufactured for glued laminated timber (glulam). Furthermore, producing much bigger size of timber, and strength could be enhanced by placing the stronger lamina in the outer layer and the weaker lamina in the inner layer [8].

Adhesive is essential in producing good quality glulam. It is mainly used synthetic glue, but it is possible to use natural adhesives. Santoso et al. [9] used tannin extract of merbau (Instia spp.) wood. It was copolymerized with resorcinol and formaldehyde for composite flooring manufacturing of some wood species. The results showed that physical-mechanical properties and shear strength were equal with the product using synthetic phenolic resin. Another researcher used tannin resin from mahogany (Swietenia sp.) bark, and was copolymerized with resorcinol and formaldehyde for glulam
manufacturing of jabon, pine \((\text{Pinus merkusii})\) and sengon \((\text{Falcataria moluccana})\), and the results showed that moisture content, rupture modulus and formaldehyde emission of glulam fulfilled Japanese standard JAS 234-2007, and the tannin resin quality was the same with synthetic phenol resorcinol formaldehyde \([8,10]\).

Tannin resin from mangium \((\text{Acacia mangium})\) bark could also be applied for jabon, mangium and sengon glulam. The results showed that the moisture content and rupture modulus of glulam fulfilled Japanese standard JAS 234-2003. The elasticity modulus of tannin glulam was similar with its solid wood and glulam using phenol resorcinol formaldehyde synthetic resin \([11]\). Isocyanate resin was also used for glulam of mangium, manii \((\text{Maesopsis eminii})\), and sengon. The results showed that all glulam was a high performance in delamination tests of cold and hot water tests, glulam of mangium and manii could fulfil JAS 234-2003 \([12]\). Another research used isocyanate glue for jabon and pine glulam manufacturing. The results showed that the moisture content of all glulam and mechanical properties of pine glulam fulfilled the Japanese standard JAS 234-2003. In contrast, jabon glulam fulfilled the standard in the modulus of rupture and shear tests \([13]\).

To improve the physical-mechanical properties of solid wood, some techniques could be applied, and one of them is the impregnation of polystyrene. The polystyrene impregnation on sengon \((\text{Falcataria moluccana})\), manii \((\text{Maesopsis eminii})\), pine \((\text{Pinus merkusii})\), duabanga \((\text{Duabanga mollucana})\) and maniani \((\text{Flindersia pimenteliana})\) succeeded in improving the physical and mechanical properties of these wood species \([14]\). Another research was conducted on polystyrene impregnation of randu \((\text{Ceiba pentandra})\) and angsana \((\text{Pterocarpus indicus})\). The results showed that the polystyrene wood had higher density, dimensional stability, hardness, modulus of elasticity, modulus of rupture and compression parallel to grain compared to untreated wood \([15]\). According to Hadjib \([16]\) polystyrene impregnation on sengon, pine and rubber-wood \((\text{Hevea brasiliensis})\) could improve the physical and mechanical properties of the wood in terms of specific gravity, moisture content, water absorption, shrinkage, swelling, compression parallel to the wood grain, modulus of elasticity, and modulus of rupture. After impregnation with styrene, Southern pine wood increased the density, water repellence, and hardness \([17]\). Pine \((\text{Pinus caribaea})\) and eucalyptus \((\text{Eucalyptus grandis})\) after polystyrene impregnation indicated a significant improvement in dimensional stability, low permeability, hardness parallel and perpendicular to grain \([18]\).

The purpose of this study was to enhance jabon wood characteristics in terms of physical and mechanical properties by manufacturing of polystyrene glulam. The laminas were impregnated with polystyrene and glued with isocyanate adhesive.

2. Materials and methods

Jabon wood \((\text{Anthocephalus cadamba})\) was collected from young plantation forest at less than 10 years old in Sukabumi, Indonesia. The logs with diameter about 20 cm were flat swan for laminas sized of 1.7 by 6 cm by 100 cm in thickness, width, and length, respectively. For comparison purposes, the solid wood of jabon with sizes of 5 cm by 6 cm by 100 cm in thickness, width, and length, respectively, were prepared. All the woods were kiln-dried to reach 12% moisture content. Some of the laminas were impregnated with polystyrene, and the polymer loading was determined.

The laminas were manufactured for three layers of untreated glulam and polystyrene glulam using isocyanate glue with a glue spread of 280 g/m² and cold-pressed for 3 hours. After conditioning for one month, all the boards were tested for density, moisture content, modulus of rupture, modulus of elasticity, shear strength, hardness, and also delamination in hot water. All tests were carried out in accordance with the Japanese Agricultural Standard JAS 234-2003 \([19]\).

3. Results and discussions

After measuring all responses, the wood properties in terms of color, physical and mechanical properties could be described as followed:
3.1. Wood color

The color of the wood is expressed in L* (lightness), a* (green to red), and b* (blue to yellow) [20] and the color change ($\Delta E$) was assessed according to CIELab [21]. The L*, a*, and b* values of untreated glulam and polystyrene glulam, also the color change ($\Delta E$) are shown in Table 1.

| Parameter       | L*      | a*     | b*     | $\Delta E$ |
|-----------------|---------|--------|--------|------------|
| Untreated glulam| 69.7 (6.5) | 4.2 (1.1) | 28.7 (5.4) | 1.8 (0.3) |
| Polystyrene glulam | 70.8 (6.8) | 3.3 (1.2) | 28.3 (1.2) | 1.8 (0.3) |

The colors of glulam were relatively light because the L* value was about 70, the color change was small changes ($2.0 < \Delta E < 3.0$; color changes visible by high quality filter). In other words, polystyrene impregnation almost did not change the wood color.

3.2. Physical properties

Physical properties including polymer loading, density, and moisture content of the boards are presented in Table 2, and the resume of variance analysis is shown in Table 3.

| Properties    | Solid wood | Untreated glulam | Polystyrene glulam |
|---------------|------------|------------------|--------------------|
| Polymer loading (%) | -         | -                | 21.2 (3.3)         |
| Density (g/cm$^3$)   | 0.30 (0.02) a | 0.32 (0.01) a | 0.37 (0.03) b     |
| Moisture content (%)  | 12.83 (0.19) a | 12.04 (0.30) b | 11.18 (0.30) c   |

Remarks: Value in parentheses is standard deviation; the same letter in a row indicates not significantly different at p $<=$ 0.05.

Polymer loading of jabon wood was 21.2% which considered as intermediate if compared to sengon ($Falcataria moluccana$) which had a density of 0.27 g/cm$^3$ and having a polymer loading varied from 7.7-16.2% [9]. However, it was lower than sengon with a density of 0.34 g/cm$^3$ with polymer loading 26.0% [17], and also with randu ($Ceiba pentandra$) with a density of 0.24 g/cm$^3$ having polymer loading 31.2-92.4% [10]. If jabon was impregnated with methyl methacrylate, the polymer loading reached 13.4% [22], and the value was lower than polystyrene. The polymer loading would impact wood density and would enhance physical-mechanical properties [16].

| Properties               | Significance |
|--------------------------|--------------|
| Density (g/cm$^3$)        | **           |
| Moisture content (%)      | **           |

Remarks: ** highly significant p $<=$ 0.01.

Referring to Table 3, treatment affected wood density resulting polystyrene glulam had the highest density compared to solid wood and untreated glulam, and both products were not different. The polystyrene glulam had a higher density because polystyrene occupied the void in the wood with a certain weight. Furthermore, the treatment also affected the moisture content (MC) of wood, and polystyrene wood had the lowest MC. Polystyrene filled-up the void, so the water could not reach that cell wall because polystyrene as a hydrophobic agent. All boards fulfilled the Japanese standard 234-2007, which stated that the MC of glued laminated timber shall be not more than 15%.
3.3. Mechanical properties and bonding quality

Mechanical properties including modulus of rupture (MOR), modulus of elasticity (MOE), shear strength, hardness, and also delamination as an indicator of bonding quality are presented in Table 4, resume of variance analysis is shown in Table 5, and the strength sample test is shown in Figure 1.

As shown in Table 5 that the treatment did not affect MOR and shear strength. In other words, the additional glue line in glulam did not affect both properties compared with solid wood, and the treatment of polystyrene impregnation in lamina prior to glulam manufacturing did not affect too. The shear strength results of polystyrene glulam were in line with the other research on sengon polystyrene glulam which mentioned that the shear strength of solid wood was not significantly different from polystyrene glulam. It means that the impregnation process of the styrene on sengon did not affect the gluing process [23].

Table 4. Mechanical properties and delamination of jabon board.

| Properties                  | Solid wood | Un-treated glulam | Polystyrene glulam |
|-----------------------------|------------|-------------------|--------------------|
| Modulus of rupture (kg/cm²) | 408 (47) a | 403 (33) a        | 372 (40) a         |
| Modulus of elasticity (1,000 kg/cm²) | 42.8 (5.3) a | 55.0 (5.4) b    | 43.4 (3.7) a       |
| Shear strength (kg/cm²)     | 41.3 (5.4) a | 38.2 (3.0) a     | 39.3 (3.9) a       |
| Hardness (kg/cm²)           | 168 (21) a | 175 (20) a        | 246 (30) b         |
| Delamination (%)            | -          | 0.67 (0.82) a     | 0.83 (0.98) b      |

Remarks: Value in parentheses is standard deviation; the same letter in a row indicates not significantly different at p =< 0.05.

Figure 1. Strength test of jabon polystyrene glulam.

Table 5. Variance analysis resume of jabon mechanical properties.

| Properties   | MOR  | MOE  | Shear strength | Hardness | Delamination |
|--------------|------|------|----------------|----------|--------------|
| Significance | ns   | **   | **             | **       | **           |

Remarks: ns for non-significantly different; ** highly significant p =< 0.01.

The results indicated that impregnated polystyrene wood had enhanced physical-mechanical properties and resistance to bio-deterioration attack [14,15,16,24,25], therefore it also could be applied to the impregnated polystyrene glulam. Regarding to Japanese standard, the MOR of three kinds of boards fulfilled JAS 234-2003 which requiring minimal MOR 294 kg/cm², but all the boards did not fulfill shear strength requirement minimal 53 kg/cm². These matters happened because the solid density of jabon was low, only 0.30 g/cm³. It could be suggested to manufacture glulam with a higher density to get higher mechanical properties, it could be a medium wood density. Furthermore, the treatment affected MOE and hardness significantly. MOE of solid wood and polystyrene glulam were not different, but both kinds of the board were different from untreated glulam which had a higher value. In another response, the treatment affected highly significantly hardness, while solid wood and untreated glulam were not different, but both kinds of the board were different from polystyrene glulam which had the highest value among them. MOE of all kinds of the boards did not fulfil Japanese standard 234-2003, the possible reason is because of a low-density wood used for this purpose.
The MOR and MOE of polystyrene glulam were lower than untreated glulam because the laminas for polystyrene glulam were impregnated with polystyrene, and this compound would be an obstacle for a good glue line production. To get better adhesion, it could be supposed that hot press should be applied.

In another response it was observed that the treatment affected hardness significantly. Hardness of solid wood and untreated glulam were not different from one to another, but both kinds of boards were different from polystyrene glulam which had the highest hardness value compared with them. The impregnation of polystyrene into lamina for glulam manufacturing could enhance the hardness properties. It could be happened because the polystyrene filled-up the wood void which could increase the wood density and also its hardness.

The delamination test can be used to assess the bonding quality of glulam. The delamination test in this study was carried out in hot water, both glulam had a good performance which indicated by very low delamination, and they fulfilled the Japanese standard 234-2003. The quality of the isocyanate binder for this test was very excellent, but this glue is very expensive. For further development it could be using the other binder with lower cost and environmentally friendly glue.

It could be wrapped up that manufacturing of polystyrene glulam could be further developed based on the fact that MOR, MOE, and shear strength of solid wood and polystyrene glulam were not different or relatively the same properties. The other advantages are that the impregnation could enhance the board hardness. The delamination in hot water of both glulams could be neglected, or they had high-performance glue line or bonding quality.

4. Conclusions
The discussion above could be summarizing that jabon polystyrene glulam had higher density and hardness, but lower moisture content than solid wood and untreated glulam. The three kinds of the board relatively had the same values of MOR and shear strength. In terms of MOE, polystyrene glulam had the same value as its solid wood, and both boards had a lower value than untreated glulam. The polystyrene glulam could fulfil JAS 234-2003 for moisture content, MOR, and delamination in hot water, but did not for MOE and shear strength. For future work, it could be suggested for manufacturing polystyrene glulam from wood species with a higher density to enhance its mechanical properties.

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