

Comparison of Physical and Mechanical Properties of Bamboo Laminates With and Without Natural Fiber Reinforcement

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Abstract

The present study of engineered bamboo as an alternative to wood aimed to determine the difference in physical-mechanical properties and the correlation of the observed properties consisting of moisture content, density, modulus of elasticity (E_{app}), and modulus of rupture (S_R). *Bambusa blumeana* Schult. & Schult. F and *Gigantochloa atrovioleacea* Widjaja, *Agave sisalana* Perrine, *Hibiscus cannabinus* L, and urea-formaldehyde resin as an adhesive were used to produce natural-fiber-reinforced and non-reinforced laminated bamboo lumber (LBL). Specimen dimension by ASTM standard D143-14. Test methods and equations by ASTM standard D198-15. Statistical analysis includes analysis of variance, correlation, and regression. The MC, density, MOE, and MOR of the interactions within *G. atrovioleacea*–without fiber (AO), *G. atrovioleacea*–*H. cannabinus* (AK), *G. atrovioleacea*–*A. sisalana* (AS), *B. blumeana*–without fiber (BO), *B. blumeana*–*H. cannabinus* (BK), and *B. blumeana*–*A. sisalana* (BS) ranged between 6.40% to 8.00%, 0.62 g/cm³ to 0.74 g/cm³, 12.71 GPa to 37.70 GPa, and 62.64 MPa to 104.24 MPa, respectively. Relationship between variables revealed a negative linear correlation between MC versus density ($R = -0.786$) and MC versus MOR ($R = -0.666$). Linear positive correlation between density versus MOE ($R = 0.508$), density versus MOR ($R = -0.578$), and MOE versus MOR ($R = -0.793$).

Keywords: Bamboo, laminated-bamboo-lumber, glubam, fiber, physical-mechanical properties

INTRODUCTION

Efforts to obtain bio-based materials as an alternative to wood as structural raw materials and their processing have received much attention. The limited availability of resources and the increasing demand for resources in today's modern industrial world make it increasingly necessary to explore the potential and opportunities of new resources as sustainable building materials (Meadows *et al.*, 1992). One of the natural resources that can be used as a substitute for wood is bamboo. Bamboo is an attractive choice and has excellent potential as an alternative to wood for many applications of structural raw

materials. (Jain *et al.*, 1993; Janssen, 1995; Lakkad and Patel, 1981; Mahdavi *et al.*, 2011).

Laminated bamboo or laminated bamboo lumber (LBL) is a solution to the limitations of the cylindrical shape of bamboo, which tends to be challenging to incorporate into structural construction, unlike wood. Bamboo-engineered products have the potential to become competitive products in the market. This product has mechanical properties comparable to or superior to structural wood and plywood. The use of processed bamboo products in construction is still a developing field (Ameh *et al.*, 2019;

Khandkar-Siddikur *et al.*, 2012; Akwada & Akinlabi, 2015).

This study will reveal differences in physical and mechanical properties between combination treatments (fiber bonding and non-fiber bonding) and the relationship between variables including moisture content, density, modulus of elasticity (modulus of elasticity, MOE, Eapp), and flexural strength (modulus of rupture, MOR, SR). The raw materials used are bamboo duri (*Bambusa blumeana*) and black Java bamboo (*Gigantochloa atrovioleacea*), compared to the modification of natural fibers as reinforcement. The vegetable fibers used were sisal (*Agave sisalana*) and kenaf (*Hibiscus cannabinus*).

MATERIAL AND METHODS

The manufacture of laminated bamboo lumber is carried out at the Civil Engineering Laboratory, State University of Malang. Physical and mechanical properties testing was carried out at the Civil Engineering Laboratory, Universitas Brawijaya (7°58'48" S 112°37'12" E).

The study used a simple research design by conducting a two-factor analysis; (1) the type of bamboo; and (2) the addition of fiber. Six treatments, consisting of *G. atrovioleacea*–without fiber (AO), *G. atrovioleacea*–*H. cannabinus* (AK), *G. atrovioleacea*–*A. sisalana* (AS), *B. blumeana*–without fiber (BO), *B. blumeana*–*H. cannabinus* (BK), and *B. blumeana*–*A. sisalana* (BS) was repeated three times. Parameters for testing physical-mechanical properties include determination of moisture content and density, modulus of elasticity (modulus of elasticity, MOE, Eapp), and flexural strength (modulus of rupture, MOR, SR). Specimen dimensions refer to ASTM D

143-14 standard. The two-point load test method and the determination of Eapp and SR refer to the ASTM D198-15 standard. Analysis of variance (ANOVA), correlation, and regression was used to determine the difference in treatment combinations and the relationship between parameters of physical-mechanical properties in the test.

The blades were obtained from the manual splitting of bamboo stems about 5 mm. The entire blade surface was planned to remove the wax and silica layer and obtain a rectangular cross-section of the blade, then air-dried to a moisture content of <15%. Urea-formaldehyde resin adhesive was applied to each side of the bamboo slats to be glued, with adhesive weight on each surface of 225 g/m². The fiber was added together with adhesive dispersal for the fiber-reinforced combination treatment of 1 gram per layer of slat adhesive and 2.5 grams per lamellae adhesive. The bamboo strip was laid out and joined into lamellae (laminated sheets of bamboo slats) by cold pressing at 30 kN. The lamellas were assembled into laminated bamboo beams by compression at 60 kN. Each compression process was followed by pressure locking using clamps for ± 24 hours. Conditioning was carried out for 14 days before testing. The beams were smoothed and cut to obtain 50 x 50 x 760 mm dimensions at the final stage.

RESULTS AND DISCUSSION

Moisture Content

The simple, completely randomized design results showed that the combination treatment of AO, AK, AS, BO, BK, and BS contained a moisture content of 7.27%, 7.57%, 8.00%, 6.80%, 6.90%, and 6.40%. The combination without the addition of fiber

reinforcement contains the lowest moisture content. Fiber types as reinforcement did not significantly affect the moisture content of bamboo laminate. The average moisture content in all samples was 6% - 8% (Table 1), more than 5% below the conditions required for the mechanical properties requirement. The ASTM D1990-16 requires an equilibrium of moisture content of 15%. A 5% difference must be avoided due to the need for normalizing, which will reduce the analysis results' accuracy.

Moisture content to density and moisture content to MOR showed a negative linear correlation (Table 2). Moisture content can be determined by 61.8% variation in density (Figure 1) and 44.3% variation in MOR (Figure 2) through the equation, density=1.164-6,780 Moisture Content, and MOR=253.5-2304Moisture Content. The coefficients of Moisture Content on density and MOR are 6.780 and 2304 Kg/cm², respectively. On average, the density and MOR of laminated bamboo will decrease by the coefficient number for every 1 unit increase in Moisture Content.

Table 1 Comparison of Average Moisture Content, Density, MOE, and MOR of Laminated Bamboo

Treatment	Moisture Content (MC, %)		Density (ρ , g/cm ³)		MOE (E_{app} , GPa)		MOR (S_R , MPa)	
Combination								
AK	7,57	a, b	0,64	b	26,03	a	85,79	a
AO	7,27	a, b	0,62	b	30,28	a	94,71	a
AS	8,00	a	0,61	b	12,71	a	62,64	a
BK	6,90	a, b	0,74	a	31,11	a	94,02	a
BO	6,40	b	0,73	a	37,70	a	104,24	a
BS	6,80	a, b	0,72	a	31,41	a	90,74	a

Information:

Numbers with different letter groups show significant differences at the 0.05 level.

Table 2 Correlation Matrix of Physical and Mechanical Properties of Laminated Bamboo

		Moisture Content (MC)		Density (ρ)		MOE (E_{app})	
Density (ρ)	<i>Pearson Correlation</i>	-0,786	**				
	<i>P-Value</i>	0,000					
MOE (E_{app})	<i>Pearson Correlation</i>	-0,294		0,508	*		
	<i>P-Value</i>	0,236		0,031			
MOR (S_R)	<i>Pearson Correlation</i>	-0,666	**	0,578	*	0,793	**
	<i>P-Value</i>	0,003		0,012		0,000	

Information:

*) The correlation is significant at the level of 0.05

**) The correlation is very significant at 0.01. level

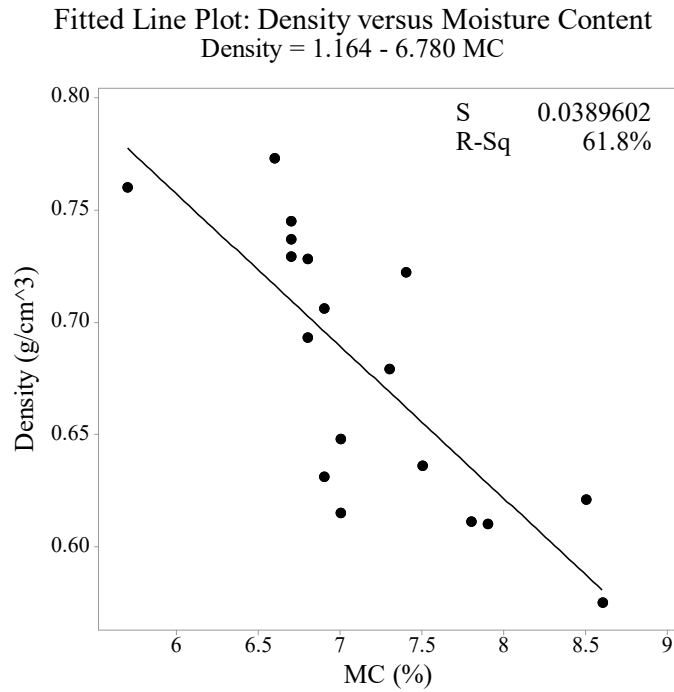


Figure 1. The plot of Linear Regression of Moisture Content (MC) against Density (ρ)

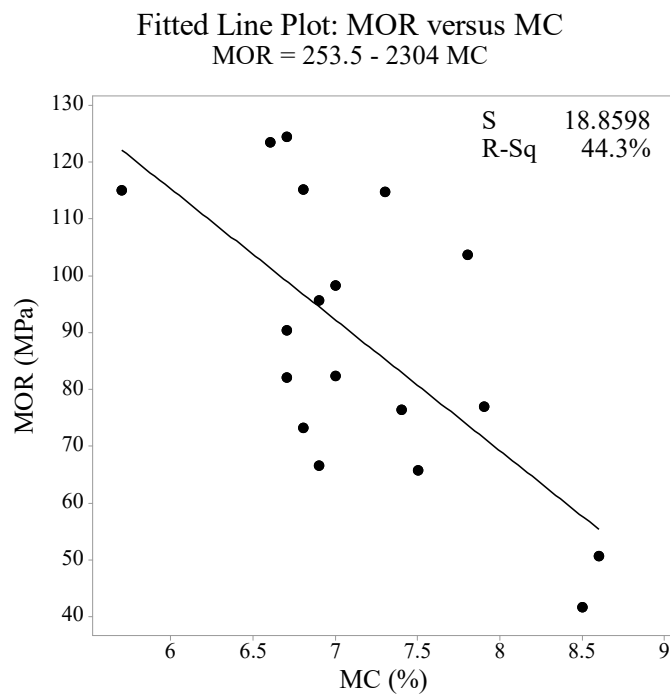


Figure 2. The plot of Moisture Content Linear Regression (MC) on Flexural Strength (MOR, S_R)

The increased moisture content of the samples indicates a decrease in density and flexural strength. As a lignocellulosic material, the mechanical properties of bamboo are also strongly influenced by changes in Moisture Content (Wang *et al.*, 2013). The same thing applies to wood products; Wood shows instability and decreases in strength when there is an increase in water content above the material saturation point (MSP)(Sharma *et al.*, 2015). Almost all mechanical properties, such as compressive strength, hardness, and modulus of elasticity, decrease with increasing water content below the fiber saturation point (FSP) (Cave, 1978; Green *et al.*, 1988; Kojima and Yamamoto, 2004; Kretschmann and Green, 1996; Wang and Wang, 1999; Zou *et al.*, 2019).

Wood Density

The combination of BK, BO, BS, AK, AO, and AS has a density of 0.74 g/cm³, 0.73 g/cm³, 0.72 g/cm³, 0.64 g/cm³, 0.62 g/cm³, and 0.61 g/cm³. The combination density in *B. blumeana* was significantly higher than in *G. atrovioleacea* (Table 1). As a comparison, the dry density of the blast furnace *B. blumeana* ranged from 0.43 g/cm³ to 0.62 g/cm³, with variations determined by the planting period (Mohmod *et al.*, 1993), while the density of *G. atrovioleacea* is ± 0.58 g/cm³ (Putri dan Masdar, 2016). The density in the form of laminated beams is relatively higher due to the modification of the composite material's shape and adhesive as a constituent.

Density to MOE and density to MOR positive linear correlation (Table 2). Density can determine a 25.8% variation in MOE (Figure 3) and 33.5% variation in MOR (figure 4) through the equation

$MOE = (-66189 + 139053) \times \text{density}$, and $MOR = (-68.81 + 232.0) \times \text{density}$. The density coefficients on MOE and MOR are 139053 and 232.0, respectively. On average, MOE and MOR of laminated bamboo will increase by the coefficient number for every 1 unit increase in density.

The flexural strength of bamboo depends on the number and quality of fibers in the reed, which determines the density value (Liese and Weiner, 1996). Density is directly proportional to the mechanical properties of the biomass material (Borůvka *et al.*, 2018; Srivaro *et al.*, 2018; Yang dan Lee, 2018). Research conducted by Chung dan Wang (2018) on scrimber from Moso bamboo (*Phyllostachys pubescens*) showed that the value of the MOR variable showed a positive relationship with density. Sharma *et al.* (2017) mentioned a correlation between specimen density and flexural elasticity modulus; in laminated bamboo, the strongest correlation is found in density and flexural elasticity.

Flexural Modulus of Elasticity (MOE, Eapp) and Modulus of Rapture (MOR, SR)

The value of elastic modulus of bending follows previous research, which states that the range of MOR values ranges from 67.7 MPa to 133 MPa. (Lee *et al.*, 1998; Ahmad and Kamke, 2011). MOE and MOR showed a positive linear correlation (Table 2). MOE can determine a 62.8% variation in MOR (Figure 5) through the $MOR = 55.91 + 0.001162 \text{ MOE}$. The MOE coefficient is 0.001162. On average, the MOR of laminated bamboo will increase by 0.001162 for every increase of 1 MOE unit (Figure 5).

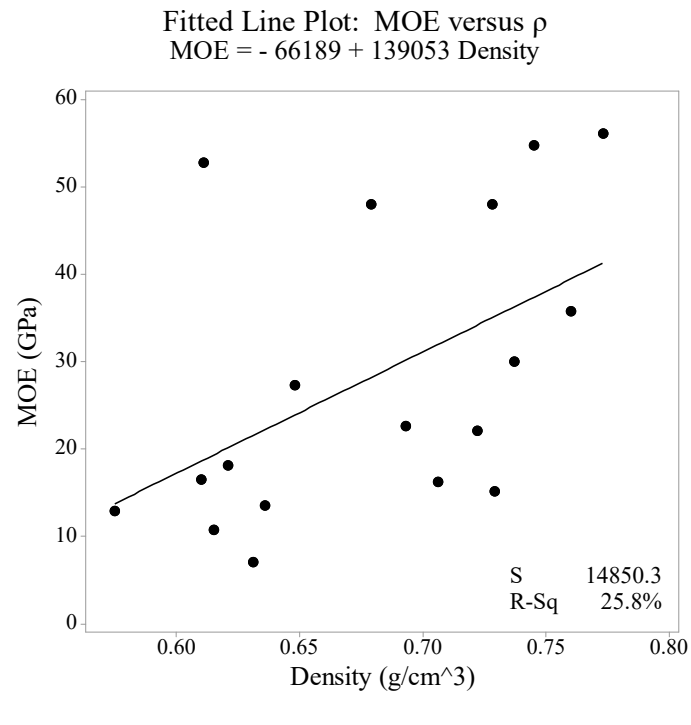


Figure 3. The plot of Density Linear Regression (ρ) against Flexural Elasticity Modulus (MOE, E_{app})

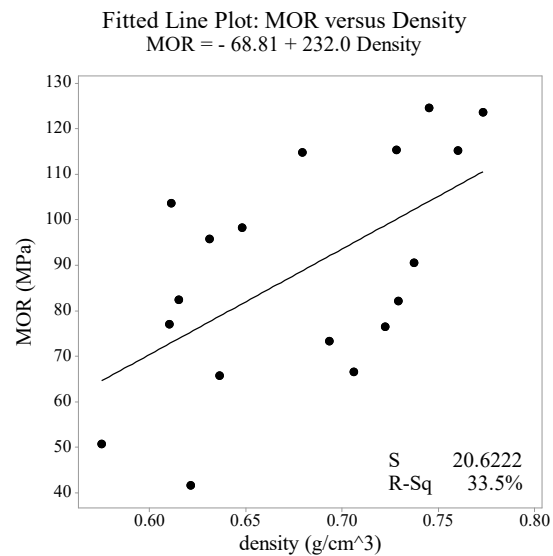


Figure 4. The plot of Density Linear Regression (ρ) against Flexural Strength (MOR, S_R)

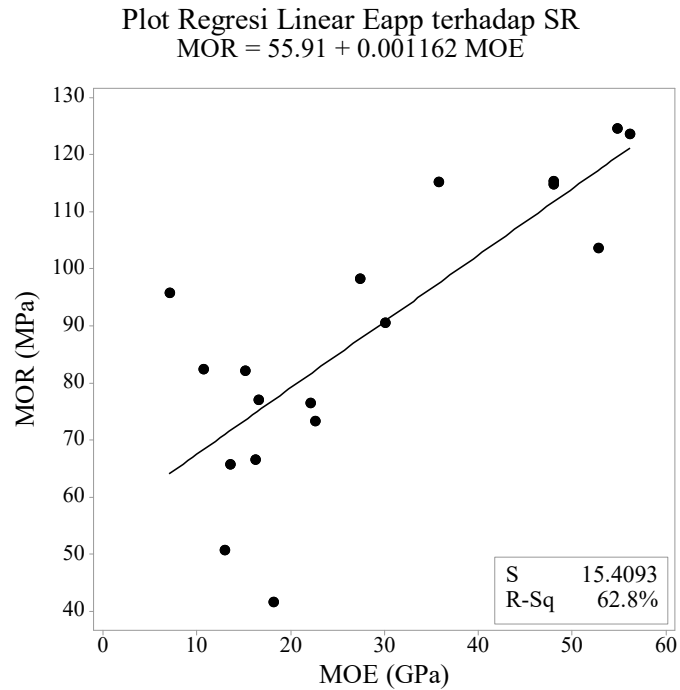


Figure 5. Bending Elasticity Modulus Linear Regression Plot (MOE, Eapp) to Bending Strength (MOR, SR)

The combination non-fiber treatment showed higher stiffness and strength than the combination fiber treatment. Significant problems, such as poor wettability, poor bonding and degradation at the fiber/matrix interface (hydrophilic and hydrophobic effects), and fiber damage during the manufacturing process are the leading causes of reduced composite strength. (Ho et al., 2012). Fiber addition that weakens the combination can be caused by technical factors during gluing of laminated bamboo. The adhesive layer requires a flat surface to minimize gaps between the bamboo. Adding vegetable fibers causes a space between the fibers; when the adhesive cannot fill the fibers, the bond between the laminae becomes weak. Surface modifications such as chemical treatment effectively remove lignin material in the fiber, thereby enabling better bonding in polymer composites.

(Sawpan *et al.*, 2011b, 2011a; Yan *et al.*, 2012; Siakeng *et al.*, 2018).

MOE in the combination treatment with vegetable fiber reinforcement, *A. sisalana*, showed the highest value for *B. blumeana*, 31.41 GPa, while *H. cannabinus* showed the highest value for *G. atrovioleacea*, which was 26.03 GPa. MOR in the combination treatment with vegetable fiber reinforcement, *H. cannabinus*, showed the highest values for the two types of bamboo used, with 94.02 MPa (BK) and 85.79 MPa (AK). The finding that the mechanical properties without fiber have the highest value certainly benefits the production process.

CONCLUSIONS

Laminated bamboo with vegetable fiber reinforcement results from combining bamboo and vegetable fibers. Moisture content with density and moisture content with MOR show a negative correlation

linear, density with MOE, density with MOR, and MOE with MOR showing a positive linear correlation. The average value of the physical and mechanical properties of the combination treatment of bamboo without adding vegetable fiber is better than that of bamboo with fiber.

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