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Dimensional Stability Test of Mahogany Wood through Heat Treatment

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Abstract

The demand for raw wood materials for construction and various other purposes is steadily increasing. Mahogany wood (*Swietenia macrophylla*), one of Indonesia's fast-growing commercial tree species, is widely used in construction due to its significant potential in the timber industry. However, it exhibits low dimensional stability and high hygroscopic properties, which can limit its applications. This study aimed to enhance the quality of mahogany wood by improving its dimensional stability through heat treatment. The samples underwent heat treatment at 180°C for three durations: untreated (control), 3 hours, and 6 hours. The results indicated that heat treatment at 180°C for 6 hours yielded the most favorable outcomes, including better dimensional stability, a lower increase in water content, higher specific gravity, reduced water absorption capacity, and minimal swelling in all three directions of the wood. Additionally, the Anti-Swelling Efficiency (ASE) values for the 6-hour treatment were superior to those for the 3-hour treatment.

Keywords: Dimensional stability, hygroscopic properties, physical properties, swelling

Introduction

The demand for raw wood materials for buildings and other products for various purposes is increasing significantly. Furthermore, the forest product processing industry serves a large international market with products such as sawn timber, furniture, pulp and paper, and composite wood. However, the timber supply from natural forests is declining, and much of the wood available in the market is suboptimal. Sushardi et al. (2021) state that the forest product industry relies heavily on natural forests. Therefore, alternative wood sources, such as plantation forests with fast-growing cycles, are urgently needed.

Mahogany (*Swietenia macrophylla*) is a fast-growing commercial tree species in Indonesia that is widely used in construction due to its considerable potential. Masdar (2018) reports that mahogany wood can be a reference material for designing structural components, furniture, ships, printing blocks, and handicrafts. Its fine features make it suitable for producing decorative veneers and plywood. However, mahogany is classified as strength class III and durability class III, with a cellulose content of 46.8% (BPPK, 2005). Moreover, it exhibits less stable dimensional properties. Therefore, modification efforts are necessary to improve the quality of mahogany wood and optimize its utilization.

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Heat treatment is an environmentally friendly modification method for altering the cell wall components of wood without using toxic chemicals. It can also enhance wood's dimensional stability and biological durability (Candelier et al., 2016; Hill, 2011). Several countries, including France, Finland, Russia, Turkey, and Estonia, already produce heat-treated wood commercially (Burnard et al., 2017; Sandberg et al., 2017). Generally, heat treatment processes vary in temperature, duration, and environmental conditions (Karlinasari et al., 2018). The success of heat modification treatment depends on several factors: the temperature and duration of heat treatment, the system used (open or closed), the type of wood, and the wood's moisture content during treatment. Heat treatment modifies the cell walls, thereby altering the properties of the wood. It is expected to improve the dimensional stability of mahogany wood and reduce hygroscopic properties, resulting in better physical characteristics.

Methodology

The test samples were obtained by cutting mahogany logs aged less than 10 years with a diameter of approximately 35 cm into boards with 2 x 2 x 5 cm^3 dimensions. Five pieces were prepared for the control group, five for heat treatment of 3 hours, and five for heat treatment of 6 hours. The samples were air-dried to an equilibrium moisture content of 12% using a fan for 14 days at room temperature. The equilibrium moisture content was measured using a moisture meter. Once the desired moisture content was achieved, the samples underwent heat treatment in an oven at a temperature of 180°C. After the heat treatment, the samples were coated on the ends with *No Drop* paint and placed back in the oven at 60°C for 7 days for conditioning. The samples were weighed (B1), and their dimensions were measured (V1). Next, the test samples were immersed in water for 2 hours, after which they were weighed (B2), and their dimensions (V2) were measured again. The samples were subsequently oven-dried at 103 ± 2°C for 2 days to determine the oven-dried weight (B3) and dimensions (V3).

The dimensional stability values were calculated using the following equations:

$$Conditioning\ moisture\ content\ (\%) = \frac{B1 - B3}{B3} x\ 100$$

$$Immersion\ moisture\ content\ (\%) = \frac{B2 - B3}{B3} x\ 100$$

$$Specific\ gravity = \frac{B3}{V3}\ x\ 100$$

$$Absorption\ (\%) = \frac{B2 - B1}{B3}\ x\ 100$$

$$Swelling\ (\%) = \frac{Swelling\ of\ T\ dimension}{Swelling\ of\ R\ dimension}$$

$$ASE\ (\%) = \frac{V\ swelling\ of\ control - V\ swelling\ of\ treatment}{V\ swelling\ of\ treatment}\ x\ 100$$

Notes:
B1 = weight of the conditioned test sample (g)
B2 = weight of the immersed test sample (g)
B3 = weight of the oven-dried test sample (g)
V1 = volume of the conditioned test sample (cm^3)

V2 = volume of the immersed test sample (cm^3)
V3 = volume of the oven-dried test sample (cm^3)

The effect of heat treatment on the dimensional stability of mahogany wood was analyzed using a completely randomized factorial design with one factor. Factor A was the heat treatment time with three levels: untreated (control), 3 hours, and 6 hours. Each treatment was repeated five times. Data were processed using Microsoft Excel 2021 and IBM SPSS 23. If the analysis of variance at the 95% confidence interval indicated a significant effect, a Duncan test was conducted.

Results and Discussion

Moisture Content

Visually, the color of wood subjected to three levels of heating time differed significantly (see Figure 1). Wood exposed to heat for 6 hours exhibited a darker color. Hajian et al. (2024) state that heat treatment results in darker timber discoloration, which depends on both the temperature and the duration of the heat treatment. Research by Karlinasari et al. (2018) revealed that significant color changes primarily occurred at temperatures ranging from 150°C to 180°C for 2 to 6 hours exposure times.

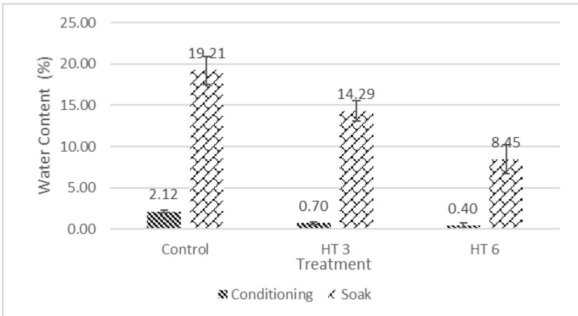
High heating temperatures significantly affect the moisture content of the wood. As the temperature increases, the moisture content tends to decrease (Missio et al., 2016). The average moisture content of the control samples, as well as those subjected to 3 hours and 6 hours of heat treatment after conditioning, was 2.12%, 0.70%, and 0.40%, respectively. However, after immersion, these values increased significantly to 19.21%, 14.29%, and 8.45%, respectively. The control samples experienced the highest increase in moisture content, followed by the samples subjected to 3 hours of heat treatment. The samples heat-treated for 6 hours exhibited the lowest increase in moisture content (see Figure 2). At the 95% confidence level, data analysis showed that heat treatment for 3 hours significantly increased the moisture content of the

Figure 1

(a) Untreated samples (control); (b) heat-treated for 3 hours; (c) heat-treated for 6 hours.

Figure 2

Moisture content under each treatment in two conditions.

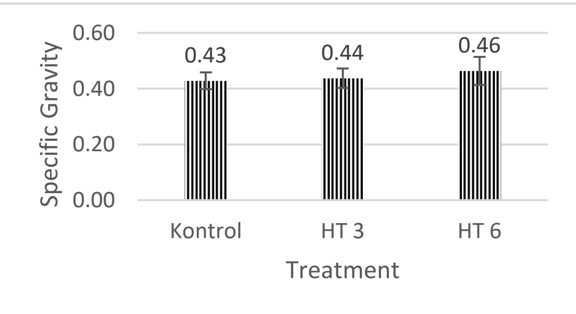


samples after conditioning. Following immersion, all treatments and wood directions showed significant differences. Due to the reduced moisture content in wood treated for 6 hours, its physical properties were found to be superior. This improvement was attributed to changes in the structure of wood cells that stored water.

Bound water in the cell walls formed intermolecular bonds between the adsorbent (wood) and the adsorbate (water) or other adsorbates. These bonds were stronger than those of free water in the lumen. When a significant amount of bound water was released, the empty molecular sites within the cell walls bonded with each other. Consequently, these wood cells developed thick cell walls and shrank the lumens, reducing water movement in and out of the wood. This stabilization enhanced the hygroscopic properties of the wood. At moisture content levels of ≤10%, the hygroscopic stability of the wood appeared to be achieved, resulting in minimal changes in moisture content. Heat treatments exceeding 140°C facilitated the degradation of bound water and structural components of the wood, leading to changes in its material properties. These changes included alterations in color, dimensional stability, crystallinity, and mechanical properties.

Figure 3

Specific gravity in each treatment under three conditions.



Specific Gravity in Oven-Dried Condition

The specific gravity of wood is one of the essential physical properties of timber, influencing its usability. A higher specific gravity value indicates stronger and heavier wood (Wahyudi et al., 2014). Conversely, lighter wood types tend to have less strength (Haygreen et al., 2003). Heat treatment is typically conducted at temperatures ranging from 180°C to 260°C. Temperatures below 140°C produce minimal changes in wood properties, while temperatures above 260°C cause significant degradation of the wood substrate (Priadi et al., 2021). The specific gravity values of oven-dried wood for the control, 3-hour heat treatment, and 6-hour heat treatment were 0.43, 0.44, and 0.46, respectively (see Figure 3). Although the specific gravity increased with each treatment, the increase was not significant and had no discernible effect. Candelier et al. (2016) explain that the weight of wood material decreases during heat treatment, which can be attributed to damage to the cell wall, loss of extractive substances, and degradation of hemicellulose caused by the high temperatures applied.

Absorption

Heat treatment reduces the hygroscopicity of wood due to the degradation of hemicellulose, cellulose, and lignin. The hydroxyl groups in hemicellulose chemically bind water (Joma et al., 2016). Heat treatment reduces the availability of these hydroxyl groups, leading to lower hygroscopicity. This was evident in the results of this study: the control sample had the highest absorption value (17.10%), followed by the 3-hour heat treatment (13.60%) and the 6-hour heat treatment (8.05%) (see Figure 4). Among the treatments, the 6-hour heat treatment resulted in the lowest absorption ability. Statistical analysis demonstrated significant differences in absorption values across treatments and wood directions. These findings indicated that the wood's dimensional stability improved with the 6-hour heat treatment, particularly in the tangential direction, which was typically the most hygroscopic. The results aligned with research by Zhou et al. (2020), which found that longer heat treatment durations reduced the wood's ability to absorb water into its cell cavities.

Swelling

Heat treatment, in addition to causing hemicellulose degradation, also induces changes in cellulose. The thermal degradation temperature of cellulose is higher than that of hemicellulose (Kuzman et al., 2015). Although cellulose is more resistant than hemicellulose, degradation of the amorphous portion of cellulose can increase its crystallinity (Priadi & Giyarto, 2019). This leads to enhanced wood durability, reduced hygroscopicity, and improved dimensional stability. However, Fendi et al. (2017), in a study on heat treatment of teak wood, reported that excessively high temperatures could decrease the degree of crystallinity, indicating a reduction in crystalline diameter. The amount of lignin

Figure 5

Swelling ability of the sample after treatment.

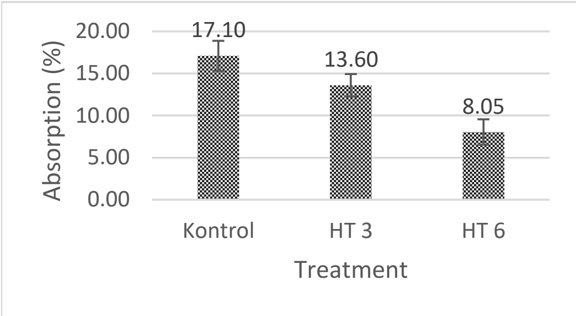


Figure 6

Swelling volume of the sample.

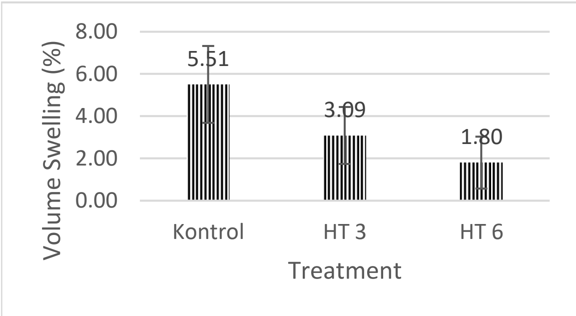
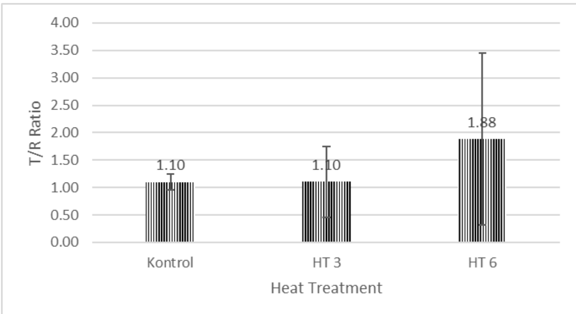


Figure 7

T/R ratio for each treatment.



degraded during heat treatment is less than that of holocellulose, yet lignin undergoes significant changes, becoming softer due to its thermoplastic nature. This softening clogs cell pores, thereby reducing water absorption (Kocaefe et al., 2015; Widyorini et al., 2014). Lignin degradation requires temperatures above 150°C, as observed in teak wood (Lukmandaru et al., 2018; Uribe & Ayala, 2015). Heat treatment significantly reduced tangential and radial swelling in mahogany, particularly in wood treated for six hours. Wood degradation increased with higher temperatures and longer heating durations. As shown in Figure 5, the swelling of wood heat-treated for six hours was minimal and significantly different from the control. Noticeable changes appeared after three hours of heat treatment, particularly in the longitudinal and tangential directions. Tangential swelling exhibited the highest dimensional instability, attributed to the vertical orientation of microfibrils in the S2 layer of the cell wall and the radial orientation of ray parenchyma cells (Priadi & Hiziroglu, 2013). This finding aligned with Hajian et al. (2024), who state that heated wood becomes more stable with increased temperature and heating duration. Reduced swelling enhances dimensional stability, which is essential for various wood applications. Kubler (1980) explains that at high temperatures, molecular vibrations intensify, leading to the disintegration of wood constituents. Thermal degradation begins in dry wood at approximately 100°C, while in wet wood, hydrolysis starts at around 70°C and becomes noticeable after a few days. In Figure 6, the swelling volume of treated samples differed significantly from the control. However, the difference between three-hour and six-hour treatments was minimal. Statistical tests at a 95% confidence level confirmed that the control significantly differed from three- and six-hour treatments. However, no significant difference was observed between the two treated groups.

As depicted in Figure 7, the T/R ratio increased with heat treatment duration, from the control to three-hour and six-hour treatments (1.10, 1.10, and 1.88, respectively).

Figure 8

ASE of the test sample in the longitudinal, radial, and tangential directions.

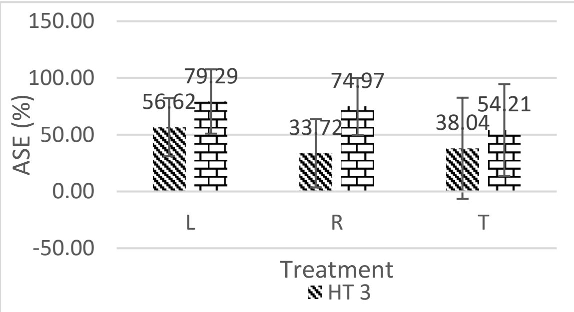
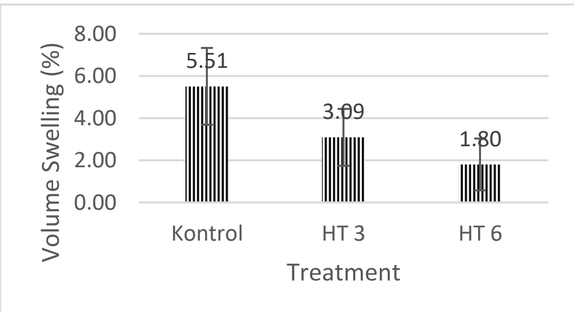


Figure 9

ASE values for the two heat-treated samples.



Nonetheless, the wood retained good stability, as the T/R ratio remained close to 1 and below 2 (Panshin & Zeeuw, 1980).

Anti-Swelling Efficiency (ASE)

Wood's dimensional stability reflects its ability to resist changes in dimensions caused by variations in moisture content. The hygroscopicity of wood contributes to its dimensional instability. ASE serves as an indicator of dimensional stability. As shown in Figure 8, heat treatment increased the ASE value in all wood directions and treatment durations. The most significant improvement occurred in the radial direction, likely due to the substantial degradation of holocellulose in that direction. Additionally, chemical changes in the wood, such as a reduction in hydroxyl groups that bound water in cell walls and cavities, contributed to decreased hygroscopicity and increased ASE values. A high ASE value indicates reduced wood hygroscopicity. Based on these findings, test samples subjected to six hours of heat treatment demonstrated the lowest water absorption capacity and, consequently, the best ASE results. Figure 9 portrays that the ASE value for six-hour heat-treated samples was higher than that for three-hour heat-treated samples, although the difference was not statistically significant.

Conclusion

Heat treatment is an environmentally friendly method that has been proven to enhance the dimensional stability of wood, improve its strength, and reduce its hygroscopicity. In this study, heat treatment at 180°C for 6 hours yielded the best results for maintaining wood dimensions, with a low increase in moisture content, higher specific gravity, reduced absorption capacity, minimal swelling in the three wood directions, and a lower ASE value compared to the 3-hour treatment.

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