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Effect of Heat Treatments on Physico-mechanical Properties of Kelempayan Wood

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ABSTRACT

The treatment of wood performs as to enhance its resistance properties, thereby improving its dimensional stability, strength, and durability as compared to untreated wood. In this study, a kelempayan wood (Neolamarckia cadamba) was used because it is one of the potential fast-growing species which can be as an alternative raw material for furniture components. The aim of this study is to determine the effect of physico-mechanical properties of kelempayan wood through oven and microwave heat treatments at different density groups. The wood billets left to air dried before cutting into the wood samples size for physical and mechanical testing. The samples were treated by using the oven at temperature of 105 °C for 24 hours, microwave at power of 90 watts with maximum rated power output of 1000 watts for 3 minutes and microwave laboratory scale. The physical test methods were performed according to ASTM D4442-20 standard. Meanwhile, the mechanical properties have been tested base to the BS 373 standard. The Scanning Electron Microscope (SEM) was used to examine microstructure of treated samples. The results revealed that all treatments had a significant effect on the physico-mechanical properties of kelempayan wood. The microwave heat treatment effectively affected kelempayan wood by lowering the physical properties and increasing both *compression and shear strength for mechanical properties. MOE and MOR strength were decreased for both oven and microwave treatment. Based on the SEM image, the microstructure of kelempayan wood shows that the heat treatment lowers the water uptake, and the wood cell walls absorb less water due to the hydroxyl groups amount reduction which as a result in decreasing of wood shrinkage and swelling. The advantages of heat-treated wood are reduced hygroscopicity and better dimensional stability. Therefore, it was suggested that heat treatment influenced the physico-mechanical properties of kelempayan wood which made it possible to be used as a raw material for furniture industry.*

Keywords: Neolamarckia cadamba; Physico-mechanical Properties; Oven and Microwave Heat Treatment

INTRODUCTION

Kelempayan wood (*Neolamarckia cadamba*) is a fast-growing tropical timber species indigenous in Southeast Asia. The adaptability of its wood to different environmental conditions and its rapid growth rate makes it a best option for reforestation projects and sustainable timber production [1]. The wood is light, physical characterised by a creamy yellow colour of heartwood upon disclosure, have even and fine texture with the presence of vessel lines and generally straight grains [2]. Besides, the sapwood is in white colour that will change to yellow colour when exposed to air [3]. Despite its advantages, kelempayan wood density is in Group D with approximately 290-465 kg/m^3 and has lower durability and strength compared to other hardwoods, limiting its commercial use [4]. Its relatively low density and ease of workability make it suitable for a various application, including furniture, plywood, panelling, and light construction materials. However, kelempayan wood is prone to certain limitations, such as low natural durability and susceptibility to insect and fungal attacks [5]. Thus, enhancing its physical and mechanical properties through heat treatments aim to improve dimensional stability, strength and resistance to biological degradation, thereby expanding the potential uses of kelempayan wood and increasing its commercial value in the global market.

Heat treatment is a thermal modification process in which wood is treated at high temperatures causing specific changes in its properties [6]. Heat treatment can modify the properties of wood to increase durability, dimensional stability, reduced hygroscopicity, and enhanced biological resistance of wood [6], [7]. The thermal treatment of wood is one of the most promising wood modification methods, where wood is exposed to high temperature, resulting in a change of chemical structure of organic constituents in the wood (cellulose, hemicellulose, lignin) which gave improvements in some properties [8]. In addition, hardness and stiffness can be improved with heat treatment. However, this process affects the mechanical properties of wood, resulting in slight reduction in some mechanical attributes, such as bending, compression and shear strength due to the degradation of hemicellulose [9]. Heat treated wood has the potential to be used in a variety of interior applications such as parquet, wall panels, and furniture as well as outdoor use, due to its increased decay resistance without the need of harmful chemical treatment [10].

There are various types of heat treatment nowadays being applied in treating wood. One of the treatments is microwave heat treatment. This treatment method computes the energy losses released by a material and the speed variation brought on by microwave propagation from the substance to the moisture content after microwaves are transmitted at it [11]. When applying microwave treatment, certain parameters related to the microwave equipment are required, such as frequency, specific power applied to the wood, energy application mode (continuous or pulse), wood species, initial moisture content, and sample dimensions. Furthermore, determining the dielectric properties of wood and the quantity of energy it absorbs requires an understanding of how microwaves interact with materials [12]. According to earlier research, different wood species responded differently to microwave heat treatment [6,13]. It is difficult to create uniform treatment parameters for all types of wood since different wood species and thicknesses may react differently to heat treatment. Whereas the kiln- dry section is being utilized for commercial operations, laboratory ovens are usually used for experimental heat treatment of wood and wood products. Both approaches take a lot of time. As thus, microwave heat treatment is a relatively recent method that offers the advantages of better temperature control, quicker, and heat distribution are more even into wood samples [6].

This study will investigate the effects of oven and microwave heat treatments on the properties of kelempayan wood, using air-dried as a control. The effect on physical and mechanical properties can be emphasised by comparing these two thermal modification methods, thereby finding suitability in improving wood performance. The novelty of this study can be seen with the comparison of typical oven to microwave treatment, providing a better knowledge of how different heat sources affect wood properties. Therefore, it is important to consider how each method affects the wood's overall durability, moisture content, and structural integrity [14]. Conventional method like oven treatment, which usually involves exposing the wood to regulated temperatures for an extended length of time. By successfully lowering the moisture content, this can help the wood stabilize and harden. The slow process, however, may result in uneven drying and raise the possibility of internal tensions and surface checking, both of which could weaken mechanical strength [15]. On the other hand, microwave treatment uses electromagnetic radiation to vibrate the water molecules in the wood, resulting in a quick heating process [16]. This technique makes it possible to reduce moisture more evenly across the wood's thickness. By minimizing the amount of time the wood exposed to heat, the microwave treatment's speed lowers the chance of thermal degradation and maintains the wood's mechanical properties [12]. Furthermore, because of the even distribution of stress during drying, microwave treatment can improve the elasticity and tensile strength of kelempayan wood.

Thus, kelempayan as raw material, which is not being studied yet in term of treating with microwave, especially in looking at the effects of treatment on wood properties. The effectiveness of heat treatment methods can be evaluated, among others, by determining changes in physical and mechanical properties.

EXPERIMENTAL METHODOLOGY

Sample Preparation

Kelempayan (*Neolamarckia cadamba*) trees were harvested from the Fruit Plot Area at Agrotechnology and Plantation of UiTM Pahang Branch and processed into sawn timber using the facilities at the Wood Industry Workshop of UiTM Pahang Branch. The logs were cut into three billets: bottom, middle, and top each approximately 180 cm in length. The sawn timbers were then left to air dry until the moisture content reduced to 20% before being divided into two density group: ≤450 kgm^{-3} and >450 kgm^{-3}. Then, air dried timbers were cut into specimens of various sizes for different tests: physical testing (25 mm x 25 mm), mechanical testing for bending (20 mm x 20 mm x 300 mm), compression parallel to grain (20 mm x 20 mm x 60 mm), compression perpendicular to grain (50 mm x 50 mm x 50 mm), shear (20 mm x 20 mm x 20 mm), as per BS 373 [17], and scanning electron microscopy (SEM) (5 mm x 5 mm). The samples for continuous microwave laboratory-scale were treated before being cut into specimen sizes. Figures 1 and 2 show the schematic diagrams of the sample cutting process and the sample preparation process, respectively.

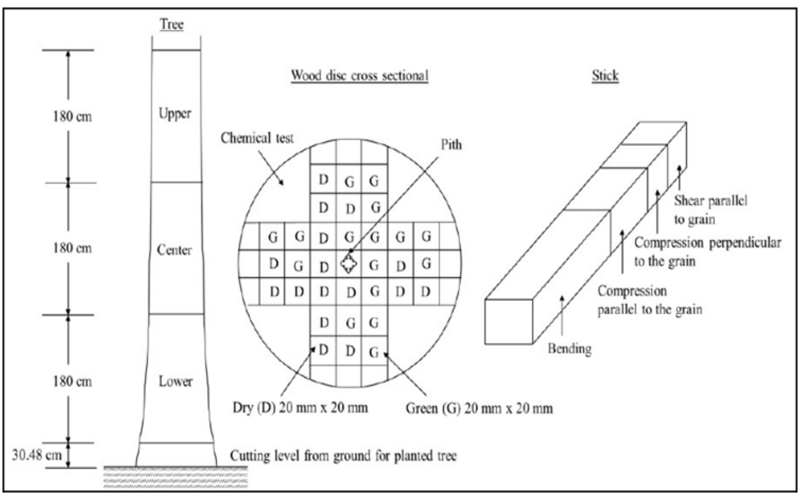


Figure 1: Schematic diagram of the sample cutting process [18].

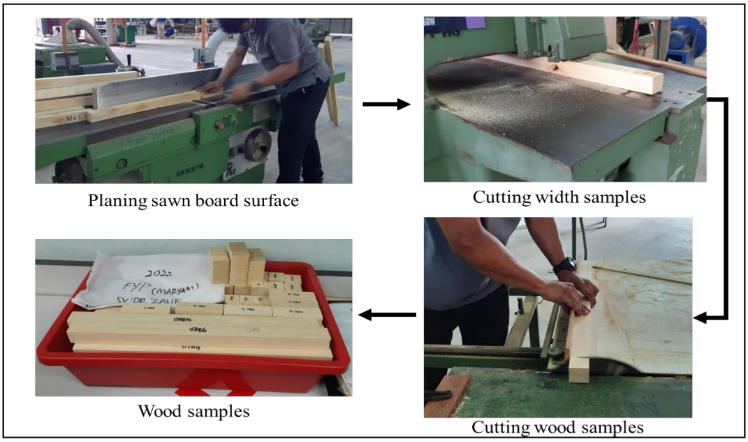


Figure 2: Sampling preparations process.

Heat Treatment Process

Three treatments were conducted: oven (OD), domestic microwave oven (MW), and continuous microwave laboratory-scale (MWC). All wood samples were left conditioned at room temperature (20 °C) for 24 hours before undergoing each heat treatment. The wood samples for oven treatment were heated in a convection electrical oven in accordance with ASTM D4442-20 [19] at a temperature of 105 °C for 24 hours. Figure 3 shows the steps involved in the oven treatment process.

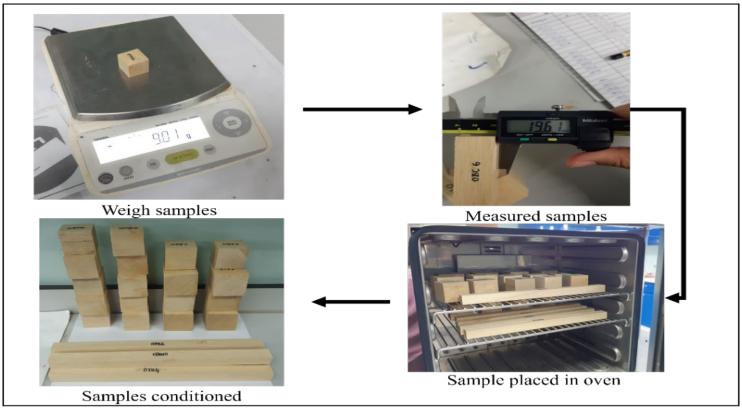


Figure 3: Oven treatment process.

For domestic microwave treatment, the samples were exposed to 90 watts of power for 3 minutes. The microwave oven had a maximum rated power output of 1000 watts. The microwave power level was set by adjusting the microwave to its lowest setting, indicated as P10 on the LED display, which corresponded to 90 watts. A trial-and-error approach was conducted to determine the optimal microwave time and power settings needed to reduce the moisture content below 10%. Figure 4 shows the domestic microwave treatment process.

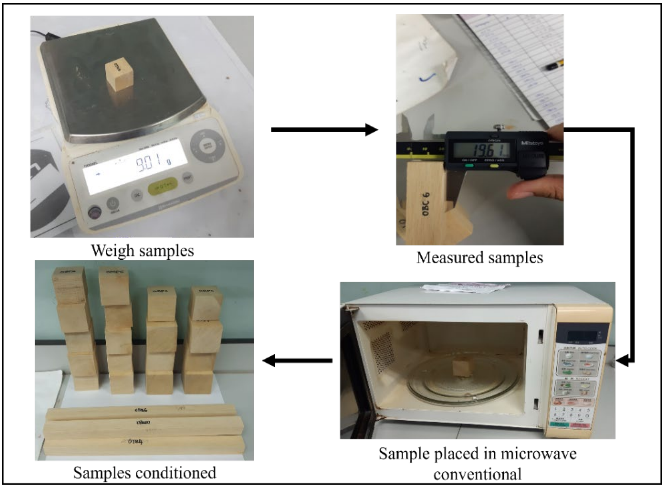


Figure 4: Domestic microwave treatment process.

In a continuous microwave laboratory-scale treatment (Figure 5), samples were passed through a microwave applicator with the generator set to a constant energy level of 550 kW/h. The amount of microwave energy density utilized was calculated by dividing the microwave power by the sample volume flow rate [20]. The microwave energy level was adjusted manually. The weight and dimensions (length, width, thickness) of the samples were measured before and after treatment. The speed of the conveyor belt was set to level 1 which equal to 10 minutes/m. The speed was selected using a trial-and-error method to achieve the desired microwave energy density. Samples that underwent a 2-cycle treatment were passed through the microwave applicator again with the same energy level applied. After treatment, the wood samples were conditioned before taking all the necessary measurements.

Figure 5: Continuous microwave laboratory-scale equipment.

SAMPLE TESTING

Physical Testing

The treated samples were weighed and measured to determine moisture content, shrinkage and swelling. Each sample with dimensions of 25 mm by 25 mm by 25 mm were marked according to wood directions: tangential, radial, and longitudinal. The moisture content was determined using Eq. (1) [21], following the ASTM D4442-20 standard [19]:

$$\text{Moisture content (\%)} = \frac{\text{Mass when cut} - \text{Oven dried mass}}{\text{Oven dried mass}} \text{ x } 100 \quad (1)$$

Samples for shrinkage determination were dried in a conditioning room, while samples for swelling were placed in a desiccator with distilled water. The dimensions of the specimens were measured before and after conditioning using a digital calliper. The formulas for determining the shrinkage and swelling of the specimens are given in Eq. (2) and Eq. (3) [22].

$$\text{Percent shrinkage (\%)} = \frac{(decrease\ in\ dimension\ or\ volume)}{original\ dimension\ or\ volume} \text{ x } 100 \qquad (2)$$

$$\text{Percent swelling (\%)} = \frac{(increase\ in\ dimension\ or\ volume)}{original\ dimension\ or\ volume} \text{ x } 100 \qquad (3)$$

Mechanical Testing

The mechanical properties of small-size specimens were determined using a Universal Testing Machine (Instron 5569) with the load capacity of 100 kN, following the BS 373 [23]. Mechanical test conducted were three- point static bending, compression parallel and perpendicular to the grain and shear parallel to the grain. For bending test, the distance between the two supports was 280 mm, and a constant loading speed of 6/min was applied throughout the test (Figure 6). The modulus of rupture (MOR) and modulus of elasticity (MOE) were calculated using the Eq. (4) and Eq. (5):

$$\text{MOR} = \frac{3}{2}\frac{F}{WT^2} \qquad (4)$$

$$\text{MOE} = \frac{L^3}{4WT^3}\frac{\Delta F}{\Delta l} \qquad (5)$$

where, F is the maximum load (N), L is the span length of the test specimen (mm), w is the width of the test specimen (mm), T is the depth of the test specimen (mm) and ΔF/Δl is the slope linear portion of the load-deflection graph (N/mm).

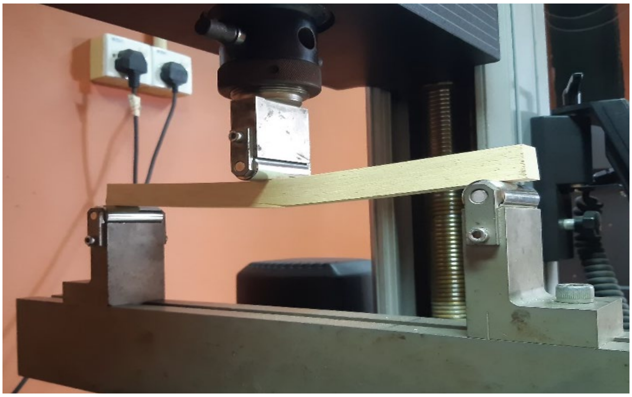
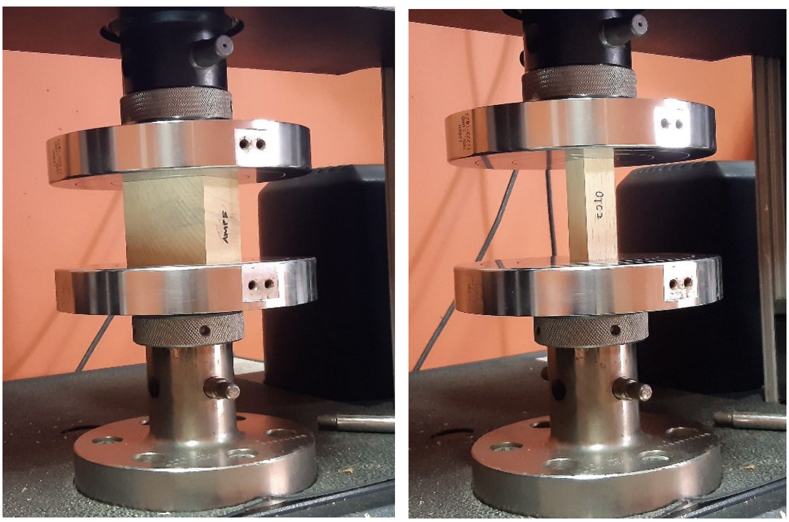


Figure 6: Three-point bending test.

The compression perpendicular to the grain tests was conducted by compressing the specimens placed between the top and bottom compression platen in both the radial and tangential directions (Figure 7(a)). In the compression parallel to the grain test (Figure 7(b)), the load was applied to the top end of specimen. The shear test (Figure 8) was performed by applying the load parallel to the grain direction, and the load-compression curve was plotted until a compression of 100 mm was reached. Throughout the test, a constant loading speed of 0.6 mm/min was applied. The compression and shear strengths were calculated using Eq. (6):

$$\text{Compressive stress at maximum load} = \frac{F}{A} \tag{6}$$

where, F is the maximum load (N) and A is the cross-sectional area (mm^2).



(a) (b)

Figure 7: Compression perpendicular to the grain test (a) and compression parallel to the grain test (b).

Figure 8: Shear test.

Scanning Electron Microscope (SEM)

The microstructure of treated wood samples was examined using Scanning Electron Microscope (SEM). Specimens were sectioned into approximately 5 mm x 5 mm pieces in transverse, radial, and tangential sections. Subsequently, the samples were gold sputtered using a using a sputter coater model Polaron SC 515 ± nm. Micrograph images of the samples were captured using an LEO Supra 50 Vp field emission scanning electron microscope.

Statistical Analysis

Statistical analysis was conducted using IBM SPSS Statistic software version 29. A one-way analysis of variance (ANOVA) was performed to determine whether the mean differences between treatments were significant. If the differences were significant, the Duncan Multivariate Range Test was conducted to determine which of the means were significantly different from one another.

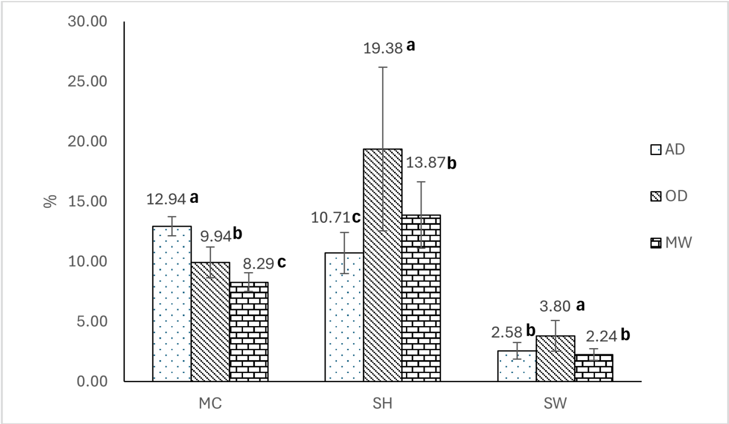
RESULTS AND DISCUSSION

Effect of Heat Treatment on Physico-mechanical Properties

Physical Properties Analysis

The moisture content (MC), shrinkage (SH) and swelling (SW) of air dried (AD) and treated (OD and MW) kelempayan wood are shown in Figure 9. The mean of moisture contents was 12.94% for AD, 9.94% for OD and 8.29% for MW. The mean differences were statistically significant ($p<0.05$). The air dried treatment used as control sample had a higher moisture content compared to the OD and MW heat treatments. This indicates that the heat produced by ovens and microwaves can reduce the moisture content of the wood by less than 10%. The air drying process is comparatively slower than heat treatment, allowing more moisture to remain in the wood. Meanwhile, heat treatment provided greater control over the ultimate moisture content because of precise temperature and humidity settings compared to air drying that more reliant on environmental factors [21].

The mean of shrinkages was 10.71% for AD, 19.38% for OD, and 13.87% for MW. The mean differences were statistically significant ($p<0.05$). Regarding swelling, the mean swelling values for AD were 2.58%, 3.80% for OD and 2.24% for MW. There was no significant difference between the AD and MW treated samples, as the difference was minimal. The heat treatment process affected shrinkage and swelling of wood. Based on previous study, prolonged exposure to high temperatures during oven heat treatment lowers the wood's equilibrium moisture content, thereby reducing dimensional change of wood [9]. This occurs because the breakdown of hemicelluloses makes the wood less hygroscopic. Overall, the physical properties of kelempayan wood were affected by heat treatment compared to the control sample.



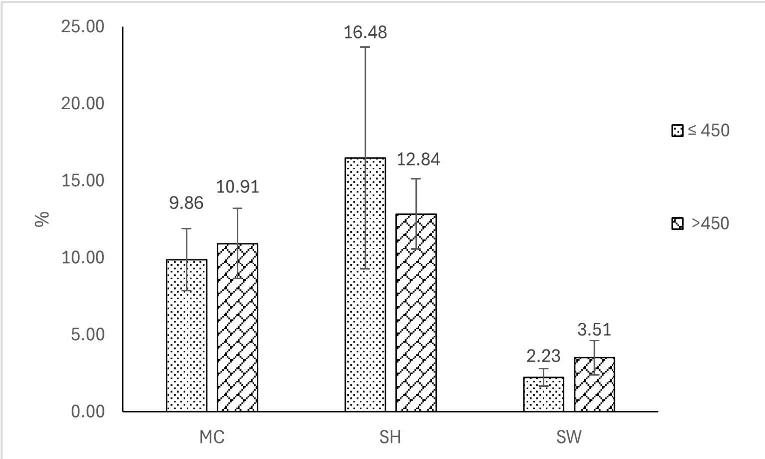
Note: Means with the same superscript letter are not significantly different at = 0.05 by Duncan Multivariate Range Test; where AD = Air dried (control), OD = Oven heat treatment, MW = Domestic microwave heat treatment, MC = Moisture content, SH = Shrinkage and SW= Swelling

Figure 9: Physical properties of kelempayan wood at different treatments.

The physical properties of kelempayan wood for two density groups are shown in Figure 10. The mean moisture content for density ≤450 kg/m³ (9.86%) was slightly lower than density >450 kg/m³ (and 10.91%). This indicates that higher wood density results in higher moisture content.

The mean of shrinkage for density ≤450 kg/m³ was 16.86% and for density >450 kg/m³ was 12.84% respectively. This showed that the higher the density of wood resulted in a lower shrinkage percentage. The mean of swelling for density ≤450 kg/m³ was 2.23% and density >450 kg/m³ was 3.51% respectively. This showed that the higher the density of wood resulted in a high swelling percentage.

High-density wood contains more cell wall substances and less pore volume, providing less available space for water than low-density wood [24]. As a result, high-density wood typically contains less water but exhibits greater shrinkage and swelling than low-density wood [25, 26]. However, the contrary result observed in this study may be attributed to the random sampling method applied. The segregation of samples into two density groups did not account for their position within the tree stem.

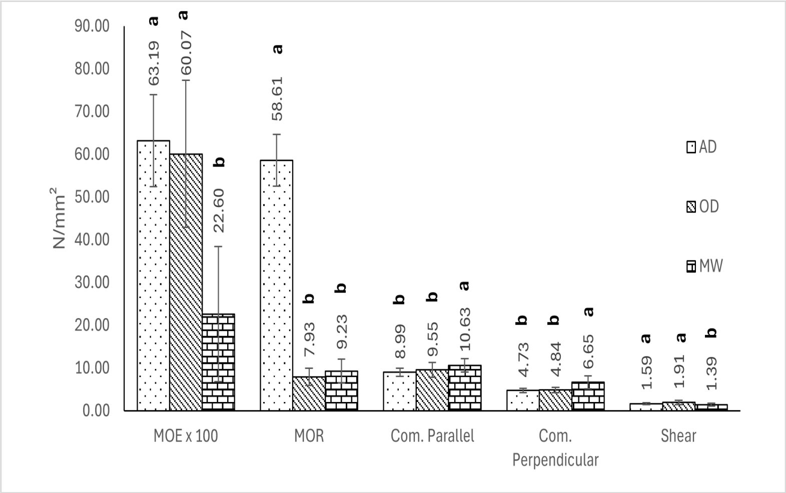


Note: MC = Moisture content, SH = Shrinkage, SW= Swelling, % = percentage

Figure 10: Physical properties of kelempayan wood for two density groups.

Mechanical Properties Analysis

The mechanical properties of kelempayan wood at different heat treatments are shown in Figure 11. The mean of MOE for AD was 6318.65 N/mm2, 6007.23 N/mm^2 for OD and 2259.55 N/mm^2 for MW respectively. The mean MOE for MW was significantly lower than AD and OD. The AD samples had the highest MOE, indicating that kelempayan wood treated with microwave heat is less resistant to deformation within the elastic range, as its elastic modulus was lower. The crosslinking of the lignin network is most likely the cause of the degradation in mechanical properties [27].



Note: Means with the same letter are not significantly different at = 0.05 by Duncan Multivariate Range Test; where AD = Air dried (control), OD = Oven heat treatment, MW = Domestic microwave heat treatment, MOE = Modulus of elasticity, MOR = Modulus of rupture and Comp.= Compression

Figure 11: Mechanical properties of untreated and heat-treated kelempayan wood.

The mean of MOR for AD was 58.61 N/mm², 7.93 N/mm² for OD and 9.23 N/mm² for MW respectively. The MOE of AD wood was significantly higher compared to OD and MW wood, indicating that it resists deformation and remains intact longer before permanent deformation compared to heat-treated wood [28].

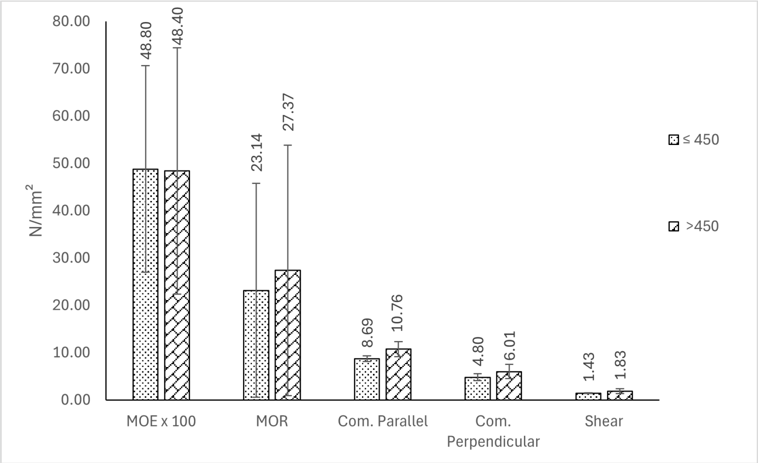
The mean of compression parallel to the grain for AD was 8.99 N/mm², 9.55 N/mm² for OD and 10.63 N/mm² for MW. The mean of compression perpendicular to the grain for AD was 4.73 N/mm², 4.88 N/mm² for OD and 6.65 N/mm² for MW respectively. Microwave- treated wood exhibited significantly higher compression parallel and perpendicular to the grain compared to AD and OD. Microwave treatment enhanced the wood's ability to withstand forces applied both parallel and perpendicular to the grain. In comparison, the grain of wood is strongest when it is parallel. As a result, the wood exhibits stronger and more rigid qualities from a direction parallel to the strength axis than from a perpendicular direction [29,30].

The mean of shear strength for AD was 1.59 N/mm², 1.91 N/mm² for OD and 1.39 N/mm² for MW respectively. The mean shear strength for microwave-treated wood was significantly lower compared to AD and MW. Previous studies showed that heat treatment decreased the hardness and shear strength of wood [31]. Furthermore, studies on how microwave treatment affects wood structure have revealed that exposure to microwaves can change the anatomical characteristics of wood, which may affect its mechanical properties.

The mechanical properties of air dried kelempayan wood for two density groups are shown in Figure 12. The mean of MOE for density ≤450 kg/m³ was 4879.66 N/mm² and density >450 kg/m³ was 4843.96 N/mm² respectively, and the mean differences were statistically insignificant. The mean of MOR for density ≤450 kg/m³ was 23,14 N/mm² and density >450 kg/m³ was 27.37 N/mm² respectively. The mean values were significantly difference. The measurement results of the mean score showed that the flexural strength (MOR), with higher density corresponded to an increase in the modulus of rupture. This is because higher density results in less porosity, which in turn enhance the strength [32].

The mean compression parallel to the grain at different densities revealed that for densities ≤ 450 kg/m³, the mean compression was 8.69 N/mm², while for densities > 450 kg/m³, it was 10.76 N/mm², with a significant difference between the two. Previous studies on young kelempayan wood planted in West Malaysia revealed that the centre section of the tree had a higher compression strength parallel to the grain than the top section [33]. This implies that changes in the tree's internal density may have an impact on its mechanical characteristics. The mean of compression perpendicular to the grain for density ≤450 kg/m³ was 4.80 N/mm² and density >450 kg/m³ was 6.01 N/mm² respectively, and the mean differences were statistically significant.

The mean of shear strength for density ≤450 kg/m³ was 1.43 N/mm² and density >450 kg/m³ was 1.83 N/mm² respectively. The mean differences were statistically significant. Wood density and mechanical properties, such as shear strength, were positively correlated, indicating that higher density woods exhibited greater shear strength due to their denser cellular structure, thicker cell walls, and less void space [34].



Note: MOE = Modulus of elasticity, MOR = Modulus of rupture and Comp.= Compression

Figure 12: Mechanical properties of air dried kelempayan wood for two density groups.

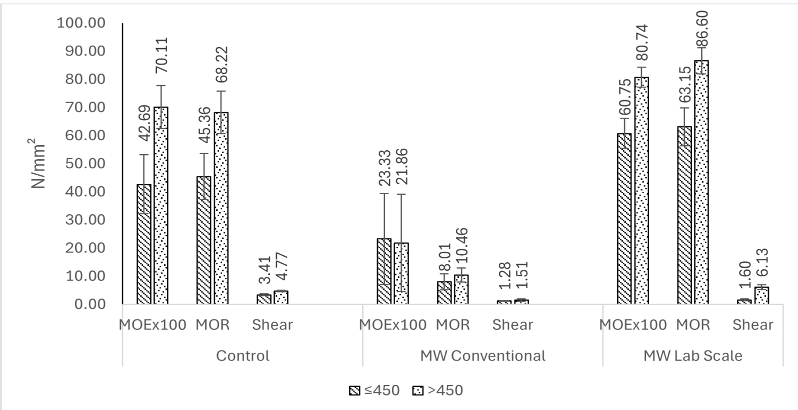
Effect of Domestic Microwave (MW) and Continuous Microwave Laboratory-scale (MWC) Treatment on Strength Properties

The strength properties of kelempayan wood for two density groups treated using microwave are shown in Figure 13. The MOEs of MWC-treated wood (6073.78 N/mm² for density ≤450 kg/m³; 8074.48 N/mm² for density >450 kg/m³) was higher than MW-treated wood (2333.337 N/mm² for density ≤450 kg/m³, 2185.772 N/mm² for density >450 kg/m³) and control sample (4269.30 N/mm² for density ≤450 kg/m³; and 7010.684 N/mm² for density >450 kg/m³).

The mean of MOR of MWC-treated wood for density ≤450 kg/m³ and >450 kg/m³ was 63.15 N/mm² and 86.60 N/mm², respectively, higher than MW-treated wood (8.01 N/mm² for density ≤450 kg/m³; 10.46 N/mm² for density >450) and control sample (45.36 N/mm² for density ≤450 kg/m³; and 68.22 N/mm² for density >450 kg/m³).

The shear strength of MWC-treated wood (1.60 N/mm² for density ≤450 kg/m³; 6.13 N/mm² for density >450 kg/m³) was also higher than

MW-treated wood (1.28 N/mm² for density ≤450 kg/m³; 1.51 N/mm² for density >450 kg/m³). The shear strength of MWC-treated wood for density ≤450 kg/m³ was lower than control sample (3.41 N/mm² ≤450 kg/m³), while for density >450 kg/m³, the shear strength of MWC-treated wood was higher than control sample (4.77 N/mm²). the shear strength of microwave laboratory scale was higher for density >450 kg/m³ while, lower for density ≤450 kg/m³ respectively. All the results showed a significant difference, indicating that density affects the strength properties for each treatment.



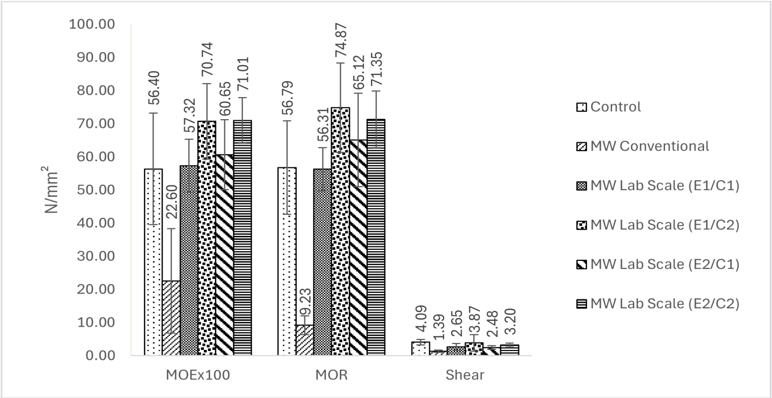
Note: MW Conventional = Domestic microwave heat treatment (MW), MW Lab Scale = Microwave laboratory scale (MWC), MOE = Modulus of elasticity and MOR = Modulus of rupture

Figure 13: Strength properties of treated and untreated kelempayan wood for two density groups.

The strength properties of MW and MWC-treated kelempayan wood are shown in Figure 14. The mean of MOE of MWC-treated (E2/C2) and (E1/C2) were 7100.52 N/mm² and 7074.13 N/mm² which higher than other microwaves. MW-treated wood had the lowest value of MOE (2259.55 N/mm²) compared to control sample (5639.99 N/mm²) and MWC-treated (7107 N/mm². The mean MOR of MWC-treated (E1/C2) and (E2/C2) was 74.87 N/mm² and 71.35 N/mm², respectively, which are higher than MW-treated wood (9.23 N/mm²) and control sample (56.79 N/mm²).

The shear strength of MWC-treated (E1/C2) was 3.87 N/mm² which is higher than MW-treated wood (1.39 N/mm²) respectively and control sample (4.09 N/mm²). All the results showed a significant difference, indicating that density affects the strength properties of kelempayan wood for each treatment. Overall, heat treatment using continuous microwave laboratory-scale equipment (MWC) enhanced the strength properties of kelempayan wood, with the best results obtained at an applied energy of 450 kW/h with two-cycle repetitive exposure.

Thus, the amount of microwave energy utilized, calculated by dividing the microwave power by the sample volume flow rate [20] for the microwave laboratory scale, may explain the difference compared to domestic microwave treatment as it applied the same power and time for each sample but differed in sizes, which could account for the variation. A comparison between both microwave treatments demonstrated that the lower wood structural strength was due to uneven heating. However, lab-scale microwave reduces structural damage by applying heat evenly and at a lower power, allowing for precision power adjustment and even heating to protect the wood's microstructure [35]. In furniture manufacturing, heat-treated wood can reduce warping and shrinkage issues that commonly occur in wooden furniture as it exposed to varying humidity levels. In addition, microwave treatment offers rapid, energy-efficient kelempayan wood modification, enhancing strength and hardness. This method extends to structurally demanding products like flooring and cabinetry.



Note: MW Conventional = Domestic microwave heat treatment (MW), MW Lab Scale = Microwave laboratory scale (MWC), E1 = Energy applied (450kW/h), E2 = Energy applied (550kW/h), C1 = Repetitive exposure (1 cycle), C2 = Repetitive exposure (2 cycle), MOE = Modulus of elasticity and MOR = Modulus of rupture

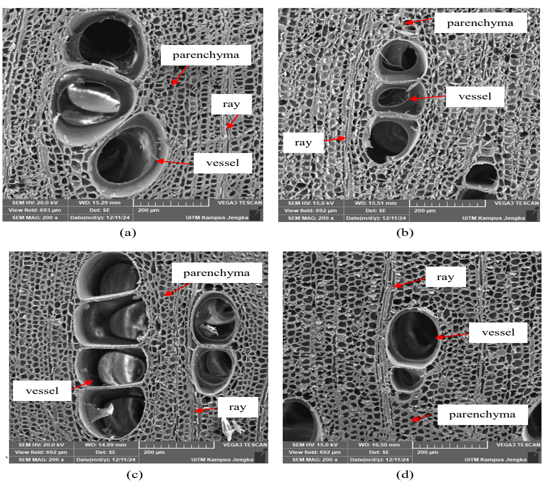
Figure 14: Strength properties of MW-treated and MWC-treated kelempayan wood.

Scanning Electron Microscope (SEM) Analysis

Cross-section on Kelempayan Wood

Figure 15 shows the microstructure of kelempayan wood captured by SEM at 200 times magnification at cross- sections for different heat treatments. The diameter of OD- and MW-treated vessels were slightly smaller than the control sample (AD). Minor damage to ray cells in OD- and MW-treated wood may result in weaker mechanical properties.

Heat treatment reduces the wood's ability to absorb moisture by degrading the cellulose and hemicellulose structures [36]. In MW- and MWC-treated wood, these changes are visible in the cross-section as a smoother and less porous appearance. The microstructure images showed that kelempayan wood consists primarily of vessels arranged in radial multiples of 2 to 4, with vessel shapes ranging from round to oval, without deposit and tyloses, and the rays were heterocellular of multiseriate with 2 to 3 cells. A previous study reported that kelempayan wood is characterized by the radial multiples of the vessel more than 3 to 6 and multiseriate rays as much as 4 cells [37].



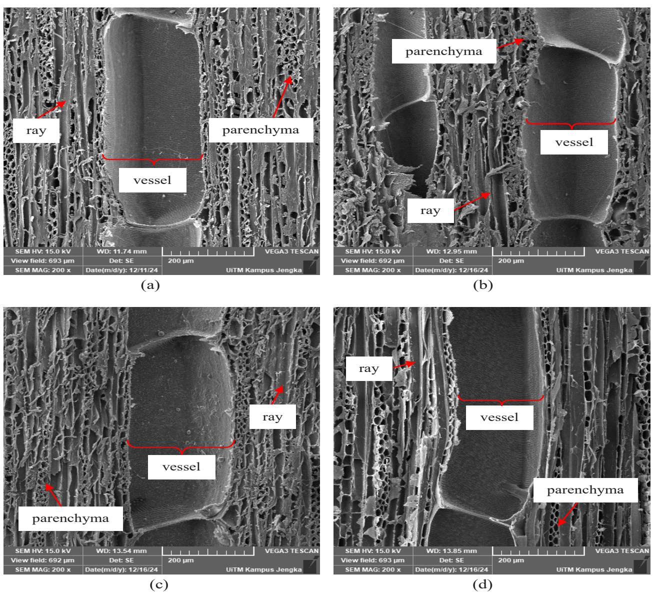
Note: Control (a), Oven heat treatment (b), Domestic microwave heat treatment (c) and Microwave laboratory scale heat treatment (E2C2; E= Energy applied, 550kW/h/ C2= Repetitive exposure, 2 cycle) (d)

Figure 15: The cross- section (200 times magnification) of kelempayan wood for different heat treatments.

Surface of Kelempayan Wood

Figure 16 shows the microstructure images of kelempayan wood captured by SEM of 200 times magnification at tangential surface for different heat treatments. The image clearly showed the presence of slightly larger vessels in the control sample compared to the heat-treated wood. In MW-treated wood, the ray formation was mostly uniseriate, whereas the upper portion of the ray was predominantly multiseriate with three cells. As a result, MW-treated wood contained fewer fibers than other portions, contributing to its lower physical and mechanical properties.

SEM analysis revealed no major anatomical changes across treatments, suggesting that the applied energy may not have been sufficient to significantly modify the wood's microstructure. This result showed that, with the good controlled in heat treating the wood can avoid damaging its microstructure.



Note: Control (a), Oven heat treatment (b), Domestic microwave heat treatment (c) and Microwave laboratory scale heat treatment (E2C2; E= Energy applied, 550kW/h/ C2= Repetitive exposure, 2 cycle) (d)

Figure 16: The tangential surface (200 times magnification) of kelempayan wood at different heat treatments.

CONCLUSION

Following this study, heat treatments influenced the physico-mechanical properties of kelempayan wood. Each treatment has a varied effect on the wood, with some improving its properties while others led it to deteriorate. It was demonstrated that oven heat treatment and domestic microwave improved physical properties by lowering moisture content and reducing shrinkage and swelling. Besides, it showed the potential for controlled heat treatment to improve kelempayan wood for the timber and furniture industries. Both oven and microwave treatments enhanced dimensional stability by physical properties hence eliminating warping and structural faults in furniture, flooring, and cabinets. While some mechanical properties such as MOE and MOR decreased, microwave treatment boosted compression and shear strength, indicating a potential for load-bearing applications. High-density wood demonstrated superior qualities, highlighting the significance of material selection and treatment optimisation. Microwave treatment also provides a cost-effective, energy-efficient alternative to traditional drying, promoting sustainable production and increasing the use of fast-growing timber species. Overall, while heat treatments successfully enhanced certain physico-mechanical characteristics of kelempayan wood, microwave treatment demonstrated a notable advantage in improving mechanical performance and structural integrity. This suggests that microwave treatment could serve as a more effective and less invasive alternative to conventional oven drying methods. The less time needed as well as offer environmentally benefits without the need of chemical treatments, provide a more sustainable alternative for wood processing. This promotes kelempayan wood as an environmentally friendly choice for sustainable furniture manufacture and other industrial applications.

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