

THE EFFECT OF THERMO-VACCUM TREATMENT ON THE PHYSICAL AND MECHANICAL PROPERTIES OF 20 LESSER-KNOWN TIMBER SPECIES FROM SRI LANKA

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Abstract: Wood is a valuable material that is often utilised in indoor and outdoor settings. This study aimed to evaluate the effect of heat treatment on the strength, dimensional stability, and colour of 20 selected timber species, to compare the performance of thermally-modified wood with untreated seasoned wood, and to recommend suitable thermal modification. Modulus of Rupture (MOR), Modulus of Elasticity (MOE), Compression parallel to grain (CPN), and wood density were measured in 20 lesser-known timber species grown in Sri Lanka. In addition, moisture content, volumetric shrinkage, water absorption, weight loss, and colour were evaluated. Timber samples were taken at the breast height of mature trees and prepared according to the BS 373:1957 standard [2]. The mechanical properties were measured through the UTM (UTM 100 PC). Thermal modification was done at 180°C and 250 mbar. A paired t-test was carried out to interpret the significant differences between samples, and regression analysis was done to identify the relationship between density and the strength properties of the control and the thermally-modified samples. Due to thermal treatment, MOR and MOE decreased in the treated samples, showing a reduction in bending strength and stiffness, while CPN increased, but these changes were not statistically significant. A strong positive correlation between MOR and MOE was observed in the control samples. It significantly weakened after heat treatment ($R^2 = 0.24$ to 0.77), the relationship between MOR and density increased after heat treatment. ($R^2 = 0.14$ to 0.37), and the relationship between MOE and density decreased after heat treatment ($R^2 = 0.09$ to 0.02). The relationship between CPN and density increased slightly after heat treatment ($R^2 = 0.04$ to 0.12), the moisture absorption of the treated samples decreased, but not significantly ($p < 0.05$), and the timber colour became darker. Heat treatment gently enhanced the physical and mechanical properties of the selected wood species.

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1. Introduction

Wood is a commonly used natural building material because of its durability, performance and effective heat insulation. The characteristics (physical and mechanical) of different timber species affect the quality of the timber. Techniques for modifying wood are utilised to increase the wood's dimensional stability and durability [12, 14]. Wood modification is an innovative approach for overcoming one or more of the drawbacks related to wood by modifying the material's chemical and physical characteristics to improve its functionality and durability over time.

Heat Treatment (HT) is also known to report on the dimensional stability of wood, but varies from species to species and is different in different directions. The dimensional stability, thus induced, is primarily due to the reduced hygroscopicity and subsequent decreased Equilibrium Moisture Content of heat-treated wood [20]. Thermal modification has shown that by exposing wood to high temperatures between 170 and 220°C without oxygen, it can change the components of wood, that are susceptible to moisture absorption and natural degradation [3, 17]. The traditional use of wood in outdoor settings is limited due to its susceptibility to decay and dimensional instability. Hygroscopicity of timber leads to the growth of microorganisms and causes the rapid decay of timber. The main objective of preserving timber is to increase the lifetime of wood, ensuring long life and enhancing quality.

To optimise benefits and improve procedure, additional investigation is

necessary to determine how the process parameters affect the qualities of thermally modified (TMW) wood. Wood modification is a technique used to enhance the characteristics of wood while developing a material that can be disposed of at the end of a product's economic life minimising risk to the environment, as opposed to when unmodified wood is discarded [6]. Timber modification has become popular as an alternative to timber protection [5]. In comparison to common wood preservation methods involving the impregnation of biochemical compounds, heat-treated wood has comparatively better wood characteristics, such as EMC, increase in dimensional stability, and higher durability [22]. Heat-treated wood is mostly used for outdoor and indoor settings like furniture, windows, doors, wall or gate boarding, bathroom cabinets, flooring, musical instruments, and kitchen furniture [21]. The effects of wood modification on both mechanical and physical characteristics can assist in influencing the usage of modified wood for various uses, as well as in the new wood modification procedures that combine with sustainability and durability [5]. The degree of change is determined by the temperature and duration of the treatment, the environment, the timber species and its qualities, the wood's starting humidity, and the dimensions of the specimens. As a result, heat-treated wood is more resistant to natural degradation. External damage such as cracking and mold growth is found less on heat-treated wood than on painted wood [1].

Thermal modification of wood is widely

acknowledged for its ability to enhance dimensional stability and decay resistance, with "ThermoWood" being a leading commercial method that is a trademark of the Finnish ThermoWood Association, involving thermal treatment with steam to prevent oxidative wood degradation and induce chemical reactions through moisture [16]. The wood's mechanical qualities are correlated with its density. The density of timber is changed during heat modification, and reduced density following heat treatment indicates a reduction in strength characteristics [11].

The main significant effect of wood modification by heat on wood is mass loss, which is sometimes referred to as a quality indicator. The mass loss resulting from thermal modification has been determined to be dependent upon the kind of wood, heating medium, temperature, and duration of processing [10]. Mass loss is affected by density as well as the type of wood. The only noticeable mass losses up to 160°C are due to the vaporisation of bound water absorbed by the wood fibres and volatile extractives. At higher temperatures, thermo-degradations start, and they become noticeable at 230°C. Species with lower densities have greater thermo-degradation stability compared to those with higher densities [19]. One of the primary physical characteristics of wood is colour. The primary reason for the colour variation in thermally modified wood is the thermal breakdown of the primary chemical constituents of wood, including cellulose, hemicellulose, lignin, and extractives. The colour shift seen in thermally-modified wood might vary from a light discoloration to a strong reddish-brown hue [13].

The process of heat treatment typically leads to a noticeable decline in the

mechanical characteristics of the structural elements, primarily caused by material degradation in the cell wall, breakdown of hemicellulose and alteration of extended chain molecules. The strength attributes start to diminish when exposed to temperatures exceeding 150°C. Consequently, the wood tends to become more fragile, resulting in a decrease of 10-30% in both bending and tensile strength [18]. Timber has been utilised for a wide range of purposes in Sri Lanka's history. A few decades ago, Sri Lanka's timber sector was primarily focused on sawmilling, furniture manufacturing, and building applications. However, at present, a lot of wooden products, including pulp, paper, and wood-based board sectors, complex building applications, outdoor applications, and timber seasoning and treating are growing in popularity. Because Sri Lanka's natural forest conservation is regulated, supporting the country's growing demand for timber is becoming extremely risky. The introduction of commercial forest plantations has been successful in addressing demand. However, the amount of timber harvested from plantations is likewise insufficient to satisfy demand. As a result, a lot of timber is imported presently. While the fact that Sri Lanka's timber sector is an important industry, the authorities lack accurate statistical data as a result of the increasing number of prohibited and unreported operations due to unregistered businesses. According to the yearly reports from the forest department, the number of companies registering has increased over the past few years.

The main objective of this study is to compare the properties of thermally modified wood with air-dried wood species. The specific objectives of the

research are to evaluate the effect of heat treatment on the strength properties, dimensional stability, and colour of 20 selected timber species and to compare the performance of thermally modified wood with seasoned wood for each species in order to evaluate suitable thermal modification processes for enhancing the mechanical properties.

2. Materials and Methods

2.1. Study Location

The study was conducted in the Wood Science Laboratory at the State Timber Corporation, Battaramulla, Sri Lanka, and at Furny Craft PVT Ltd, Wattala, from 2024 April to 2024 September.

2.2. Timber Sample Selection

In this experiment, 20 locally available timber species, classified in Table 1, were selected. The species were supplied by the State Timber Corporation, Battaramulla and the Forest Department of Sri Lanka.

2.3. Sample Preparation

Samples were prepared by using a wood cutting machine and selected if they were free from knots, resin pockets, insect attack, wane, spring, splits, cracks, bows, twists, and other timber defects. Four samples were prepared from one species for one test. The samples were air-dried to reduce moisture content (MC) up to 12-15%. All the samples were cut from the heartwood of the mature trees. All the samples were organized according to the standard on BS 373:1957 [2].

The moisture metre (Model No DELMHORST BD-2100) was used to verify the MC of all specimens. This metre can be

used to measure MC from 6 to 40% MC of wood. The two probes should be inserted into the wood sample and instantaneously, it shows the MC. The MC was measured as a direct measurement for the treated and untreated samples. The MC of the initial samples was measured. After the heat treatment process, the MC was measured by the gravimetric method – Eq. (1). Firstly, the initial weight was measured and then all samples were dried in the oven at $103 \pm 2^\circ\text{C}$ for 48 hours up to constant weight. After the final weight was measured, MC was measured for all the samples.

$$MC = \frac{m_1 - m_2}{m_1} \cdot 100 \quad (1)$$

where:

MC is the moisture content [%];

m_1 – the initial weight [g];

m_2 – the final weight [g].

A Universal Test Machine (UTM) is also identified as a material testing machine. (Model: OZ-UMT-100PC. Capacity: 100kN, power: 220-240Hz). It is used to measure the strength properties. Both the three-point bending test and the CPN test can be carried out by using the machine according to British Standard BS 373:1957 [2]. The deflections and the corresponding loads were recorded and the load deflection curves were taken automatically by the computer connected to the UTM machine.

2.4. Modulus of Rupture

The modulus of rupture (MOR) was calculated with Equation (2) – [8].

$$MOR = \frac{3 \cdot F \cdot L}{2 \cdot W \cdot H^2} \quad (2)$$

where:
 MOR is the modulus of rupture [N/mm^2];
 F – the maximum load [N];
 L – the length of the specimen [mm];
 W – the width of the specimen [mm];
 H – the depth or thickness of the specimen [mm].

Selected wood species

Table 1

No.	Common name	Scientific name	Family name	STC Category
1.	Acacia mangium	<i>Acacia mangium</i>	Fabaceae	Class II
2.	Albizia	<i>Albizia falcataria</i>	Fabaceae	Class III lower grade
3.	Araukeriya	<i>Araucaria columnaris</i>	Araucariaceae	Class III lower grade
4.	Batadomba	<i>Syzygium operculatum</i>	Myrtaceae	Class III
5.	Boradamaniya	<i>Grewia helicterifolia</i>	Malvaceae	Class III lower grade
6.	Imbul	<i>Ceiba pentandra</i>	Malvaceae	Class III lower grade
7.	Ipil ipil	<i>Leucaena leucocephala</i>	Fabaceae	Class III lower grade
8.	Kanda	<i>Macaranga peltata</i>	Euphorbiaceae	Class III lower grade
9.	Katakela	<i>Bridelia retusa</i>	Phyllanthaceae	Class I
10.	Kon	<i>Schleichera oleosa</i>	Sapindaceae	Class I
11.	Lunumidella	<i>Melia dubia</i>	Meliaceae	Class II
12.	Mahogany	<i>Swietenia macrophylla</i>	Meliaceae	Luxury class
13.	Mango	<i>Mangifera indica</i>	Anacardiaceae	Class III
14.	Milla	<i>Vitex altissima</i>	Verbenaceae	Luxury class
15.	Neem	<i>Azadirachta indica</i>	Meliaceae	Special class upper
16.	Pine	<i>Pinus caribaea</i>	pinaceae	Class III
17.	Rambutan	<i>Nephelium lappaceum</i>	Sapindaceae	Class III lower grade
18.	Rubber	<i>Hevea brasiliensis</i>	Euphorbiaceae	Class III
19.	Teak	<i>Tectona grandis</i>	Lamiaceae	Super luxury class
20.	Wood apple	<i>Limonia acidissima</i>	Rutaceae	Class III lower grade

Note: These timber species represent all classes in the timber classification chart of the State Timber Corporation (STC), Sri Lanka.

2.5. Modulus of Elasticity

The modulus of elasticity (MOE) was calculated with Equation (3) – [12].

$$MOE = \frac{F \cdot L^3}{4 \cdot \delta \cdot W \cdot H^3} \quad (3)$$

where:

MOE – is the modulus of elasticity [N/mm²];

F – the proportional load [N];

L – the length of the specimen [mm];

δ – the deflection of the specimen [mm];

W – the width of the specimen [mm];

H – the depth or thickness of the specimen [mm].

Bending strength, which is usually called the specimen's strength, is measured by MOR and it gives a measurement of a specimen's strength before the rupture – Eq. (2). The stiffness of timber is indicated by MOE – Eq. (3). It is a very significant parameter to identify the deflection of wood beams.

2.6. Compression Test

The next part of the research was to carry out the CPN test. This test was also conducted by the same UTM. The sample was set to the bottom plungers of the UTM and the CPN was calculated using Equation (4) – [8].

$$CPN = \frac{P}{b \cdot d} \quad (4)$$

where:

CPN is the compressive stress at the limit of proportionality [N/mm²];

b – the width of the sample [mm];

d – the depth of the sample [mm];

P – the load [N].

The weight of the sample was measured with an electric balance [4]. The lowest count of the scale was 0.1 g. Weight loss was calculated by using the Equation (5) and the electric scale was used for measurement.

$$WL = \frac{(W_o - W_t)}{W_t} \cdot 100 \quad (5)$$

where:

WL is the weight loss [%];

W_o – the oven-dry weight of the wood samples before the modification [g];

W_t – the dry weight of the samples after thermal modification [g].

The modified and the control wood samples were waterlogged in distilled water in a stainless steel container. A metallic screen was placed over the samples to keep them nearly 2.5 cm below the surface. Water absorption was assessed after water soaking. From the measurement of the weights of the specimens, water uptake (WU) was measured by Equation (6).

$$WU = \frac{W_2 - W_1}{W_1} \cdot 100 \quad (6)$$

where:

WU is the water uptake [%];

W₂ – the final mass of the timber sample after treatment [g];

W₁ – the mass of the conditioned wood sample before immersion [g].

The longitudinal, radial, and tangential axes were measured and recorded by using a digital Vernier calliper with a minimum measurement of 0.05 mm.

2.7. Dimensional Stability

The dimensional stability of the timber

$$AV = \frac{(L_{max} \cdot b_{max} \cdot g_{max}) - (L_{min} \cdot b_{min} \cdot g_{min})}{(L_{min} \cdot b_{min} \cdot g_{min})} \cdot 100 \quad (7)$$

where:

AV is the dimensional stability of the sample [%];

L – the sample length [mm];

b – the sample width [mm];

g – the thickness of the sample [mm].

av – the whole sample volume [mm³].

2.8. Colour

The colour values were measured by the CIELab system with a spectrophotometer (model SN : 2003059) before and after heat treatment. Three samples were treated at 180°C temperature, colour was measured at three places on each sample, and the average value was automatically calculated. The three coordinates of CIELab show the lightness (L*=0 indicates pure black and L*=100 indicates pure white), its point between red and green (a*negative values indicate green, while positive values indicate red), and its point between yellow and blue (b* negative values indicate blue and positive values indicate yellow). The total colour difference (ΔE^*) was designed according to Equation (8).

$$\Delta E = \sqrt{(\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})} \quad (8)$$

where ΔL^* , Δa^* , and Δb^* represent the changes of lightness (L*) and chromatic

species was evaluated by applying Equation (7).

parameters (a* and b*) between initial and after treatment on the same wood.

2.9. Density

Density in the air-dry phase was determined according to the National Standard of GB/T 1933:2009 [8]. A treated timber sample from each species was calculated (20 × 20 × 60 mm). The dimensions of the samples were measured using a digital calliper and the weight was measured by an electric balance. The density (D) was calculated by Equation (9).

$$D = \frac{m}{v} \quad (9)$$

where:

D is the density [kg/m³];

m – the weight [kg];

v – the volume [m³].

2.10. Equipment for Heat Treatment

The equipment used for the wood thermal modification was a heating chamber (model - THERMO VACCUME SYSTEM TVS ROLL 2.05 E 9 L 6000). The temperature and relative humidity inside the chamber can be controlled up to 160°C and 100%, respectively (Figure 1).



Fig. 1. *Thermal vacuum system and interior view of the thermos-vacuum plant*

The heat treatments were conducted in a Thermo-vacuum system. The wood samples were subjected to heat treatment at 190°C. They were introduced into the machine and then arranged uniformly on the sample holder, with gaps between them. The closed the chamber door was closed to ensure an airtight seal. The thermal cycles (temperature and vacuum pressure) were set on the control panel. The characterised samples were modified at the following standard process conditions: Vacuum drying to final MC < 5% at T° not higher than 100°C, constant pressure = 250 mbar, rate of T° increase from 100°C to the process temperature of 15°C/h. At the end of the treatment time period, the samples were cooled. Thereafter, MC, strength properties, weights, and dimensions were measured to calculate the changes in the wood samples. The weight loss, moisture reduction, and volumetric shrinkage were calculated using the equations above.

2.11. Statistical Analysis

To determine a statistically significant difference among each species of data, a paired t-test with a confidence level of 0.05 was considered. SPSS 25 software, Minitab 17, and Microsoft Excel were also used. Regression analysis was carried out to

identify the relationship between each variable.

3. Results and Discussion

3.1. Comparative Moisture Content

In this study, the initial MC varied among the different wood species, reflecting their natural differences in hygroscopicity and cellular structure. Despite the differences in initial MC, all wood species exhibited a significant reduction in MC after undergoing thermal modification (Figure 2).

According to BS 373:1957 [2], the mean MC for testing should be approximately 12% at normal conditions, and the final MC of the thermally-modified species varied between 1.4- 5%. The drastic reduction in MC can be attributed to the evaporation of free water and bound water within the wood's cellular structure during the high-temperature treatment.

3.2. Mass Loss

Mass loss (ML) is the major indicator of the intensity of thermal modification. The dependence of mass loss from wood species, procedure environment, temperature, and heat impact duration in wood [15]. Thermal modification exhibited

a reduction in mass due to thermal degradation.

The results show a clear trend of mass loss (ML) in the thermally-modified samples. Between the samples, the lowest

ML (4.55%) was identified in the Albizia wood and the highest ML (76.14%) was observed in the Imbul wood. The average mass loss of each species is shown in Figure 3.

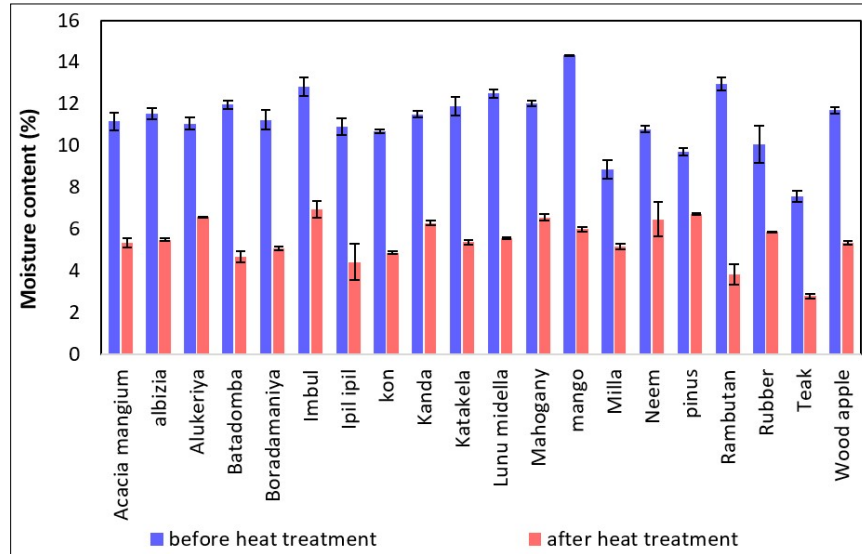


Fig. 2. Comparative moisture content of the selected timber species before and after treatments

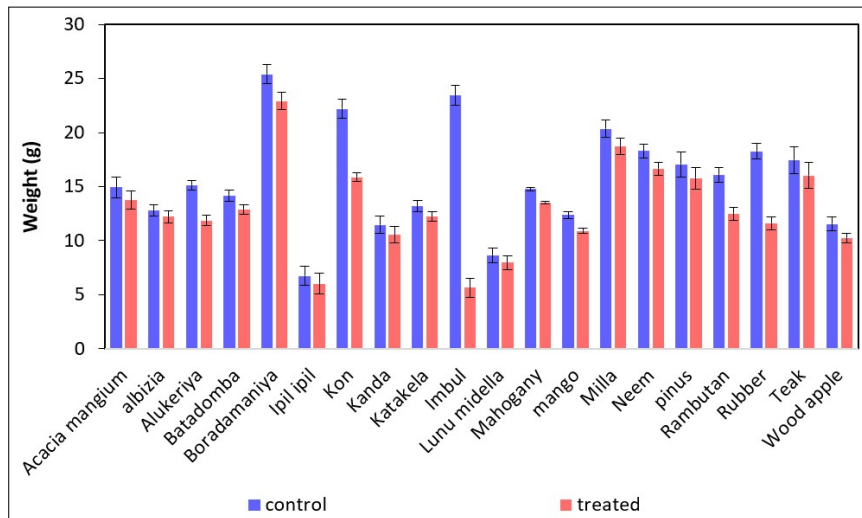


Fig. 3. Comparative weight changes in the control and treated samples of the selected timber species before and after treatment

3.3. Colour

The results of the colour comparison are shown in Table 2. The treated wood was darker than the untreated wood species, as shown by the lower ΔL^* value. The value of difference was large enough to be known visually since colour changes where $\Delta E^* >$

3 are visible to the naked human eye [15]. The highest total colour difference (ΔE^*) was observed in Acacia mangium, Ipilpil, Milla, and Wood apple. In the heat-treated wood, the darkest colour (L^*) was detected in the Rumbutan wood. The L^* component varied from 38.25 to 20.91 for all species.

Colour change values of the control and treated timber

Table 2

Species	ΔL^*	Δa^*	Δb^*	Δc^*	ΔE^*
Acacia mangium	-29.42	3.83	-5.76	-2.57	30.22
albizia	-10.44	2.43	2.86	3.74	11.09
Arawkeriya	-19.02	3.03	-4.23	-2.12	19.72
Batadomba	-9.98	2.96	1.34	2.67	10.50
Boradamaniya	-10.25	1.81	-8.04	-3.21	13.15
Imbul	-10.58	5.39	1.12	3.67	11.93
Ipil	-20.01	2.57	-9.33	-6.09	22.22
Kanda	-7.76	1.64	2.67	3.13	8.36
Katakela	-17.15	0.98	-6.40	-4.67	18.34
kon	-2.56	2.24	0.05	1.60	3.41
Lunu midella	-15.08	1.49	-2.83	-1.22	15.42
Mahogany	-8.47	-1.85	-4.64	-4.76	9.83
mango	-11.94	4.56	-2.10	0.79	12.95
Milla	-21.33	3.54	-6.08	-2.72	22.46
Neem	-5.94	3.06	0.43	1.92	6.69
pine	-5.94	-0.12	-2.83	-2.49	6.58
Rambutan	-3.09	-3.22	2.17	-0.02	4.96
Rubber	-7.62	2.93	-1.94	0.07	8.39
Teak	6.57	-1.48	4.44	1.90	8.06
Wood apple	-18.78	4.76	-9.59	-1.78	21.61

Note: Lightness (L^*) from 0% (black) to 100% (white), a^* from green (-a) to red (+a), and b^* from blue (-b) to yellow (+b).

3.4. Density

Wood density is decreased overall after thermal modification. The density change was mainly due to the mass change caused by component degradation [9]. Density has a close relationship to the mechanical

properties of timber and can be used as a parameter to predict some of them (e.g., MOR and MOE) [7].

Density decreased during the thermal modification process (Figure 4). The highest density reduction was seen in Imbul, Rubber and Kon.

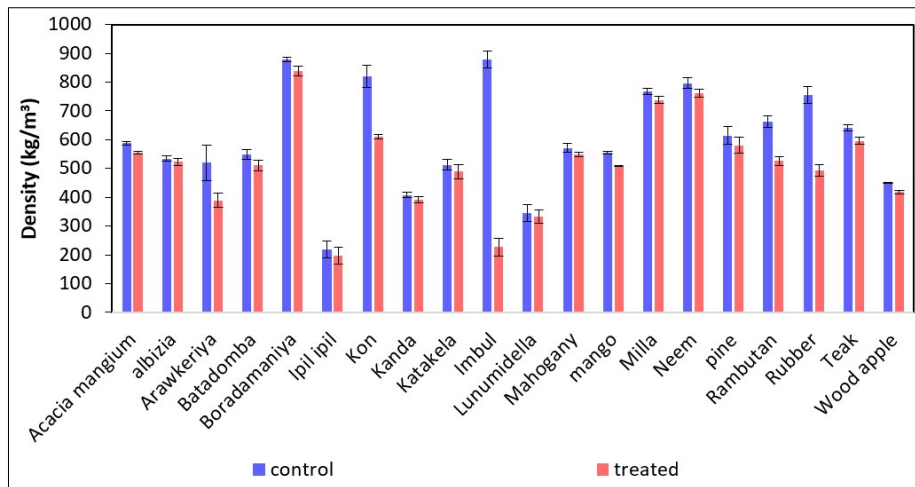


Fig. 4. Density values of the control and treated samples

3.5. Volumetric Shrinkage

Volumetric shrinkage is a key indicator of dimensional stability. During heat treatment, wood is exposed to high temperatures, typically 180°C, in an oxygen-controlled environment. In this study, several wood species were subjected to thermal modification, and their volume changes were measured and analysed.

The results indicated that the extent of volume shrinkage varied significantly among species, suggesting that different species respond uniquely to thermal treatment due to their intrinsic anatomical and chemical properties. Figure 5 demonstrates that the volumetric

shrinkage reductions are significantly reduced with treatment, varying between 1.22-7.1%. The highest volume reduction was identified in Imbul and the lowest volume reduction was noted in Teak.

3.6. Water Uptake

The thermal modification of wood resulted in a significant decline in water uptake (Figure 6). The accessibility of the free hydroxyl groups (OH-) of the timber carbohydrates plays a significant role in the process of water adsorption and desorption.

There was no significant difference between species due to heat treatment $p > 0.05$ (confidence interval 95%). The

paired t-test showed that there were no significant differences between the control and the modified wood for several species. However, Batadomba, Katakela, Mango,

and Wood apple indicated that thermal modification can significantly reduce the water uptake of wood ($p < 0.05$), but did not present a noticeable declining trend.

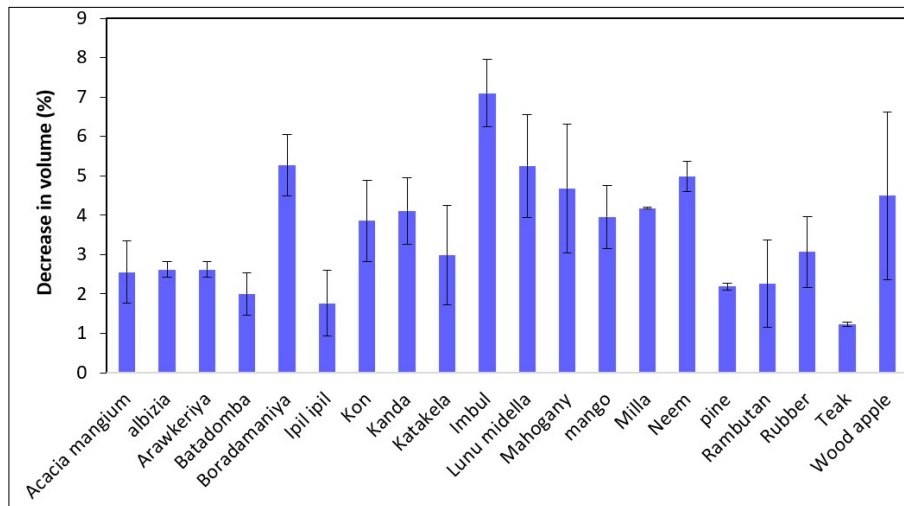


Fig. 5. *Decrease in volume percentage for the timber species*

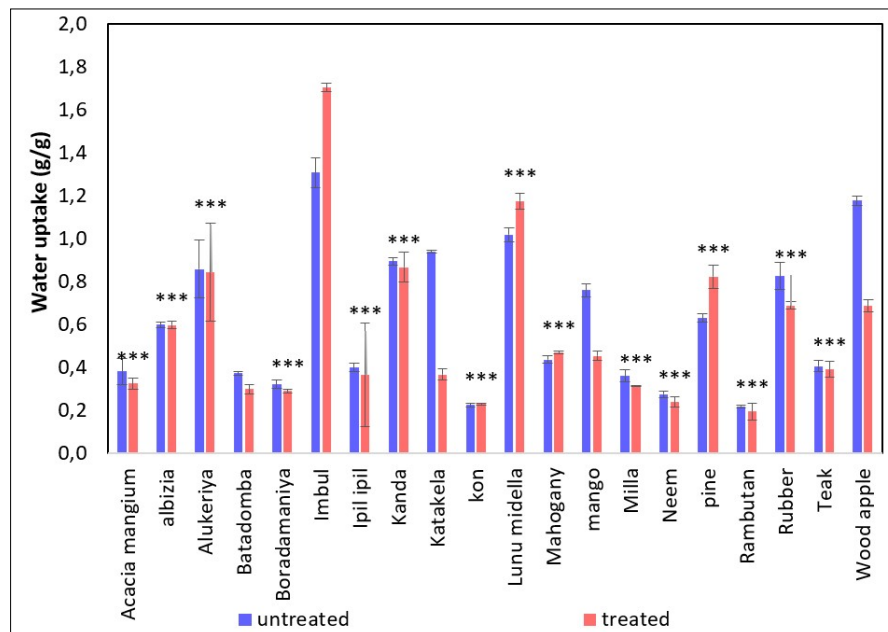


Fig. 6. *Water uptake for the control and treated timber species*

3.7. Mechanical Properties

To determine the heating effect on the mechanical properties of timber, the testing of impact bending strength and hardness was performed. The decrease in wood strength properties is related to the degree of thermal fragmentation. The measured mechanical characteristics of the untreated and treated wood are presented in Table 3.

The effect of the heat treatment on MOR was proven to decrease for *Acacia mangium*, *Arawkeriya*, *Batadomba*, *Boradamaniya*, *Ipil ipil*, *Kon*, *Katakela*, *Imbul*, *Mango*, *Neem*, *Pine*, *Rambutan*, *Teak* and *Wood apple*. However, among them, a few species show a statistically significant reduction for *Pine*, *Rambutan* and *Wood apple* ($\alpha=0.05$). MOR displayed an increase for *Albizia*, *Kanda*, *Lunumidella*, *Mahogany*, and *Milla*.

Modulus of rupture, modulus of elasticity, and compression parallel to grain of the control and treated timber samples Table 3

Species	Modulus of rupture [N/mm ²]			Modulus of elasticity [N/mm ²]			Compression parallel to grain [N/mm ²]		
	Control	Treated	P	Control	Treated	P	Control	Treated	P
<i>Acacia mangium</i>	84.89	57.42	0.08	9,347.38	10,294.33	0.63	39.38	51.57	0.07
<i>albizia</i>	26.65	32.94	0.37	3,171.85	6,442.47	0.01	18.57	27.86	0.06
<i>Arawkeriya</i>	51.85	44.03	0.09	3,171.85	8,550.65	0.01	25.02	31.44	0.05
<i>Batadomba</i>	42.26	36.56	0.62	5,712.04	8,308.05	0.03	45.51	22.04	0.17
<i>Boradamaniya</i>	121.31	115.34	0.74	14,567.56	13,835.82	0.83	48.76	68.80	0.00
<i>Imbul</i>	29.59	17.13	0.19	2,889.13	10,941.82	0.00	31.87	43.56	0.16
<i>Ipil ipil</i>	76.49	72.83	0.84	8,226.24	14,830.37	0.11	40.69	52.01	0.12
<i>Kanda</i>	24.70	33.76	0.09	5,305.46	6,335.82	0.02	17.34	23.03	0.02
<i>Katakela</i>	48.74	43.28	0.33	8726.23	7961.42	0.61	23.12	24.61	0.67
<i>Kon</i>	123.42	81.18	0.12	14612.67	2318.75	0.00	8.88	8.87	0.99
<i>Lunu midella</i>	29.43	36.08	0.49	7956.51	6312.95	0.56	17.04	20.85	0.37
<i>Mahogany</i>	66.12	92.65	0.14	8742.66	10982.35	0.03	37.58	42.84	0.43
<i>Mango</i>	45.57	43.99	0.66	5327.39	6669.30	0.10	19.82	23.63	0.23
<i>Milla</i>	66.48	103.96	0.01	11018.68	14312.92	0.09	51.40	64.87	0.17
<i>Neem</i>	69.38	47.22	0.34	9651.33	8615.41	0.48	32.31	42.79	0.01
<i>Pine</i>	119.73	51.57	0.00	13525.93	8414.17	0.00	28.30	31.63	0.09
<i>Rambutan</i>	97.19	56.87	0.02	6264.36	8994.76	0.11	32.76	35.75	0.61
<i>Rubber</i>	49.45	56.99	0.40	9915.53	7978.33	0.07	18.92	24.75	0.33
<i>Teak</i>	86.65	84.87	0.50	8606.92	9472.72	0.37	52.18	41.72	0.33
<i>Wood apple</i>	91.50	37.96	0.00	12200.00	6336.25	0.00	20.90	31.36	0.00

Note: The p-value is derived from a paired t-test, used to determine if there is a statistically significant difference between the paired data set. A p-value less than 0.05 is considered and there is significant difference between species due to heat treatment.

Some species showed increases and decreases of MOE, depending on the type of wood. The effect of thermal modification on MOE was proven to decrease for Boradamaniya, Katakela, Lunumidella, Neem, Pine, Rubber and Wood apple. However, among them, a few species showed a statistically significant reduction for Imbul and Pine ($\alpha=0.05$). MOE displayed an increase for Acacia mangium, Albizia, Arawkeriya, Batadomba, Ipil ipil, Kanda, Mahogany, Mango, Milla, Rambutan and Teak. Also, Acacia mangium, Mango, Milla, Rambutan, and Teak showed no statistically significant effects.

Most of the wood species showed increases of the CPN. Some of them were not statistically significant increases ($\alpha=0.05$). The effect of thermal modification on CPN was proven to decrease for Batadomba and Teak. However, all species show statistically insignificant results ($\alpha=0.05$). CPN displayed an increase for Acacia mangium, Albizia, Arawkeriya, Boradamaniya, Ipil ipil, Kon, Kanda, Katakela, Lunumidella, Mahogany, Mango, Milla, Neem, Pine, Rambutan, Rubber and Wood apple. Also, Arawkeriya, Boradamaniya, Kanda, Neem, and Wood apple showed statistically significant effects.

3.8. Relationship between Wood Density and Key Mechanical Properties

The Pearson correlation test was done among densities with other variables (MOR, MOE, and CPN) shown in the results. To find out the relationship between densities and mechanical properties, a linear regression test was done.

The results of the Pearson correlation

analysis show a correlation coefficient value for the control samples (r) 0.377 with a p-value of 0.10 and for the treated samples (r) 0.612 with a p-value of 0.004 ($\alpha=0.05$). Accordingly, this indicates that there is a positive linear relationship between the density and MOR of the control and treated samples but that the correlation is not statistically significant. In the regression analysis, before heat treatment, the R^2 value was 0.14, indicating a weak relationship, while after heat treatment, the R^2 value increased to 0.37, suggesting a strong association compared with the R^2 value of the controls (Figure 7).

The results of the Pearson correlation analysis show a correlation coefficient value for the control samples (r) 0.299 with a p-value of 0.201 and for the treated samples (r) 0.125 with a p-value of 0.599 ($\alpha=0.05$). Accordingly, this indicates that there is a positive linear relationship between the density and MOE of the control and treated samples but that the correlation is not statistically significant. In the regression analysis, the control samples displayed a weak relationship with an R^2 of 0.08. After heat treatment, this relationship further weakened with the R^2 value dropping to 0.02 (Figure 8).

The results of the Pearson correlation analysis showed a correlation coefficient value for the control samples (r) of 0.227 with a p-value of 0.335 and for the treated samples (r) of 0.367 with a p-value of 0.111 ($\alpha=0.05$). Accordingly, this indicates that there is a positive linear relationship between the density and CPN of the control and treated samples, but that the correlation is not statistically significant. In the regression analysis, control samples displayed a weak relationship with an R^2 of

0.04. After heat treatment, this value of 0.12 (Figure 9). relationship slightly improved with an R^2

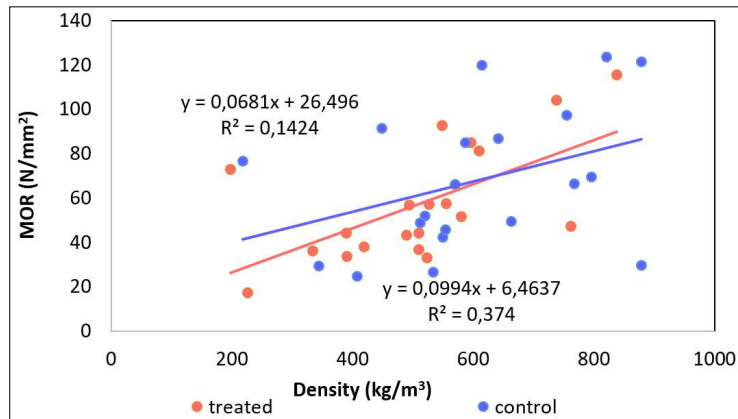


Fig. 7. *The relationship between wood density (kg/m³) versus MOR (N/mm²)*

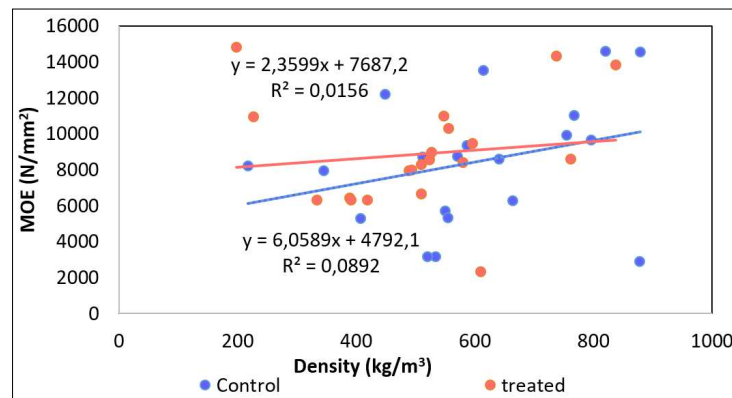


Fig. 8. *The relationship between wood density (kg/m³) versus MOE (N/mm²)*

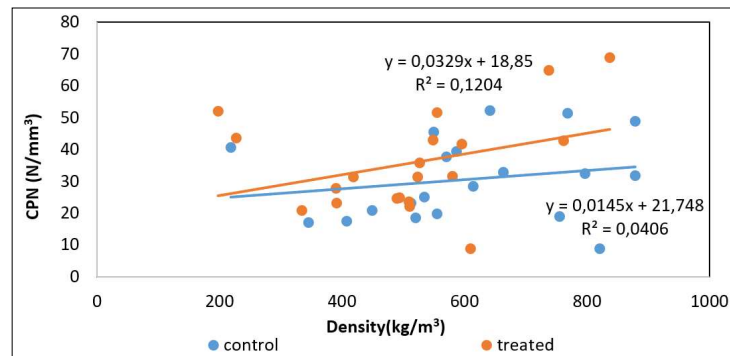


Fig. 9. *The relationship between wood density (kg/m³) versus CNP (N/mm²)*

3.9. Relationship Between Stiffness and Bending Strength

The results of the Pearson correlation analysis show a correlation coefficient value for the control samples (r) 0.882 with a p -value of 0.00 and for the treated samples (r) 0.493 with a p -value of 0.02 ($\alpha=0.05$). Accordingly, this indicates that there is a positive linear relationship

between the MOR and the MOE of the control samples and treated samples and that the correlation is statistically significant. In the regression analysis, control samples displayed a strong relationship with an R^2 value of 0.78. However, after heat treatment, this relationship weakened significantly with the R^2 value dropping to 0.24 (Figure 10).

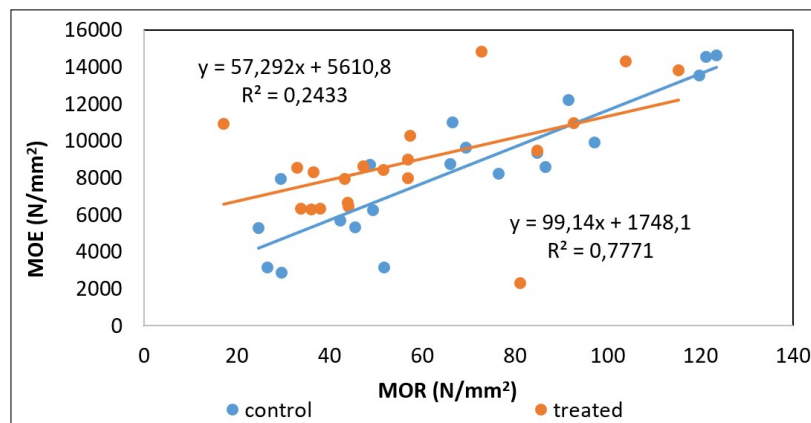


Fig. 10. Correlation between the bending strength and MOE

4. Conclusion

The results demonstrate that heat treatment had a notable impact on the physical and mechanical properties of the studied timber species. Following thermal modification, all species showed reductions in moisture content, volume, density, and weight, indicating improved dimensional stability. Moisture absorption was also reduced in the treated samples compared to the controls, although the decrease was not statistically significant ($p < 0.05$). In addition, all species exhibited a consistent reduction in volume and a visible darkening of colour after treatment, confirming the effect of heat on both

structural and aesthetic properties. The mechanical performance, however, varied among species and treatment conditions. While the modulus of rupture (MOR) and the modulus of elasticity (MOE) were affected by heat treatment, the extent of change differed depending on the timber type, highlighting species-specific responses. The strong positive correlation between the MOR and the MOE observed in the control samples weakened after treatment, suggesting that thermal modification alters the interdependence of strength and stiffness properties. Conversely, the relationship between MOR and density increased, while that between MOE and density decreased. A slight

increase was also observed in the relationship between compression parallel to grain (CPN) and density after treatment. Overall, the findings indicate that heat treatment can enhance dimensional stability and reduce hygroscopicity of timber, but may also modify mechanical performance depending on the species. Among the studied species, those that retained comparatively higher strength and stiffness after treatment can be recommended for structural or load-bearing applications, while others with improved stability and reduced moisture sensitivity may be more suitable for non-structural or exterior uses. Therefore, careful selection of species and treatment conditions is essential to optimise performance for intended applications.

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