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Thermal modification of fast-growing *Firmiana simplex* wood using tin alloy: Evaluation of physical and mechanical properties

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Abstract:
Wood is an important structural material, but some undesirable properties limit its application in construction. This study investigated the effect of tin alloy thermal modification (TTM) on selected physical and mechanical properties of *Firmiana simplex* (Chinese bottletree) wood. Tin alloy thermal modification of *F. simplex* was performed in a tin alloy bath at two different temperatures (150 °C and 210 °C for 2 h and 8 h). Physical properties such as swelling, water absorption and density and mechanical properties like modulus of elasticity, modulus of rupture, impact bending, compression strength and Brinell hardness of tin alloy thermal modified and control samples were evaluated. The results showed that tin alloy thermal modification decreased the swelling of the wood to 4,85 %, 1,45 % and 6,99 % along the tangential, radial and volumetric coefficient and water absorption and density decreased to 53,10 % and 290 kg/m^3 respectively compared to the control. Modulus of elasticity, modulus of rupture, impact bending, compression strength and Brinell hardness of tin alloy thermal modified *F. simplex* at 210 °C for 8 h decreased to 6366,1 MPa, 54,9 MPa, 2,7 MPa, 29,4 MPa and 1113,5 MPa respectively compared to the control. In conclusion, the tin alloy thermal modified wood at 210 °C significantly affected the physical and mechanical properties of the wood.

Keywords: Density, *Firmiana simplex*, mechanical properties, swelling, tin alloy thermal modification, water absorption.

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Introduction

Chinese bottletree (*Firmiana simplex* (L.) W. Wight) wood is a small to medium-sized, fast-growing, deciduous tree, that has been grown as an ornamental or street tree and is native to some Southeast Asian countries. In the past, *F. simplex* trees were used as fuel wood, but presently, its favourable colour makes it a good substitute for many wood species. *F. simplex* is now one of the major sources of timber used to manufacture furniture for export. Still, due to its dimensional instability and moderately low density, its application in wood product industries is limited.

Wood modification with thermal treatment is one of the preferred ways to improve wood properties (i.e., dimensional stability, biological resistance, reduced shrinkage and swelling) (Santos 2000). It is gaining more recognition due to its eco-friendly approach to wood modification (i.e., non-toxic, as no chemical is involved). Thermal modification of wood is performed by exposing wood to higher temperatures (between 160 ^{o}C to 240 ^{o}C) without oxygen (Esteves 2009, Okon *et al*. 2018a, Yildiz *et al*. 2006). As a result, the physical and mechanical properties of wood are transformed, the wood becomes dimensionally stable, resistant to decay and more hydrophobic following thermal modification and the wood density and some of the mechanical properties are affected (Esteves 2009).

The degree of modification of the physical and mechanical properties depends on the temperature and time of thermal treatment (Corleto *et al*. 2020, González-Peña *et al*. 2009), higher temperature and longer treatment time result in a substantial modification in the wood properties. Heat treatment schedules also depend on the wood species and end-uses of the wood products (Bal and Bektaş 2013).

Several thermal modification processes can be identified by their used process parameters (temperature and time) and the heat-transferring medium (steam, water, nitrogen or oil) such as the Thermowood process in Finland, the Bios Perdure and Rectification process in France, the Oil Heat Treatment (OHT) process in Germany, the Plato process in the Netherlands and the Westwood process in the United States of America. The main difference between these thermal modification processes is the media used to treat the wood (Esteves 2009). Following this development, various heating media such as vegetable oils, linseed and coconut oils, silicone oil, and rapeseed oil, have been used in previous research works for fast and uniform heat transfer in wood and prevention of the oxidation of the wood (Lee *et al*. 2018, Tjeerdsma and Militz 2005, Tang *et al*. 2019, He *et al*. 2019, Mahmoud Kia *et al*. 2020, He *et al*. 2020).

Tin alloy is used in this study as the heating medium to treat *F. simplex* wood because it is an effective heat transfer medium, isolates oxygen from the treated wood, is thermally stable and an effective heat conductor, and is a potential carrier of the substances contained in the preservative mixture as well as shorten the processing time. Additionally, tin alloy is composed of bismuth (0,69 %) and tin (0,26 %) (Okon *et al*. 2018b) and it is a low energy-consuming medium, a more energy-efficient, cost-effective green method for thermal modification of wood.

It was reported in previous studies that tin alloy presents much higher thermal conductivities than most other heating media by excluding oxygen from the treated wood which minimises the thermal degradation of wood constituents (Okon *et al*. 2018a, Okon *et al*. 2018b). Tin alloy is a low melting point alloy (Okon 2018b) with a possible phase change in thermal storage materials and heat transfer agents due to its high thermal storage densities, excellent thermal stability and high boiling points. It is a non-flammable, non-toxic, tasteless and odourless material and a widely available material, making it an ideal heating medium for thermal modification of wood. Furthermore, there is an increasing environmental awareness and legislature that encourages the use of eco-friendly wood modification methods, tin alloy thermal modification can be a substitute for environmentally friendly wood modification methods since no toxic chemical is applied. Limited information is available on the use of tin alloy as a heating medium for the thermal modification of wood, this lack of adequate information limits its development and application.

The objective of this research was to investigate the effect of tin alloy thermal modification (TTM) on selected physical and mechanical properties, i.e., swelling, water absorption, density, modulus of elasticity, modulus of rupture, impact bending, compression strength and Brinell hardness of *F. simplex* wood.

Materials and methods

Chinese bottletree (*Firmiana simplex* (L.) W. Wight) wood was obtained from Fuzhou, Fujian Province, People's Republic of China. Tin alloy was purchased from Beijing, People's Republic of China and was used as received. The wood was cut into logs, that were sawn to 400 mm radial planks, further conversion was done to produce test samples with dimensions 20 mm (radial) x 20 mm (tangential) x 300 mm (longitudinal) for physical and mechanical properties tests. The wood samples were conditioned at 65 % ± 2 % relative humidity and 20 °C ± 2 °C temperature to obtain 12 % moisture content.

Tin alloy thermal modification (TTM)

The wood samples were placed in a tin alloy thermal modification bath. The thermal modification was carried out in three steps: the temperature increased to reach 150 ºC, 180 ºC and 210 °C, the desired temperature was maintained for 4 h and 8 h for each temperature and at the end, the temperature was allowed to decrease gradually to 40 °C before the wood samples removed. The unmodified samples were used as control samples. The schematic flow of the tin alloy thermal modification experiment is shown in Figure 1.

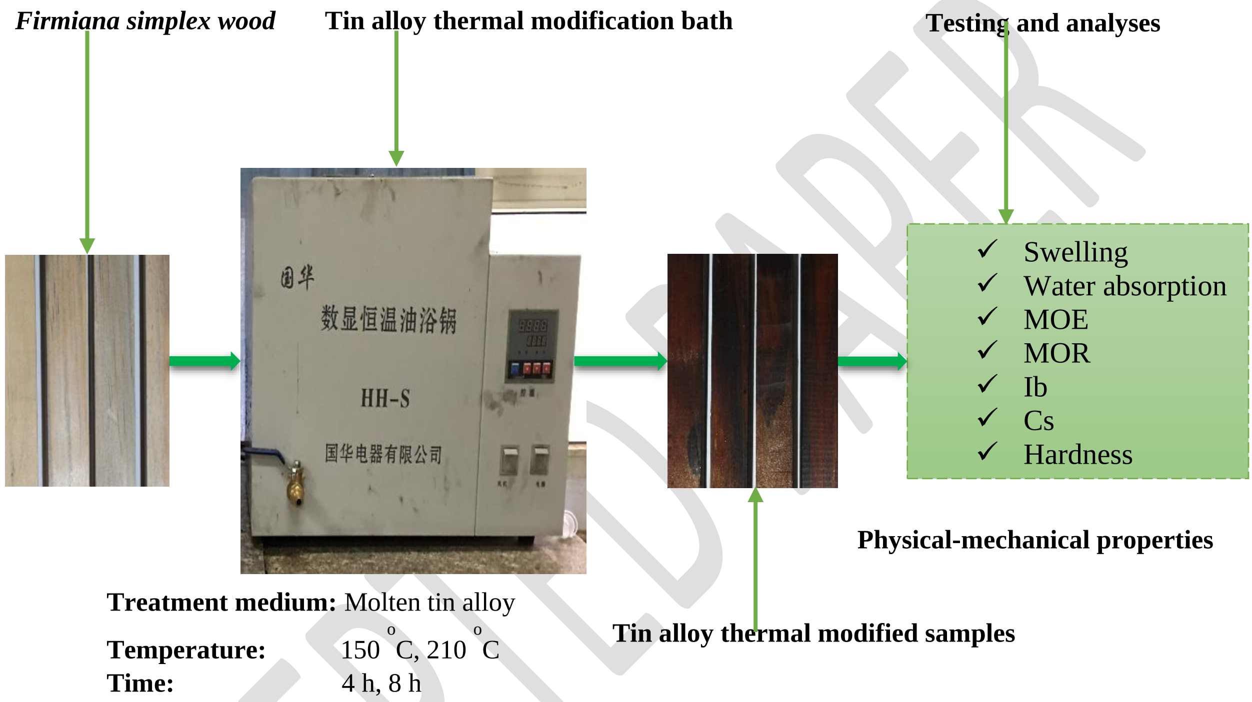

Figure 1: Schematic diagram of tin alloy thermal modification experiment.

Physical properties test-swelling, water absorption and density

For these tests, 15 replicates with dimensions of 20 mm x 20 mm x 60 mm from TTM and the control (i.e., unmodified) were conditioned at 65 % relative humidity and 20 °C temperature to attain a constant weight.

The test samples were dried in an oven at a temperature of 103 °C. The dimensions and weights of the oven-dried samples were measured using a digital calliper with an accuracy of 0,01m and a digital balance with an accuracy of 0,01 g, then the wood samples were soaked in a water bath filled with distilled water for 24 h. The saturated samples were removed and the dimensions and weights were measured again. The swelling test was conducted according to ASTM D1037-06a 2006 standard. The tangential and radial swelling coefficients were calculated using Equation 1.

$$S_w = \frac{S_2 - S_1}{S_1} \times 100\ \% \qquad (1)$$

Where S_w is the radial and tangential swelling coefficient (%), S_1 is the oven-dried dimension before soaking in distilled water (mm), and S_2 is saturated dimension after soaking in distilled water (mm). The volumetric swelling coefficient, water absorption and density were calculated using Equation 2, Equation 3 and Equation 4.

$$V_s = \frac{V_2 - V_1}{V_1} \times 100\ \% \qquad (2)$$

Where V_s is the volumetric swelling coefficient (%), V_1 is the oven-dried volume before soaking in distilled water (mm^3), V_2 is the saturated volume after soaking in distilled water (mm^3).

$$Wa = \frac{M_2 - M_1}{M_1} \times 100 \qquad (3)$$

Where W_a is the water absorption (%), M_1 is the oven-dried weight before soaking in distilled water (g), M_2 is the saturated weight after soaking in distilled water (g).

$$D_o = \frac{M}{V} \quad (4)$$

Where D_o is density (kg/m^3), M is the oven-dried weight of the samples (kg), V is the volume (length, width, thickness) of the samples (m^3).

Mechanical properties test - modulus of elasticity (MOE), modulus of rupture (MOR), impact bending (I_b), compression strength (C_s) and Brinell hardness (B_h), 15 replicates were used for each test.

A three-point bending test was carried out to determine the effect of TTM on the MOE and MOR of *F. simplex* wood. The bending test was performed on samples with dimensions 20 mm x 20 mm x 300 mm according to EN 310 (1993) using a universal testing machine (FPZ 100- TIRA, Germany). Continuous load was applied on the centre of the sample span through the movable head of the machine moving at a speed of 4 mm/min. MOE, MOR, I_b, C_s and B_h were calculated using Equation 5, Equation 6, Equation 7, Equation 8 and Equation 9.

$$MOE = \frac{pl^3}{4dbh^3} \quad (5)$$

MOE is Modulus of elasticity (MPa), p is the load at the limit of proportionality, l is span length (mm), d is deflection at the limit of proportionality (mm), b is the width of the sample (mm), h is the thickness of the samples (mm).

$$MOR = \frac{3 p_{max} l}{2bh^2} \quad (6)$$

Where MOR is the Modulus of elasticity (MPa), p is the maximum load, l is span length (mm), b is the width of the sample (mm), h is the thickness of the samples (mm). The dimensions of the I_b test samples were 20 mm x 20 mm x 300 mm and were determined according to EN ISO 179-1 (2010).

$$I_b = \frac{A_e}{b \times h} \quad (7)$$

Where I_b is the impact bending (kJ/m^2), A_e is the absorbing energy (kJ), b is the width of the sample (m), and h is the thickness (m). The dimension of the C_s test samples was 20 mm x 20 mm x 60 mm and was calculated according to ISO 13061-17 (2017).

$$C_s = \frac{P_{max}}{b \times h} \quad (8)$$

C_s is compression strength (MPa), P_{max} is the maximum load applied to the samples, b is the width of the samples (mm), h is the thickness of the samples (mm).

The dimensions of B_h samples were 50 mm x 50 mm x 70 mm. The test was performed according to EN 1534 (2003) standard with an indentation force of 500 N. The force was applied using an indenter with a diameter of 10 mm. Two indentations were performed on the radial and tangential directions of the samples. The force was applied in three steps. It gradually increased during the first 15 s. After this period, the force was maintained for 30 s and finally, the applied force was decreased to 45 s. The load was removed after 20 s, and the diameter of the indentation left on the surface by the indenter penetration was measured.

$$B_h = \frac{F}{\pi \times D \times h_{max}} \quad (9)$$

B_h is the Brinell hardness (MPa), F is the applied load, D is the diameter of the indenter, h_{max} is the maximum depth of the indentation after unloading.

Statistical analysis

Data of swelling, water absorption, density, MOR, MOE, I_b, C_s and B_h, were analysed using the R statistics version 3,4,1 (R Core Team 2013) and were presented as mean and standard deviation. Means were tested for significant differences using one-way analysis of variance (ANOVA), followed by a Tukey post hoc test, at $p < 0{,}05$ significance level.

Results and discussion

Physical properties - swelling, water absorption and density

Table 1 shows the results of TTM on the swelling of *F. simplex* wood. Swelling significantly reduced in the tangential and radial directions and volumetric coefficient (Table 2). The mean tangential swelling for the control samples was 11,28 %, while the mean tangential swelling of TTM samples at 150 ^{o}C for 4 h was 8,42 % which means it decreased by 25,35 % and the mean tangential swelling of TTM samples at 210 ^{o}C for 8 h was 4,85 % which was a decrease of 57 %. The mean radial swelling of the control was 5,36 %, while, the mean radial swelling of TTM samples at 150 ^{o}C for 4 h was 4,59 % which was a decrease of 14,84 % and the mean radial swelling of TTM samples at 210 ^{o}C for 8 h was 1,45 %, which was a decrease of 73,09 %. The mean volumetric swelling of the control was 21,09 %, the mean volumetric swelling of TTM samples at 150 ^{o}C for 4 h was 14,50 %, (31,24 % decrease) and the mean volumetric swelling of TTM samples at 210 ^{o}C for 8 h was 6,99 % (66,85 % decrease). Based on these results, it was apparent that TTM remarkedly improved the dimensional stability of *F. simplex* wood. Previous studies reported that depending on the wood species several properties of wood are altered by thermal treatment (Militz and Altgen 2014), this is evidence that TTM is an effective thermal modification method. Some wood components, such as hemicellulose, which contains moisture-absorbing groups (free hydroxyl), are reduced at higher modification temperatures (Esteves 2009, Militz and Altgen 2014). However, Rautkari *et al*. (2013) suggested that there may be an additional phenomenon other than the amount of available free hydroxyl groups that reduce the swelling of thermally modified wood.

Table 1: Swelling of tin alloy thermal modified Chinese bottletree (*Firmiana simplex* (L.) W. Wight) wood.

Treatment temperature (°C)	Time (h)	Swelling (%)		
		Tangential	Radial	Volumetric
Control		a11,28 (7,56)	a5,39 (2,15)	a21,09 (2,39)
TTM150	4	b8,42 (1,96)	a4,59 (1,76)	b14,50 (3,00)
	8	b7,82 (2,62)	a4,37 (1,35)	b13,56 (3,27)
TTM210	4	c4,86 (2,58)	b2,48 (1,11)	c8,13 (2,84)
	8	c4,85 (1,21)	b1,45 (0,33)	c6,99 (1,37)

The values outside the ( ) represent the mean and in ( ) is the standard deviation. Means within a column, followed by the same letter are not significantly different by Tukey tests *at* $p < 0,05$.

Table 2: ANOVA of swelling of tin alloy thermal modified Chinese bottletree (*Firmiana simplex* (L.) W. Wight) wood.

Variables	Factor	df	Sum of square	Mean square	F-value	P-significant level
Tangential	Treatment	4	436,1	109,02	25,85	0,0000
	Error	70	295,2	4,22		
Radial	Treatment	4	159,0	39,75	18,23	0,0000
	Error	70	152,6	2,18		
Volumetric	Treatment	4	1915,5	478,9	68,33	0,0000
	Error	70	490,6	7,0		

Significant, $P < 0,05$ (Tukey's test).

Table 3 shows the results of water absorption and density of the control samples and TTM Chinese bottletree *F. simplex* wood. The ANOVA shows that water absorption and density of TTM *F. simplex* wood were significant (Table 4). The mean water absorption for the control samples was 150,24 %, the mean water absorption of TTM samples at 150 °C for 4 h was 136,77 % and the mean water absorption of TTM samples at 210 °C for 8 h was 53,10 % which shows a decrease of 8,96 % and 64,65 % respectively. Tin alloy is water repellent material and was impregnated into the wood which reduced the water absorption ability of *F. simplex* wood, thus, TTM increased the wood stability. On the other hand, reduced accessible hydroxyl (OH) groups and possible lignin cross-linking reactions (Hill 2007, Rautkari *et al.* 2014) containing many water-absorbing hydroxyl groups are reduced when the temperature increases and are attributed to the decrease in water absorption and improving dimensional stability of TTM wood. According to studies by Korošec *et al*. (2009) and Bächle *et al*. (2010), the increase in cellulose crystallite width and degree of crystallinity in thermally modified wood may be the cause of the improvement in dimensional stability. TTM wood can be used in many applications, including windows, claddings, playground equipment, bathrooms, parquet flooring, decking etc. The mean density for the control samples was 390 kg/m^3 while the mean density of TTM samples at 150 ^oC for 4 h and 210 ^oC for 8 h were 360 kg/m^3 (7,69 % decrease) and 290 kg/m^3 (25,64 % decrease) respectively. There was a remarkable decrease in the density of TTM *F. simplex* wood after treatment compared to the control. The decrease in the wood density was attributed to changes in the chemical composition of the wood as a result of the degradation of extractives and cell wall compounds (Rautkari *et al*. 2014) during TTM, thus leading to mass loss and a decrease in wood density. The results are consistent with the reports by other researchers (Alén *et al*. 2002, Corleto *et al*. 2020, Esteves *et al*. 2007).

Table 3: Water absorption and density of tin alloy thermal modified Chinese bottletree (*Firmiana simplex* (L.) W. Wight) wood.

Treatment temperature (ºC)	Time (h)	Water absorption (%)	Density (kg/m^3)
Control		a150,24 (32,07)	a390 (50)
TTM150	4	a136,77 (12,70)	ab360 (60)
	8	a121,67 (3,13)	ac350 (40)
TTM210	4	c67,04 (36,70)	bc310 (50)
	8	c53,10 (8,08)	c290 (90)

The values outside the ( ) represent the mean and in ( ) is the standard deviation. Means within a column, followed by the same letter are not significantly different by Tukey tests at $p < 0,05$.

Table 4: ANOVA of water absorption and density of tin alloy thermal modified Chinese bottletree (*Firmiana simplex* (L.) W. Wight) wood.

Variables	Factor	df	Sum of square	Mean square	F-value	P-significant level
Water absorption	Treatment	4	111994	27998	20,05	0,0000
	Error	70	97752	1396		
Density	Treatment	4	0,09969	0,024922	7,117	0,0000
	Error	70	0,24513	0,003502		

Significant, *P < 0,05* (Tukey's test).

Mechanical properties - modulus of elasticity, modulus of rupture, impact bending, compression strength and brinell hardness

The results of the MOE, MOR, I_b and C_s are shown in Table 5. ANOVA shows that the MOE, MOR, I_b and C_s of TTM samples were significantly different from the control samples (Table 6). TTM influenced all the mechanical properties tested, the mean MOE of the control was 7827,87 MPa, while the mean MOE for TTM samples at 150 ^oC for 4 h was 7659,46 MPa which showed a decrease of 2,51 % and the mean MOE of TTM samples at 210 ^oC for 8 h was 6134,48 MPa which was a decrease of 21,63 %. The reduction in the MOE of TTM wood was related to the alterations in the chemistry of the cell wall constituents such as modifications to the cellulose, hemicellulose, lignin structures and increased crystallinity. This assertion was affirmed by Kačíková *et al*. (2013) that the reduction in MOE was due to the thermal degradation of saccharides and changes in lignin macromolecules.

Furthermore, it may be caused by the formation of new chemical bonds with higher binding energy (Gaff *et al*. 2019). The mean MOR of the control was 93,17 MPa, the mean MOR of TTM samples at 150 ^oC for 4 h was 86,41 MPa (7,25 % decrease) and the mean MOR of TTM samples at 210 ^oC for 8 h was 54,85 MPa (41,21 % decrease). In this study, the decrease in MOR was attributed to the accelerated thermal degradation of the chemical components of the wood at higher temperatures and longer times (Srinivas and Pandey 2012, Kačíková *et al*. 2013, Boonstra *et al*. 2007). Other studies supported this conclusion (Ayrilmis *et al*. 2011, Kačíková *et al*. 2013).

The mean I_b of the control was 6,25 kJ/m^2, the mean I_b of TTM samples at 150 ^{o}C for 4 h was 5,27 kJ/m^2 (15,36 % decrease) and the mean I_b of samples at 210 ^{o}C for 8 h was 2,66 kJ/m^2 (57,44 % decrease). The I_b of the TTM wood decreased considerably because the wood became inelastic due to the modification. Militz and Altgen (2014) reported that reductions in the impact bending strength were up to 80 % in several wood species thermally treated in the temperature range between 185 ^{o}C and 220 °. The mean control of the C_s was 41,57 MPa and the mean C_s of TTM samples at 150 ^{o}C for 4 h and 210 ^{o}C for 8 h were 39,99 MPa (3,80 % decrease) and 29,39 MPa (29,29 % decrease) respectively. TTM at a lower temperature (150 ^{o}C) resulted in a reduction of all the tested mechanical properties, further increase in the modification temperature (210 ^{o}C) decreased the properties significantly.

The process conditions and the properties of the wood species play a significant role in how much the mechanical properties are altered. During the TTM process, *F. simplex* wood did not exhibit a high resistance against heat transfer, which led to a high strength loss. Wang *et al*. (2012) reported that maximum hemicellulose breakdown took place as the modification temperature increased (to 210 ^{o}C), which corresponded to a significant reduction in the strength properties of the modified wood.

Table 5: MOE, MOR, I_b and C_s of tin alloy thermal modified Chinese bottletree (*Firmiana simplex* (L.) W. Wight) wood.

Treatment temperature (^{o}C)	Time (h)	MOE (MPa)	MOR (MPa)	I_b (kJ/m^2)	C_s (MPa)
Control		a7827,87(1592,51)	a93,17(12,71)	a6,25(1,28)	a41,57(5,85)
TTM150	4	ab7659,46(971,23)	a86,41(13,23)	ab5,29 (1,09)	a39,99 (2,52)
	8	ac7534,74(1466,66)	a85,75(20,35)	c5,09(0,62)	ab39,60(4,66)
TTM210	4	c6366,04(628,09)	b63,18(11,01)	c2,95(0,55)	c34,34(4,11)
	8	c6134,48(603,82)	b54,85(9,93)	c2,66(0,77)	c29,39(3,84)

The values outside the ( ) represent the mean and in ( ) is the standard deviation. Means within a column, followed by the same letter are not significantly different by Tukey tests at $p < 0,05$.

Table 6: ANOVA of MOE, MOR, I_b and C_s of tin alloy thermal modified Chinese bottletree (*Firmiana simplex* (L.) W. Wight) wood.

Variables	Factor	df	Sum of square	Mean square	F-value	P-significant level
MOE	Treatment	4	25026199	6256550	4,998	0,0020
	Error	45	56337048	1251934		
MOR	Treatment	4	11076	2769	14,02	0,0000
	Error	45	8887	197,5		
I_b	Treatment	4	98,21	24,55	29,94	0,0000
	Error	45	36,9	0,82		
C_s	Treatment	4	1017	254,24	13,48	0,0000
	Error	45	848,7	18,86		

Significant, $P < 0,05$ (Tukey's test).

Results of B_h are shown in Figure 2 and ANOVA shows that the B_h of TTM samples in the tangential and radial directions were significantly different from the control (Table 7). The mean tangential hardness for the control was 3035,03 MPa while the mean tangential hardness of TTM samples at 150 ^oC for 4 h was 1920,78 MPa which means it decreased by 36,75 % and the mean tangential hardness of TTM samples at 210 ^oC for 8 h was 1113,45 MPa which was a decrease of 54,84 %. The mean control of the radial hardness was 2732,87 MPa while the mean hardness of TTM samples at 150 ^oC for 4 h and 210 ^oC for 8 h were 1591,88 MPa (41,75 % decrease) and 1113,45 MPa (59,25 % decrease) respectively. In this study, the decrease in hardness of TTM *F. simplex* wood was caused by cell wall degradation, making the cell walls of the modified wood more brittle (Cai *et al*. 2020, Rautkari *et al*. 2014). Junkkonen and Heräjärvi (2006) further affirmed that thermal modification changes the hardness of wood due to the loss in elasticity.

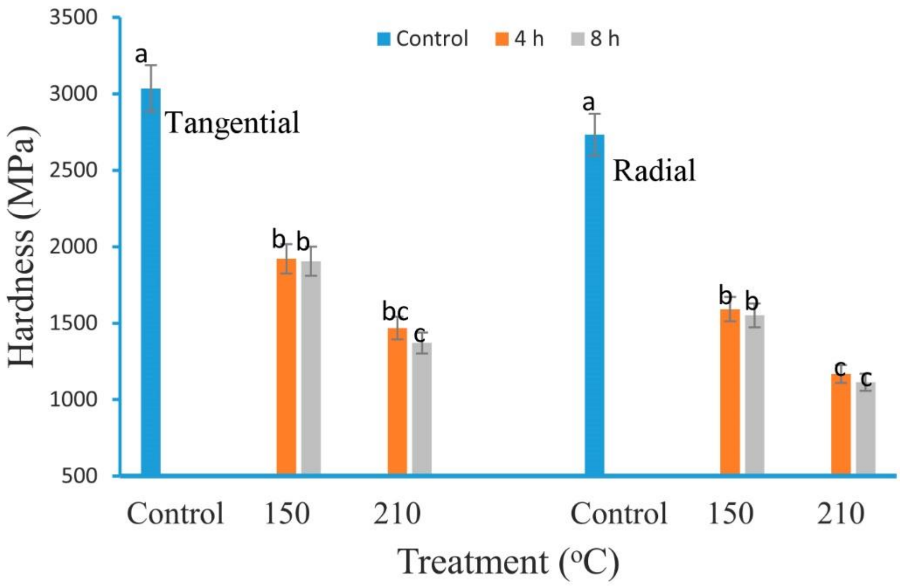

Figure 2: Brinell hardness of tin alloy thermal modified Chinese bottletree (*Firmiana simplex* (L.) W. Wight) wood.

Table 7: ANOVA of Brinell hardness of tin alloy thermal modified Chinese bottletree (*Firmiana simplex* (L.) W. Wight) wood**.**

Variables	Factor	df	Sum of square	Mean square	F-value	P-significant level
Tangential	Treatment	4	17478087	4369522	29,71	0,0000
	Error	45	6618193	147071		
Radial	Treatment	4	17043959	4260990	58,52	0,0000
	Error	45	3276664	72815		

Significant, P < 0,05 (Tukey's test).

Conclusions

The influence of tin alloy thermal modification (TTM) on some selected physical and mechanical properties of *Firmiana simplex* wood was examined in this study. TTM had a significant effect on the physical and mechanical properties of *F. simplex* wood.

TTM samples showed a considerable reduction in swelling, water absorption and density compared to the control. Volumetric swelling of the modified *F. simplex* was 14,50 % at 150

^{o}C for 4 h and 6,99 % at 210 ^{o}C for 8 h. Water absorption values were 136,77 % and 53,10 % when treated at 150 ^{o}C and 210 ^{o}C for 4 h and 8 h, thus improving the wood dimensional stability as the TTM temperature increased. The density of the wood was 390 kg/m^3 at TTM of 150 ^{o}C for 4 h and 290 kg/m^3 at TTM of 210 ^{o}C for 8 h respectively, indicating that tin alloy thermal modification reduced the density of *F. simplex* wood.

The MOE, MOR, I_b and C_s of TTM samples significantly decreased compared to the control. At TTM150 ^{o}C for 4 h and 210 ^{o}C for 8 h, MOE were 7659,46 and 6134,48 MPa, MOR were 86,41 and 54,85 MPa, I_b were 5,29 and 2,66 kJ/m^2 and C_s were 39,99 and 29,39 MPa respectively. At TTM150 ^{o}C for 4 h and 210 ^{o}C for 8 h, brinell hardness was 1920,78 and 1370,60 MPa in the tangential and 1591,88 and 1113,45 MPa in the radial directions respectively. To increase the mechanical properties of TTM wood it is important to determine a reasonable and optimal modification processing temperature and time.

The physical and mechanical properties of *F. simplex* wood were significantly impacted by TTM temperature, and this impact increased substantially at a thermal modification temperature of 210 ^{o}C. In conclusion, the physical properties of *F. simplex* wood were enhanced by TTM. Compared to the commercial wood thermal modification methods with other types of heating medium, tin alloy is a water repellent material, characterised by thermal stability and good heat conduction, fast heat transfer to wood and short process time. It is recommended that further research be carried out to determine the effect of TTM on wood hygroscopicity and strength properties at low temperatures (80 ^{o}C and 100 ^{o}C). Further experiments are needed to investigate the influence of TTM temperature and time on the wood properties of *F. simplex*.

Author contributions

K. E. O.: Conceptualization, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, writing – original draft preparation. N. B. N.: Data curation, funding acquisition, investigation, methodology, visualisation, writing – review and editing.

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