

EFFECT OF TEMPERATURE ON TIN-BASED METAL BATH MODIFICATION ON THE PROPERTIES OF *CUNNINGHAMIA LANCEOLATA* L. WOOD: MECHANICAL AND PHYSICAL PROPERTIES

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Abstract:

Developing an eco-friendly, efficient and cost-effective wood modification technique should be prioritised due to increasing environmental concerns. In this study, the effect of temperature on tin-based metal bath modification of Cunninghamia lanceolata wood properties was investigated. The wood was treated at 150°C and 210°C for 120min and 480min and the mechanical (modulus of elasticity and rupture, impact bending, compression strength and hardness) and physical (contact angle, colour and water absorption) properties of the wood were compared with the untreated. The results showed that with increased modification temperature and time, the modulus of elasticity and rupture, impact bending, compression strength, hardness and water absorption decreased. In contrast, contact angle and colour increased significantly after thermal modification. Tin-based metal bath modification technology was an effective treatment method and the treatment of the wood at high temperature significantly impacted the properties of the wood.

Key words: colour; contact angle; *Cunninghamia lanceolata*; heat treatment; high temperature; modulus of elasticity; thermal modification; water absorption; wood.

INTRODUCTION

High temperature treatment of wood is an eco-friendly method of wood modification, it gained significant attention in recent years because it serves as an alternative to the chemical treatment of wood (Poncsák *et al.* 2006), and it is a cost-effective and simple method of wood modification. Increased environmental concerns and the introduction of legislation, such as the European Biocides Directive on the usage of preservative treated wood in some countries in Europe led to the development of thermally modified wood, as a non-biocidal alternative to conventional preservation techniques.

Thermal modification of wood is not a new technology because it has existed as far back as 1915 and attracted no commercial interest due to the copious availability of tropical hardwoods. In the 1930s and 1940s, the Forest Products Laboratory continued the research on thermal modification of wood which led to the granting of a patent (Stamm 1942). Research and development continued in the 1970s and 1980s, with further attempts at commercialisation in Germany (Burmester 1973, Giebler 1983), but again without success. However, in the 1990s the needed commercial exploitation of this technology set in, because the tropical hardwoods had been exploited to near extinction while the demand for wood was increasing, this rekindled the renewed interest in the thermal modification of wood, thus making this technology immensely valuable. Thermal modification is mostly applied to low-quality woods for value addition. It gives the wood industries a fresh source of wood that replaces high-value tropical hardwood species (Shukla and Sharma 2014).

Thermal modification involves exposing the wood to high temperatures (Militz 2002). The temperature and time of treatment generally vary from 180 to 280°C and 15min to 24h depending on the heat treatment process, wood species, sample size, moisture content of the sample and the desired mechanical properties (Inoue *et al.* 1993, Militz 2002). Temperature has the greatest effect on the wood properties compared to time and prolonged treatment at lower temperatures does not significantly modify the wood compared to

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treatments at higher temperatures (Korkut *et al.* 2008a). According to earlier reports, the physical and chemical characteristics of wood gradually changed at temperatures above 150°C, and the greater the treatment temperature, the more the properties of the wood were modified (Okon *et al.* 2017, Syrjanen 2001).

Previous research on the effect of high temperatures on the mechanical properties of treated wood showed that the properties of wood after treatment varied based on the chemical and anatomical characteristics of the wood as well as the methods of treatment used (Inoue *et al.* 1993, Korkut *et al.* 2008b, Militz 2002). According to Korkut *et al.* (2008b), the method of thermal modification applied and other factors affect the extent of the change in wood properties during thermal modification.

Many studies have reported the effectiveness of thermal modification in enhancing wood properties (Ditomaso *et al.* 2020, Hill *et al.* 2021, Lee *et al.* 2018b). Thermal modification results in favourable changes in the physical properties of the wood such as improved dimensional stability, increased biological durability, reduced shrinkage and swelling, low equilibrium moisture content, reduced water absorption and improved colour and contact angle of the wood (Allegretti *et al.* 2021, Yildiz 2002). Shukla and Sharma (2014) reported that thermal modification reduces the mechanical strength of wood.

The necessity for developing an eco-friendly, sustainable, effective and cost-effective wood modification technique should be given continual priority due to rising environmental concerns. Without the addition of any hazardous chemicals, thermal modification significantly modifies the behaviour of wood. Sailer *et al.* (2000) used an oil heat treatment technique to modify the properties of some wood for various applications. In the current study, *Cunninghamia lanceolata* wood characteristics are altered using a tin-based metal bath modification process at different temperatures. According to Okon *et al.* (2018a) and Okon *et al.* (2018b) tin-alloy (i.e. tin-based metal) is a low melting point alloy and heat transfer agent due to its properties such as high thermal storage densities, excellent thermal stability and high boiling points. They further stated that tin-alloy is a non-flammable, non-toxic, tasteless and odourless material and it is a readily available heating medium for thermal modification of wood. The lack of adequate information is limiting the development and application of tin-based metal bath modification. It is expected that the results of this study will offer useful information to wood industries in processing thermally modified wood for value addition.

MATERIALS AND METHODS

Materials and preparation

Chinese fir (*Cunninghamia lanceolata*) wood (100mm x 25mm x 2000mm, tangential x radial x longitudinal) was purchased from a local timber market in Fuzhou, China and prepared according to GB/T 1927.2 (2021). The moisture content and wood density determinations were conducted according to GB/T 1927.4 (2021) and GB/T 1927.5 (2021). The moisture content and density of the wood were tested to be 0.45g/cm³ and 11% respectively. The check and knots free wood was sawn into samples with dimensions 100mm (T) x 25mm (R) x 300mm (L). A total of five groups of samples were prepared and there were fifteen replicates in each group. One group was used as a control (untreated), while the other groups were used for tin-based metal bath modification at 150°C for 120min and 210°C for 480min respectively. The tin-based metal used to modify the wood was purchased from Beijing, China and was used as received.

Equipment and instrument

The equipment used for the wood modification was a heating bath (Guangdong Hongzhan Technology Company Limited, Hangzhou, China). The temperature in the equipment can be controlled up to 250°C. Other equipments are a laboratory drying oven (Shanghai Yiheng Scientific Instrument Company Limited, Shanghai, China), electronic balance (Shanghai Hochoice Apparatus Manufacturer Company Limited, Shanghai, China), digital calliper (Shanghai Fuley Measuring Equipment Company Limited, Shanghai, China), universal testing machine (Jinan Tianchen Experimental Machinery Manufacturing Company Limited, Jinan, China), programable temperature and humidity test chamber (Guangdong Grande Automatic Test Equipment Limited Hongzhan, China) drop shape analyser DSA100 (Krüss GmbH, Hamburg, Germany) and X-rite spectrophotometer Ci7860 (Neu-Isenburg GmbH, Germany).

Tin-based metal bath modification

Before the commencement of the modification, the temperature in the tin-based heating bath fixed with a thermocouple was set to each designated temperature. Upon stabilisation, wood samples were inserted in the bath. Two temperature levels were selected: 150°C and 210°C with two exposure times employed at each of the selected temperature levels: 120min and 480min respectively. After this, all samples were removed from the heating bath and cooled in a desiccator to room temperature. To ensure consistency and control in experimental results, all samples were conditioned in a humidity chamber maintained at 20°C and 65% relative humidity until they reached equilibrium moisture content before testing was conducted.

Mechanical properties tests

Three-point bending strength, modulus of rupture test (MOR) and modulus of elasticity (MOE) of untreated and tin-based metal bath modified wood samples were performed according to GB/T 1936.1 and 1936.2 (2009) with samples dimensions 20mm x 20mm x 300mm. Impact bending (IB) and compressive strength parallel to grain (CS) tests were performed according to GB/T 1940 and 1935 (2009) using samples with dimensions 20mm x 20mm x 300mm and 20mm x 20mm x 30mm respectively. Displacement-controlled loading was applied to compressive and bending samples at loading rates of 1, 2 and 5mm min⁻¹ respectively, until the samples reached their maximum load. Hardness (HN) test was conducted on the tangential surface of the samples with dimensions 50mm x 50mm x 70mm according to GB/T 1941 (2009) by driving a steel hemisphere with a diameter of 11.2mm into each test sample. 15 replicates were used for each test making a total of 75 samples for each treatment.

Physical properties tests

Contact angle measurement

The measurement of the contact angle of the untreated and tin-based metal bath modified samples was performed with a Drop Shape Analyser DSA100 (Krüss GmbH, Hamburg, Germany). 15 samples were used for each treatment, 2 drops per sample were captured, 30 measurements of contact angles were obtained and the mean value was reported. Deionised water (5µL) was dropped at the tangential surface of the samples and the acquisition of the contact angle was taken automatically every 3 seconds with the general conic section method (tangential method 1). All samples were maintained at standard room temperature (25 ± 2°) and relative humidity of 20 ± 2°C.

Colour measurement

Colour measurements of the untreated and tin-based metal bath modified samples were taken at 2 points on the tangential surface of the samples. The CIELAB system was characterised by three parameters L*, a* and b*. L* axis represents the lightness, + a* represents red, - a* represents green, + b* represents yellow, - b* represents blue and L* varied between 100 and 0 (100 represented white and 0 represented black). The L*, a* and b* colour coordinates of each sample before modification and the differences in lightness ΔL^* , chroma corresponding to Δa^* and Δb^* after modification were used to calculate the colour changes ΔE^* according to Zwinkels (1996) and Okon *et al.* (2018). 5 replicates were used for each treatment making a total of 25 samples for colour measurement.

Water absorption test

Water absorption tests of untreated and tin-based metal bath modified samples were oven-dried at 103°C to a constant weight and weight recorded before soaking in deionised water for 48 hours. After this, the samples were removed from the water and the weight taken in the saturated condition and water absorption was measured according to Dong *et al.* (2016). 15 replicates were used for each treatment making a total of 75 samples for the water absorption test.

Statistical analysis

Data of mechanical and physical properties 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 Duncan's multiple range tests, at $p < 0.05$ significance level.

RESULT AND DISCUSSIONS

The effect of tin-based metal bath modification on MOE is shown in Fig. 1. The results showed that a higher temperature (210°C) and longer treatment time (480min) led to a reduction in MOE compared to the untreated. As observed, temperature had a more significant effect on MOE than time.

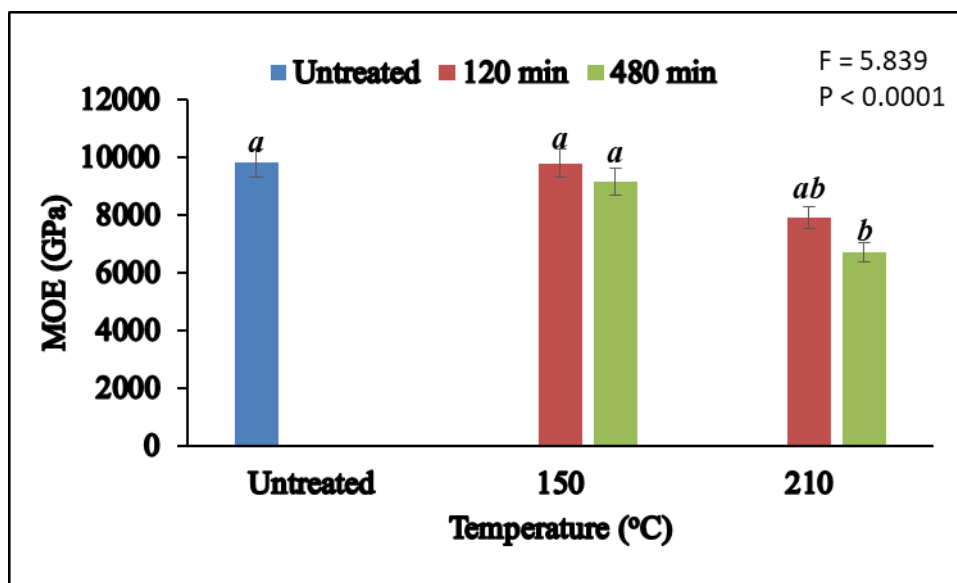


Fig. 1.

Modulus of rupture (MOE) of untreated and tin-based metal bath modified samples.

Table 1 shows the MOR ($F = 3.536$; $p < 0.05$), IB ($F = 0.767$; $p < 0.552$), CS ($F = 19.88$; $p < 0.0001$) and HN ($F = 4.163$; $p < 0.01$) values in *C. lanceolata* wood heat treated using tin-based metal bath modification at different temperatures and durations. According to Duncan's multiple range tests (at $p < 0.05$) all tin-based metal bath modified samples were significantly different from the untreated samples. As observed in Fig. 1 and Table 1 tin-based metal bath modification led to a reduction in the mechanical properties of the wood. Reduction in MOE in Fig. 1, MOR, IB, CS and HN (Table 1) of samples after the treatment at 210°C for 480min were 31.56%, 33.02%, 22.94%, 41.13% and 70.10% compared to the untreated respectively. The effect of temperature on the wood properties was pronounced, as high heating temperature and time particularly at (210°C for 480min) resulted in a higher reduction in the mechanical properties of the wood relative to the untreated. It has been observed that the increase in the modification temperature, increases the brittleness of the wood thereby making the wood lose its elasticity. The loss in mechanical properties was attributed to the rapid thermal degradation of hemicellulose (Boonstra *et al.* 2007, Kačíková *et al.* 2013, Srinivas and Pandey 2012) as it is the most labile wood cell wall polymers and cellulose decomposition (Adibaskoro *et al.* 2021) at higher temperatures and longer treatment durations. The degradation of cellulose according to earlier research is limited to the amorphous regions which directly increases the proportion of crystalline cellulose in thermally modified wood (Sivonen *et al.* 2002). It should be noted that the crystalline cellulose was unaffected by temperatures between 150°C and 210°C which were the highest modification temperatures in this study. Previous studies have reported a reduction in the mechanical properties (MOR, MOE, hardness, compressive strength and impact strength) of wood after thermal modification (Cademartori *et al.* 2015, Esteves 2007, Esteves 2009, Kesik *et al.* 2014, Srinivas and Pandey 2012). Decreases in the mechanical strength of thermally modified wood have been linked to the loss of amorphous polysaccharides in addition to the crystallization of amorphous cellulose (Esteves and Pereira 2007, Yildiz and Gümüşkaya 2007, Nhacila *et al.* 2020). Degradation reactions in wood during thermal modification are intricate and may be influenced by the wood species and the process conditions applied.

Table 1

Mechanical properties of untreated and tin-based metal bath modified samples

Treatment	Untreated	150°C		210°C	
Time (min)		120	480	120	480
MOR (GPa)	^a 109.18(15.41)	^a 108.65(27.51)	^{ab} 94.29(13.56)	^{ab} 86.81(38.21)	^b 73.12(25.22)
IB (GPa)	^a 5.10(1.22)	^a 4.89(1.30)	^a 4.51(2.81)	^a 4.20(1.57)	^a 3.93(1.26)
CS (GPa)	^a 59.15(9.72)	^b 41.76(5.54)	^b 38.59(9.99)	^b 36.22(3.92)	^b 34.82(2.31)
HN (GPa)	^a 2915.55(3064.22)	^{ab} 1537.80(142.54)	^{ab} 1513.36(163.49)	^{ab} 1114.67(325.83)	^b 871.57(125.73)

The values represent the mean (standard deviation). Means within a row, followed by different superscripts are significantly different by Duncan's multiple range tests at $p < 0.05$. MOR represents the modulus of rupture, IB represents impact bending, CS represents compression strength parallel to grains and HN represents hardness.

Figs. 2 a and b show the contact angle of untreated and tin-based metal bath modified *C. lanceolata* wood samples at different temperatures and times. The contact angle of the tin-based metal bath modified *C. lanceolata* wood samples increased significantly compared to the untreated. The results of the ANOVA showed that the contact angles of the modified wood at different temperatures were significantly different (Figure 2a). In the untreated samples, the contact angle was 63.30° because the water was rapidly absorbed by the wood resulting in a small contact angle. However, with the increase in the tin-based metal bath modification temperature, the contact angle increasingly increased to 140.11° for the samples treated at 210°C for 480min. Higher modification temperature and prolonged duration resulted in round-shaped water droplets on the wood surface, indicating that tin-based metal bath modification was effective in improving the hydrophobicity of the wood. This may be due to a reduction in the number of hydrophilic groups and limited access of free hydroxyl groups to water during thermal modification and the consequent dehydration reaction of carbohydrates (Gérardin *et al.* 2007). Earlier studies reported that thermal modification reduces the wettability of the wood with a resultant increase in contact angle (Altgen and Militz 2017, Hakkou *et al.* 2005, Pétrissans *et al.* 2003).

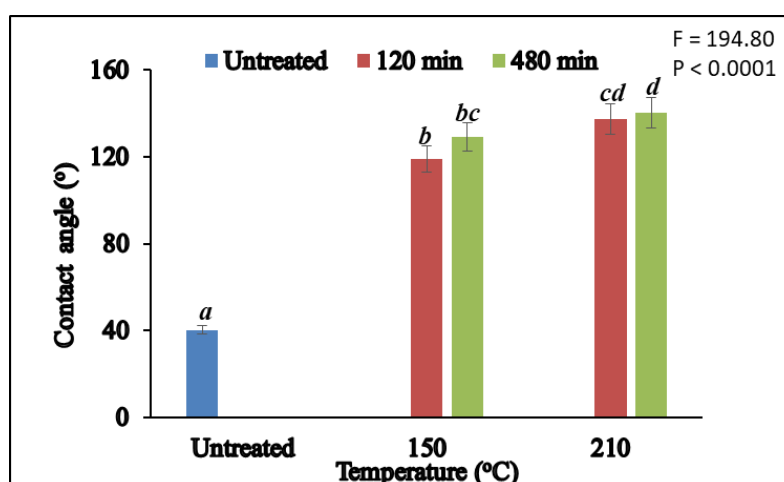


Fig. 2a.

Contact angle of untreated and tin-based metal bath modified samples.

These results are in line with earlier works by Bakar *et al.* (2013), who reported in their study that the contact angle of red oak thermally modified at 190°C for 8h increased from 68° in the control samples to 143° . Lee *et al.* (2018a) reported that the contact angle of bamboo thermally modified at 210°C for 4h increased from 53.20° in the control to 116.80° . In another study, the wettability of *Fraxinus americana* and *Acer rubrum* woods was reported to reduce after thermal modification at 205°C - 215°C and *Eucalyptus cloeziana* wood at 180°C - 240°C .

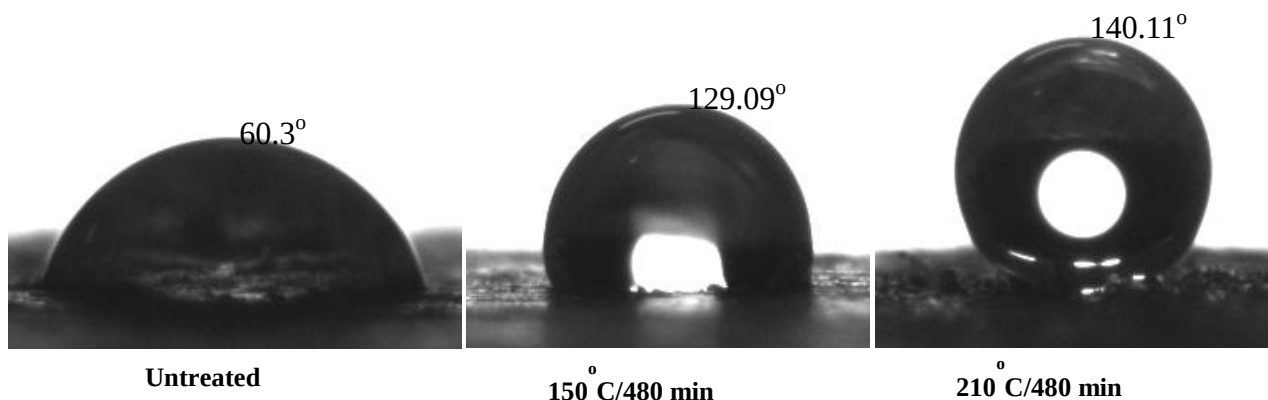


Fig. 2b.

Contact angle in the tangential surface of the untreated and tin-based metal bath modified samples.

The results of the colour test for the untreated and tin-based metal bath modified *C. lanceolata* wood samples are shown in Table 2 and Fig. 3. The total colour difference (ΔE^*) of the tin-based metal bath modified samples increased from 7.07 at 150°C for 120min to 22.17 at 210°C (Table 2). The results showed that tin-based metal bath modification impacted remarkable colour disparities in the wood colour and the higher the modification temperatures and durations the darker the colour of the wood (Fig. 3). The ΔL^* (lightness coordinate), Δa^* (red/green coordinate) and Δb^* (yellow /blue coordinate) values were negative, indicating large colour disparities and all the colour parameters increased with an increase in the intensity of modification temperatures and durations. The tin-based metal bath modified samples showed negative lightness (ΔL^*), i.e., the wood samples changed their colour from light white to dark brown. The ΔL^* of the samples changed from 3.94L at 150°C for 120min to 20.62D at 210°C for 480min, making the colour to be more darkening. Similarly, Δa^* and Δb^* increased from -1.86 to -3.81 and -4.39 to -6.31 at 150°C for 120min and 210°C for 480min resulting in the wood samples becoming radish and yellowish colour respectively. An earlier study reported that the Δb^* of thermally modified wood at 150°C was 6 - 7 times darker in colour compared to the control samples (Bekhta and Niemz 2003).

Table 2

Colour parameter of the wood before and after the tin-based metal bath modified wood.						
Treatment		Untreated	150 °C		210 °C	
Time (min)			120	480	120	480
Colour	L^*	65.25	60.92	58.72	52.07	44.11
	a^*	6.35	4.16	4.83	5.91	6.45
	b^*	15.84	18.03	19.49	17.98	12.32
	ΔL^*	-	3.94L	8.13D	14.55D	20.62D
	Δa^*	-	-1.86	1.6	1.85	-3.81
	Δb^*	-	-4.39	5.15	-4.56	-6.31
	ΔE^*	-	7.07	10.15	15.67	22.17

The colour differences were caused by the increase of chromophores formed during the thermal modification of the wood. According to Srinivas and Pandey (2012), the formation of acetic acid by the deacetylation of hemicellulose acted as a catalyst to enable oxidation and dehydration reactions in lignin and carbohydrates to form new chromophores in carbonyl and carboxyl groups. Furthermore, the acetic acid formed led to a substitution reaction of free hydroxyl groups to form ether bonds and polycondensation of phenolic hydroxyl groups to form ketone and quinones giving the modified wood a darker colour (Kačíková et al. 2013, Sundqvist et al. 2006, Tomak et al. 2014). Additionally, Srinivas and Pandey (2012) affirmed that the extractives content of wood such as phenols, ketones and quinones has a significant influence on the colour of the wood, besides temperature and duration of thermal modification.

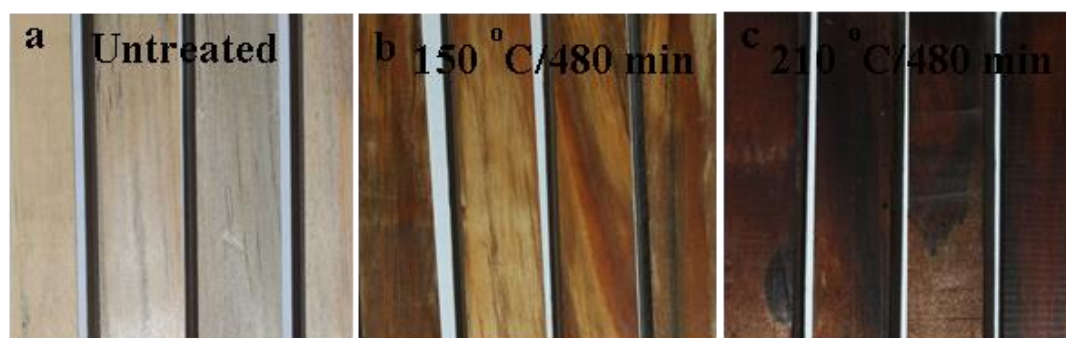


Fig. 3.

Visual surface colour comparison of the untreated and tin-based metal bath modified *C. lanceolata* wood samples at 150°C for 480min and 210°C for 480min.

Fig. 4 shows the water absorption of the untreated and tin-based metal bath modified *C. lanceolata* wood samples. There was a significant difference between the water absorption of the untreated compared to the tin-based metal bath modified samples ($F = 67.97$, $p < 0.0001$). The water absorption of the tin-based metal bath modified *C. lanceolata* wood was positively influenced, as the modification temperature

increased, the wood absorbed less water. Compared to the untreated, the water absorption of the tin-based metal bath modified wood at 150°C for 120min and 210°C for 480min were reduced by 9.00% and 63.78% respectively. Metsä-Kortelainen *et al.* (2006) investigated the water absorption in Scots pine and Norway spruce heat treated at temperatures 170°C, 190°C, 210°C and 230°C and observed that both wood species absorbed less water after thermal modification.

It was observed that the increase in the treatment temperature and duration resulted in reduced water absorption by the wood, this may be caused by the inhibition of water penetration into the wood by the tin alloy, thereby impeding water movement within the cell wall and subsequently reducing water absorption. Thermal modification of wood resulted in a significant reduction in water absorption by the wood and enhanced its dimensional stability. The reduction in water absorption is linked to the degradation of the hemicelluloses accompanied by a decrease in the polymer mobility of the cell wall and crosslinking reactions within the cell wall (Hill *et al.* 2021).

The accessibility of the free hydroxyl groups by the carbohydrates in wood plays an important role in the process of water adsorption. Other studies affirmed that heat treatment leads to a reduction in accessible free hydroxyl groups, depolymerisation of the carbohydrates particularly hemicelluloses and an increase in the relative proportion of the crystalline cellulose as well as cross-linking of the lignin network (Boonstra 2008, Kocaefe *et al.* 2007). Furthermore, Thybring *et al.* (2020) reported that improved dimensional stability was achieved through the removal of hydroxyl groups, which decreased the hydrophilicity of the wood. Further confirmation from earlier studies indicates that thermal treatment at high temperatures makes treated wood less hygroscopic through hemicelluloses' degradation, which represents a major contributor to dimensional stability as the number of free hydroxyl groups available for bonding to moisture is severely reduced (Gündüz *et al.* 2008, Inoue *et al.* 1993, Baysal *et al.* 2014).

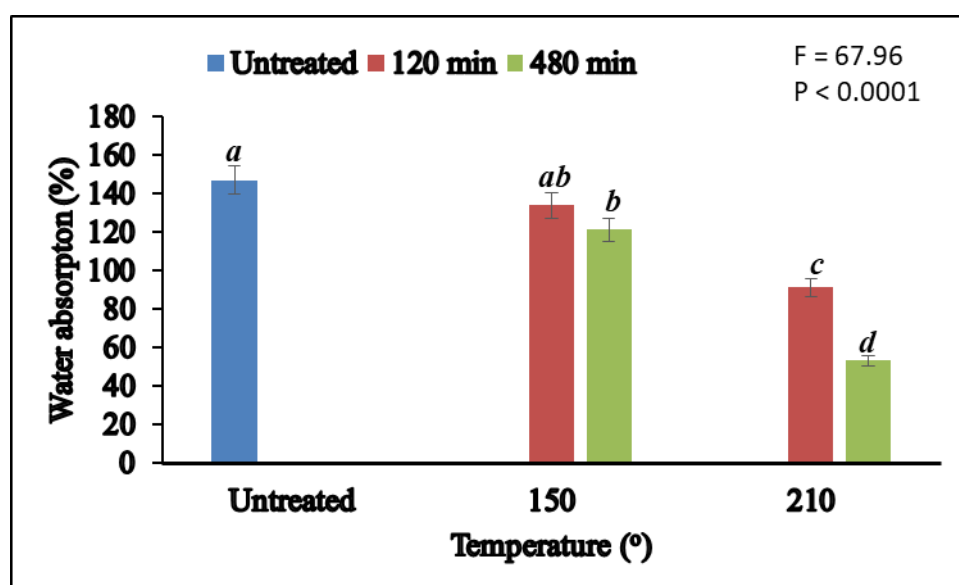


Fig. 4.

Water absorption of the untreated and tin-based metal bath modified samples.

CONCLUSION

The mechanical properties (modulus of rupture, modulus of elasticity, impact bending, compression strength, and hardness) and physical properties (contact angle, colour and water absorption) of the tin-based metal bath modified *C. lanceolata* wood changed significantly. The results indicated that the mechanical properties decreased after tin-based metal bath modification. The increase in the modification temperature, increased the brittleness of the wood making the wood lose its elasticity. The highest decrease was obtained when the wood samples were treated at 210°C for 480min probably due to the thermal degradation of hemicellulose and cellulose, but the crystalline cellulose was unaffected at this temperature since it was not above 300°C. However, degradation during thermal modification was also influenced by the wood species and the process conditions applied. The physical properties improved remarkably with increasing temperature and duration. The water absorption of tin-based metal bath modified wood at 210°C for 480min decreased by 63.78% due to the reduction of hydrophilic hydroxyl which increases the dimensional stability of the modified wood. Modification of the wood at higher temperatures and prolonged duration resulted in round-shaped water droplets on the wood surface and a reduction in the wettability of the wood, which is an indication that tin-based metal bath modification was effective in increasing the hydrophobicity of the wood.

Tin-based metal bath modification impacted extraordinary colour on the wood and the colour became darker at higher modification temperatures and durations. Tin-based metal bath modification technology is an effective treatment method that improves wood properties; however, moderate temperature has to be applied to reduce its overwhelming effect on the mechanical properties of the wood. Furthermore, compared to other commercial methods of thermal modification of wood using other types of heating media such as steam, hot oil, and inert gas like nitrogen, molten tin-alloy is a water-repellent material, characterised by thermal stability and good heat conduction, fast heat transfer to wood and short process time.

REFERENCES

- Adibaskoro T, Makowska M, Rinta-Paavola A, Fortino S, Hostikka S (2021) Elastic modulus, thermal expansion, and pyrolysis shrinkage of Norway spruce under high temperature. *Fire Technology* 57(5):2451-2490.
- Allegretti O, Cuccui I, Terziev N, Sorini L (2021) A model to predict the kinetics of mass loss in wood during thermo-vacuum modification. *Holzforschung* 75(5):474-479.
- Altgen M, Militz H (2017) Thermally modified Scots pine and Norway spruce wood as substrate for coating systems. *Journal of Coating Technology Resources* 14:531-541.
- Bakar BFA, Hiziroglu S, Tahir PM (2013) Properties of some thermally modified wood species. *Materials and Design* 43:348-355.
- Baysal E, Kart S, Toker H, Degirmençtepe S (2014) Some Physical Characteristics of Thermally Modified Oriental-Beech Wood. *Maderas Ciencia Tecnologia* 16: 291-298.
- Bekhta P, Niemz P (2003) Effect of high temperature on the change in colour, dimensional stability and mechanical properties of spruce wood. *Holzforschung* 57(5):539-546.
- Boonstra M (2008) A Two-Stage Thermal Modification of Wood. Ghent University, Ph. D. Tezi, Belgium.
- Boonstra MJ, Van Acker J, Tjeerdsma BF, Kegel EV (2007) Strength properties of thermally modified softwoods and its relation to polymeric structural wood constituents. *Annals of Forest Science* 64(7):679-690.
- Burmester A (1973) Effects of heat-pressure treatments of semi-dry wood on its dimensional stability. *Holz Als Roh-und Werkstoff* 31:237-243.
- Cademartori PHGD, Missio AL, Mattos BD, Gatto DA (2015) Effect of thermal treatments on technological properties of wood from two Eucalyptus species. *Anais da Academia Brasileira de Ciências* 87:471-481.
- Ditommaso G, Gaff M, Kačík F, Sikora A, Sethy A, Corleto R, Razaei F, Kaplan L, Kubš J, Das S (2020) Interaction of technical and technological factors on qualitative and energy/ecological/economic indicators in the production and processing of thermally modified merbau wood. *Journal of Cleaner Production* 252:119793.
- Dong Y, Yan Y, Wang K, Li J, Zhang S, Xia C, Shi SQ, Cai L (2016) Improvement of water resistance, dimensional stability, and mechanical properties of poplar wood by rosin impregnation. *European Journal of Wood and Wood Products* 74:177-184.
- Esteves B, Pereira HM (2007) Wood Modification by Heat Treatment: A Review. *BioResources* 4:370-404.
- Esteves B (2007) Improvement of technological quality of eucalypt wood by heat treatment in air at 170-200°C. *Forest Products Journal*, pp. 47-52.
- Esteves B (2009) Wood modification by heat treatment: A review. *BioResources*, pp. 370-404.
- GB/T 1935-2009 (2009) Method of testing in compressive strength parallel to the grain of wood. Chinese National Standard, The People's Republic of China.
- GB/T 1936. 1-2009 (2009) Method of testing in bending strength of wood. Chinese National Standard, The People's Republic of China.
- GB/T 1936. 2-2009 (2009) Method for determination of the modulus of elasticity in static. Chinese National Standard, The People's Republic of China.
- GB/T 1940- 2009 (2009) Method of testing in toughness of wood. Chinese National Standard, The People's Republic of China.
- GB/T 1941-2009 (2009) Method of testing in hardness of wood. Chinese National Standard. Chinese National Standard, The People's Republic of China.

GB/T 1927. 2-2021 (2021) Test Methods for Physical and Mechanical Properties of Small Clear Wood Specimens-Part 2: Sampling Methods and General Requirements. Chinese National Standard, The People's Republic of China.

GB/T 1927. 4-2021 (2021) Test Methods for Physical and Mechanical Properties of Small Clear Wood Specimens-Part 4: Determination of Moisture Content Chinese National Standard, The People's Republic of China.

GB/T 1927. 5-2021 (2021) Test Methods for Physical and Mechanical Properties of Small Clear Wood Specimens-Part 2: Determination of Density. Chinese National Standard, The People's Republic of China.

GB/T 1927. 9-2021 (2021) Test Methods for Physical and Mechanical Properties of Small Clear Wood Specimens-Part 9: Determination of Bending Strength. Chinese National Standard, The People's Republic of China.

Gérardin P, Petrič M, Petrissans M, Lambert J, Ehrhardt JJ (2007) Evolution of wood surface free energy after heat treatment. *Polymer degradation and stability* 92(4):653-657.

Giebler E (1983) Dimensional stabilisation of wood by moisture-heat-pressure-treatment. *Holz Als Roh-und Werkst* 41:87-94.

Gündüz G, Korkut S, Korkut DS (2008) The Effects of Heat Treatment on Physical and Technological Properties and Surface Roughness of Camiyanı Black Pine (*Pinus nigra* Arn. Subsp. *pallasiana* var. *pallasiana*) Wood. *Bioresource Technology* 99:2275-2280.

Hakkou M, Pétrissans M, El Bakali I, Gerard P, Zoulalian A (2005) Wettability changes and mass loss during heat treatment of wood. *Holzforschung* 59:35-37.

Hill C, Altgen M, Rautkari L (2021) Thermal modification of wood - A review: Chemical changes and hygroscopicity. *Journal of Materials Science* 56:6581-6614.

Inoue M, Norimoto M, Tanahashi M, Rowell RM (1993) Steam or heat fixation of compressed wood. *Wood and Fiber Science*, pp. 224-235.

Inoue M, Norimoto M, Tanahashi M, Rowell RM (1993) Steam or Heat Fixation of Compressed Wood. *Wood Fiber Science* 25:224-235.

Kačíková D, Kačík F, Čabalová I, Ďurkovič J (2013) Effects of thermal treatment on chemical, mechanical and colour traits in Norway spruce wood. *Bioresource Technology* 144: 669-674.

Kesik HI, Korkut S, Hiziroglu S, Sevik H (2014) An evaluation of properties of four heat treated wood species. *Industrial Crops and Products* 60:60-65.

Kocaepe D, Chaudhry B, Poncsak S, Bouazara M, Pichette A (2007) Thermogravimetric study of high temperature treatment of aspen: effect of treatment parameters on weight loss and mechanical properties. *Journal of Materials Science* 42:854-866.

Kocaepe D, Poncsak S, Dor GV, Younsi R (2008) Effect of heat treatment on the wettability of white ash and soft maple by water. *Holz als roh-und werkstoff* 66(5):355-361.

Korkut DS, Korkut S, Bekar I, Budakci M, Dilik T, Çakicier N (2008a) The effects of heat treatment on the physical properties and surface roughness of Turkish hazel (*Corylus colurna* L.) wood. *International Journal of Molecular Sciences* 9(9):1772-1783.

Korkut S, Akgül M, Dündar T (2008b) The effects of heat treatment on some technological properties of Scots pine (*Pinus sylvestris* L.) wood. *Bioresource Technology* 99(6):1861-1868.

Korkut S, Budakci M (2010) The effects of high-temperature heat treatment on physical properties and surface roughness of rowan (*Sorbus aucuparia* L.) wood. *Wood Research* 55(1):67-78.

Lee CH, Yang TH, Cheng YW, Lee CJ (2018a) Effects of thermal modification on the surface and chemical properties of moso bamboo. *Construction and Building Materials* 178: 59-71.

Lee SH, Ashaari Z, Lum WC, Halip JA, Ang AF, Tan LP, Chin KL, Tahir PM (2018b) Thermal treatment of wood using vegetable oils: A review. *Construction and Building Materials*, 181:408-419.

Lopes JDO, Garcia RA, Nascimento AMD (2018) Wettability of the surface of heat-treated juvenile teak wood assessed by drop shape analyser. *Maderas. Ciencia y tecnología* 20(2):249-256.

Militz, H (2002) Thermal treatment of wood, European processes and their background. *IRG/WP*, 2002.

- Nhacila F, Siteo E, Uetimane E, Manhica A, Egas A, Möttönen V (2020) Effects of Thermal Modification on Physical and Mechanical Properties of Mozambican *Brachystegia spiciformis* and *Julbernardia globiflora* Wood. *European Journal of Wood and Wood Product* 78:871-878.
- Okon, KE, Lin F, Chen Y, Huang B (2017) Effect of silicone oil heat treatment on the chemical composition, cellulose crystalline structure and contact angle of Chinese parasol wood. *Carbohydrate Polymers* 164:179-185.
- Pétrissans M, Gérardin P, Bakali IE, Serraj M (2003) Wettability of heat-treated wood. *Holzforschung* 57:301-307.
- Poncsák S, Kocaefer D, Bouazara M, Pichette A (2006) Effect of high temperature treatment on the mechanical properties of birch (*Betula papyrifera*). *Wood Science and Technology* 40:647-663.
- Shukla S, Sharma S (2014) Effect of high temperature processing under different environments on physical and surface properties of rubberwood (*Hevea brasiliensis*). *Journal of the Indian Academy of Wood Science* 11:182-189.
- Sivonen H, Maunu SL, Sundholm F, Jämsä S, Viitaniemi P (2002) *Magnetic Resonance Studies of Thermally Modified Wood*; Walter de Gruyter: Berlin, Germany.
- Srinivas K, Pandey KK (2012) Effect of heat treatment on colour changes, dimensional stability, and mechanical properties of wood. *Journal of Wood Chemistry and Technology* 32(4):304-316.
- Stamm AJ (1942) Antishrink treatment for wood. US Patent No. 2:296-316.
- Sundqvist B, Karlsson O, Westermarck U (2006) Determination of formic-acid and acetic acid concentrations formed during hydrothermal treatment of birch wood and its relation to colour, strength and hardness. *Wood Science and Technology* 40(7):549-561.
- Syrjänen T (2001) Production and classification of heat-treated wood in Finland. *Proceedings of the special seminar held in Antibes, France, 2001*.
- Team RC (2016) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <http://www.R-project.org/>
- Thybring EE, Piqueras S, Tarmian A, Burgert I (2020) Water accessibility to hydroxyls confined in solid wood cell walls. *Cellulose* 27:5617-5627.
- Tomak ED, Ustaomer D, Yildiz S, Pesman E (2014) Changes in surface and mechanical properties of heat treated wood during natural weathering. *Measurement* 53:30-39.
- Yildiz S (2002) Physical, mechanical, technological and chemical properties of beech and spruce wood treated by heating. *Unpublished doctoral dissertation, Karadeniz Technical University, Trabzon*.
- Zwinkels JC (1996) Colour-measuring instruments and their calibration. *Displays* 16:163-171.
- Yildiz S, Gümüşkaya E (2007) The Effects of Thermal Modification on Crystalline Structure of Cellulose in Soft and Hardwood. *Building Environment* 42:62-67.