ISSN impresa 0717-3644
ISSN online 0718-221X

Maderas. Ciencia y tecnología 21(4): 433 - 446, 2019

DOI: 10.4067/S0718-221X2019005000401

EVALUATION OF DIMENSIONAL STABILITY, SURFACE ROUGHNESS, COLOUR, FLEXURAL PROPERTIES AND DECAY RESISTANCE OF THERMALLY MODIFIED *Acacia auriculiformis*

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ABSTRACT

This paper presents the effect of thermal modification of 14-15 year-old plantation grown *Acacia auriculiformis* wood in the 150-240ºC temperature range under vacuum condition. Important techno-mechanical parameters of thermally modified wood such as density, dimensional stability, colour, surface roughness, decay resistance against brown and white rot fungi and flexural properties were evaluated and compared with control. Depending on severity of heat treatment, colour of modified sapwood was turned from light to dark brownish. Moreover, the change in colour was found to be uniform throughout the thickness of wood blocks. Amount of shrinkage of *Acacia auriculiformis* wood was observed to be decreased with increasing treatment temperatures. Maximum dimensional stability of wood thermally modified at 240ºC was in the range of 60-65%. The surface roughness parameters (R_a and R_z) were reduced significantly after the treatment. The flexural strength (modulus of rupture-MOR) was observed to be reduced with increasing treatment temperatures. However, flexural stiffness (modulus of elasticity-MOE) was not found to be affected significantly up to 210ºC temperature. The lower amount of weight loss of thermally modified wood compared to untreated control showed improved decay resistance against white and brown rot fungi. With desirable improvements in various esthetic and technologically important quality parameters such as enhanced dimensional stability, biological durability against fungi and certain other properties, thermally modified wood from short-rotation *Acacia auriculiformis* may be considered as viable alternative to scarcely available timber resource for different value-added applications.

Keywords: Density, heat treatment, MOR, MOE, plantation species, shrinkage.

INTRODUCTION

Because of the rapid industrialization and increasing population, forest wealth is depleting at a rapid rate. Thus, it has become imperative to make use of fast grown plantation species for various timber applications. But, most of fast growing plantation speciesgenerally contains a high proportion of juvenile wood. The wood of such species is often characterized by certain inherent material problems such as low dimensional stability, low mechanical properties and poor decay resistance against bio-deteriorating agents. These are mostly accepted as undesirable features for many timber applications. Selection of decay resistant and dimensionally stable wood species for a specific use, therefore, plays an important role in achieving its most economic utilization. Moreover, efficient usage of locally grown wood resource from plantations as a source of raw material is very important for growth of wood-based industry. In order to overcome one or more limitations, wood material is generally modified by thermal or chemical techniques so as to improve certain quality parameters specific to various end-use requirements (Gerardin 2016, Hill 2006, Rep and Pohleven 2001). Thermal modification

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Received: 09.11.2018 Accepted: 24.05.2019

of wood is mostly performed at higher temperatures (below 250ºC) depending on the required level of product performance and species. Heat treatment process is found to provide wood with certain novel properties by changing its behavior (Bakar *et al*. 2013, Esteves and Pereira 2009, Niemz and Bekhta 2003). Moreover, changes in wood characteristics are achieved without adding toxic chemicals/preservatives. Thermally modified wood exhibits improved performance and provide value-addition to traditionally poor quality woods as a substitute for certain high value tropical species (Kim *et al*. 1998, Shukla and Sharma 2014, Shukla and Sharma 2018). Many fast grown plantation woods having lower commercial value can be thermally modified so as to become new source of raw material for the timber industry. At the same time, this process also has huge growth potential due to gradual banning of chemically treated wood for environmental reasons (Gerardin 2016).

Acacia auriculiformis from Leguminosae family is a fast-growing medium sized tree native to coastal lowlands of Northern Australia, Papua and New Guinea. Because of its ability to grow on very poor soil and in areas with an extended dry season, it has been introduced into countries such as India, Indonesia, Malaysia, Tanzania and Nigeria. Initially, this species was grown in India to meet the demand of pulp and fire wood. It is mostly raised in plantation forestry under many afforestation programmes in the country and also planted in agro-fields, as well as shelter and ornamental tree.Detailed studies on various physical and mechanical properties of *A. auriculiformis* woodhave showed that this timber can be utilized for joinery, tool handles, turnery articles and for construction purposes (Shukla *et al*. 2007). One of the most important drawbacks of wood from this species is its lower dimensional stability (Shukla *et al*. 2007) and low durability of sapwood (Ashaduzzaman *et al.* 2011, Sundararaj *et al*. 2015). The natural decay resistance of *A. auriculiformis* was evaluated by accelerated decay test method against white rot fungus. The average weight loss in sapwood was found to be 22,19% (Ashaduzzaman *et al.* 2011) which is considered to be not durable and require treatments to improve the service life.

The fast grown plantation timbers may be subjected to thermal modification at high temperatures under inert environment to improve the dimensional stability, colour and decay resistance. This process is expected to open up certain potential applications taking advantage of the chemical free process. Various chemical changes occurring during thermal treatment invariably lead to the alteration in various wood properties (Esteves and Pereira 2009, Kamdem *et al.* 2000, Kamdem *et al.* 2002, Obataya and Tomita 2002). The effect of steam pretreatment on wood was investigated by various researchers (Inoue *et al.* 1993, Inoue *et al.* 1996, Kawai *et al.*1992). The effect of heat on dimensional stability of compressed wood is reported by Dwianto *et al.* (1996) while thermo-hygro-mechanical treatment for producing densified wood with stable deformation was carried out by Navi and Girardet (2000). During heat treatment, there are considerable changes in chemical composition of wood (Hofmann *et al*. 2008). Various chemical changes invariably lead to the alteration of various physical properties of wood (Obataya *et al.* 2000, Obataya and Tomita 2002). Repellin and Guyonnet (2005) investigated the effect of treatment temperature and duration on swelling behavior of heat-treated wood. Not much research work is reported in the literature on effect of heat treatment of *A. auriculiformis*on various wood properties. The aim of the present study was to investigate the effect of heat treatments of *A. auriculiformis* wood at different temperatures under vacuum on certain important quality parameters such as density, shrinkage, colour, surface roughness, decay resistance against brown and white rot fungi and flexural properties. The improved characteristics of thermally modified wood are expected to offer the timber industry an alternate timber resource for producing various value-added wood products.

MATERIALS AND METHODS

Wood

Ten logs of plantation grown14-15 year-old *Acacia auriculiformis* A. Cunn. Ex. Benth trees were selected for processing and converted into thirty wooden planks of the size 1,8-2,4 m length, 15-25 cm width and 5,0-7,5 cm thickness. The planks were stacked for drying under the shade having good ventilation for about 6 months to obtain the equilibrium moisture content (EMC) in the range 10±3%. The seasoned material was used for further conversion and processing into test specimens of different sizes as specified in Indian standards (IS 1708-1986).

Heat treatment

Heat treatment was carried out by in a microprocessor controlled camber. Three steel meshes were used in which the wood samples were placed inside the oven. For an 8 h heat treatment, total cycle was about 48 h including initial heating ramp of about 8 h, conditioning at 105ºC for about 10 h followed by ramping to actual target temperature in about 15 h and finally cooling down slowly in about 15 h. All the heating and cooling processes were carried out inside an oven under vacuum (below 10 milli bar). During actual heat treatment phase, temperature was increased to desired level between 150 to 240°C and remained constant for duration up to a maximum of 8 h. Conditioning of treated wood samples was carried out at 23±3°C temperature and 65±5% relative humidity in a conditioning chamber to bring them to equilibrium moisture level.

Testing of properties

The test samples of untreated control and heat treated wood species were prepared and different physical, mechanical and biological properties were tested. Volumetric shrinkage and flexural properties were evaluated following standard procedures as laid down in IS1708- 1986. Flexural tests were performed on a 50kN capacity universal testing machine (Shimadzu AG-50) installed in a conditioning chamber set at 23±3°C temperature and 65±5% relative humidity. Following procedures were adopted for various tests.

Density

The specimen size was 2×2 cm^2 in cross-section and 6 cm in length. Eight specimens of each heat treatment and untreated control wood were weighed correctly to 0,001g and dimensions were measured correctly to 0,01 mm. Density (D) of wood specimens was calculated using the following Equation 1:

$$D = W / V \qquad (1)$$

Where W and V are weight (kg) and volume (m^3) of test specimen respectively.

Volumetric shrinkage

Test specimens were 2×2 cm^2 in cross-section and 6 cm in length. Six specimens from each treatment were weighed initially correctly to 0,01 g and volume was determined by immersion method. Specimens were allowed to air-dry and weighed periodically, then kept in an oven at 103±2°C until an approximately constant weight is reached. After oven-drying, specimens were weighed and volumes were determined again. Volumetric shrinkage (S) from initial condition to oven-dry condition is computed as follows Equation 2a:

$$\mathrm{S}(\%) = \left(\left(\mathrm{V}_1 - \mathrm{V}_0\right) / \mathrm{V}_1\right) \times 100 \qquad (2a)$$

Where V_1=volume in cc at initial condition (usually green), V_0=volume in cc at the oven dry condition. The anti-shrinkage efficiency (ASE) was computed using average total volumetric shrinkage of untreated (S_1) and treated (S_2) wood samples using following Equation 2b:

$$ASE(\%) = \frac{S_1 - S_2}{S_1} \times 100 \qquad (2b)$$

Surface roughness

Effect of thermal modification of wood at different temperatures under vacuum was studied on the surface properties. Surface roughness profile of *A. auriculiformis* wood was measured using a stylus-based profilometer (Mitutoyo Surftest SJ-401) before and after heat treatments (Shukla and Sharma 2014). The measuring speed, pin diameter, and pin top angle of the tool were 10 mm/min, 4 µm, and 90° respectively. Five to six points of roughness measurement were randomly marked on the surface of three wood samples from each treatment. Measurements were carried out in the fiber direction (along) and in perpendicular to the fiber direction (across).Two roughness parameters viz., arithmetical mean roughness (R_a) which is average distance from the profile to the mean line over the length of assessment and mean roughness (R_z) were used to evaluate surface roughness characteristics of heat treated wood.

Surface colour

The LabScan XE system (Model: LSXE-2, LSXE/VSI-2) from Hunter Associates Laboratory, Inc., Virginia was used for measuring colour parameters (L, a, b) in a wavelength range of 400-700 nm. In CIELab system, total change of color, ΔE*, is commonly used to represent a color difference: Δ*L** is difference in lightness $L^*-L^*_{control}$, Δa* is difference in a* coordinates $a^*-a^*_{control}$, Δb* is difference in b* coordinates $b^*-b^*_{control}$ where $L^*_{control}$, $a^*_{control}$ and $b^*_{control}$ are mean values of these colour components for untreated control sets, and L*, a* and b* are colour variables of each treated specimen. For maximum stability, the instrument was standardized to an internal reference tile once every 4-5 h during color measurements. Before and after heat treatment, L*, a* and b* color coordinates of each sample were used to calculate total colour change according to following Equation 3a and Equation 3b:

$$\Delta L^* = L^*_{ht} - L^*_i ; \Delta a^* = a^*_{ht} - a^*_i ; \Delta b^* = b^*_{ht} - b^*_i \qquad (3a)$$

$$\Delta E = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{1/2} \qquad (3b)$$

Where ΔL*, Δa*, Δb* are changes between untreated and treated values. L*, a*, b* contribute to total color change ΔE.

Flexural properties

For flexural properties (3-point static bending test), 20 specimens of the size 2×2×30 cm^3 were selected as specified in IS:1708-1986 from each treatment. The span length and rate of loading was kept constant at 28,0 cm and 1,0 mm/min respectively. Load was applied on tangential surface nearer to heart of each specimen. Two different flexural parameters: modulus of rupture (MOR) and modulus of elasticity (MOE) were computed using following Equation 4a and Equation 4b:

$$\mathrm{MOR} = (3 \times P_{max} \times l) / (2 \times b \times h^2) \qquad (4a)$$

$$\mathrm{MOE} = (P \times l^3) / (4 \times D \times b \times h^3) \qquad (4b)$$

Where:

P - load at the limit of proportionality (kN)

$\mathbf{P_{max}}$ - maximum load (kN)

l - span of the test specimen (mm)

b - breadth of the test specimen (mm)

h - depth of the test specimen (mm)

D - deflection at the limit of proportionality (mm)

Decay resistance against fungi

Decay resistance of heat treated *A. auriculiformis* wood was determined against two types of fungi, viz. brown rot (*Polyporus meliae*) and white rot (*Coriolus versicolor,*also known as *Trametes versicolor* and *Polyporus versicolor*). Six small cubic blocks measuring 20×20×20 mm^3 of control and heat treated *A. auriculiformis* wood were tested by adopting modified Aagar block (Kolle flask) procedure as prescribed in IS:4873 (Part-1)with a slight variation in the size of the test blocks (IS 4873-2008). A mixture of the nutrient medium consisting of agar and malt extract (1:1 wt %) was prepared in a liter of distilled water. The medium was inoculated with the test fungi within 6 days after preparation of the flasks. Test blocks were exposed to the fungal attack of brown and white rots separately by placing them in flask having actively growing cultures of two fungi. The bottles containing the test blocks were placed in an incubator at 25±1°C and 70±4% relative humidity and kept there for a period of 12 weeks. At the end of the incubation period, exposed blocks were removed and mycelium was cleaned properly. The blocks were then dried at 30°C to constant weight. Finally, weight of the blocks was recorded to determine the weight loss (WL) caused by the fungal decay Equation 5:

$$WL(\%) = \left[\left(W_i - W_t \right) / W_i \right] \times 100 \quad (5)$$

Where:

$\mathbf{W_i}$ - weight of wood block before test (g)

$\mathbf{W_t}$ - weight of dried block after test (g).

Statistical analysis

Variation in the density and flexural properties of treated and untreated wood were compared and analyzed by one-way analysis of variance (ANOVA) at the 5% level of significance using with SigmaStat statistical software (Systat 2004).

RESULTS AND DISCUSSION

Heat treatment of wood material at high temperature causes a lot of chemical and physical changes into the wood. Certain volatile organic compounds and extractives present in the wood material get evaporated during the process of heat treatment. The change in the physical properties of wood is realized through the transformation of chemical components and through the alteration of the wood structure (Hill 2006, Hofmann *et al.* 2008, Niemz *et al*. 2010).

Density and EMC

Table 1 summarizes mean density values of wood heat treated at different temperatures under vacuum. Percentage change in density of thermally modified wood compared to untreated control showed that heat treatment temperatures up to 210°C did not alter it much (7,7%). However, higher heat treatment temperature of 240°C caused greater reduction in the range of 14-15%. Similarly, no significant variations were observed in density of wood heat treated to different durations at the same temperature for lower than 210°C. The average EMC was also found to be strongly affected by heat treatment process. EMC of wood samples was found to be drastically reduced depending on severity of heat treatments. It was observed that heat treated *A. auriculiformis* wood has average EMC in the range of (6±1%) compared to untreated wood (12±1%). Reduction in the EMC of heat-treated wood has shown influence not only on the dimensional stability (shrinkage and swelling), but on many other important wood properties. The changes in hygroscopic properties of wood are mainly caused by degradation of hemicelluloses due to high temperature heating. During this process, the organic acid coming from hemicelluloses creates an acidic environment which is combined with high temperature to break down the lignin-polysaccharide linkages in wood structure. This process changes the wood from a hygroscopic to hydrophobic material (Wikberg and Liisa 2004). Water absorption of wood after heat treatment is thus reduced because a large number of hydroxyl groups (-OH) of carbon-hydrogen compounds are reported to be decreased (Nakano and Miyazaki 2003).

Table 1: Density and EMC of *A. auriculiformis* wood heat treated at different temperatures.

Property	**Untreated wood**	**Treatment temperatures (8h)**			
		150°C	**180°C**	**210°C**	**240°C**
Density (kg/m^3)	702,80± 64,83 ^{a}	671,81± 77,03 ^{ab}	657,74± 67,78 ^{b}	648,48± 72,43 ^{b}	599,58± 56,10 ^{c}
% Change	-	4,41	6,41	7,73	14,69
EMC (%)	11,80± 0,82 ^{a}	7,29± 0,63 ^{b}	6,93± 1,12 ^{b}	4,94± 0,58 ^{c}	4,57± 0,43 ^{c}
% Change	-	38,2	41,3	58,2	61,3

Mean values (±standard deviations) in the same row followed by the identical letters are not statistically significantly different at level of 5%, Tukey Test).

Dimensional stability

Real-time tangential swelling profile of *A. auriculiformis* wood heat treated in vacuum for 8 h at different temperatures is shown in Figure 1. Wood sample starts swelling first at higher rate and then slowly levels-off to certain value. The rate of swelling was found to decrease with increasing heat treatment temperature of wood. Total tangential swelling of untreated control wood was highest and heat treatments of wood systematically reduced the amount of total saturated swelling as shown in the real-time graph. Similarly, volumetric shrinkage was found to be reduced with increasing treatment temperature. A linear relationship of the form: S = (-) 0,06T+17,92 (R^2=0,98) was observed between volumetric shrinkage (S) and treatment temperature (150≤T≤240). The percentage of reduction of total volumetric swelling of wood treated at 240°C was about highest compared to untreated control.

The anti-shrinkage efficiency (ASE) of *A. auriculiformis* wood heat treated at different temperatures for 8 h duration is depicted in Figure 2. The ASE values of wood were found to increase with the temperature of heat treatment. Higher treatment temperatures made the wood more dimensionally stable as shown by increasing ASE values (up to 65%). Chu (2013) reported that the dimensional stability (anti-swelling coefficient) of *Acacia mangium* wood was increased by about 15-46% afterheat treatment at high temperature (170-210°C.) in air. The results also indicated that both treatment temperature and treatment duration significantly affect the wood properties of this species. As explained above, heating process is known to cause various changes in the chemical structure of wood. First, hemicelluloses start to degrade resulting in the reduction of -OH bonds and formation of O-acetyl groups. With subsequent cross-linking between wood fibers, wood becomes more hydrophobic. Reduction in water absorption causes a decrease in swelling and shrinking of wood leading to improved dimensional stability. Repellin and Guyonnet (2005) also investigated the effect of treatment temperature and duration on swelling behaviour of heat-treated wood. Increased temperature and longer duration of heat treatment resulted into reduced wood swelling. Modification of cell-wall structure and changes in sorption properties due to decomposition of hydrophilic hydroxyl-groups are considered to be responsible for lower water absorption, improved dimensional stability and durability of thermally modified wood. Reduction of adsorption sites along with structural changes in process of heat modification were suggested to be responsible for reduced swelling and shrinkage of heat treated wood. Therefore, changed cell wall chemistry has been attributed to improved dimensional stability and reduced water absorption capacity of heat treated wood

(Metsa-Kortelainen *et al.* 2006).

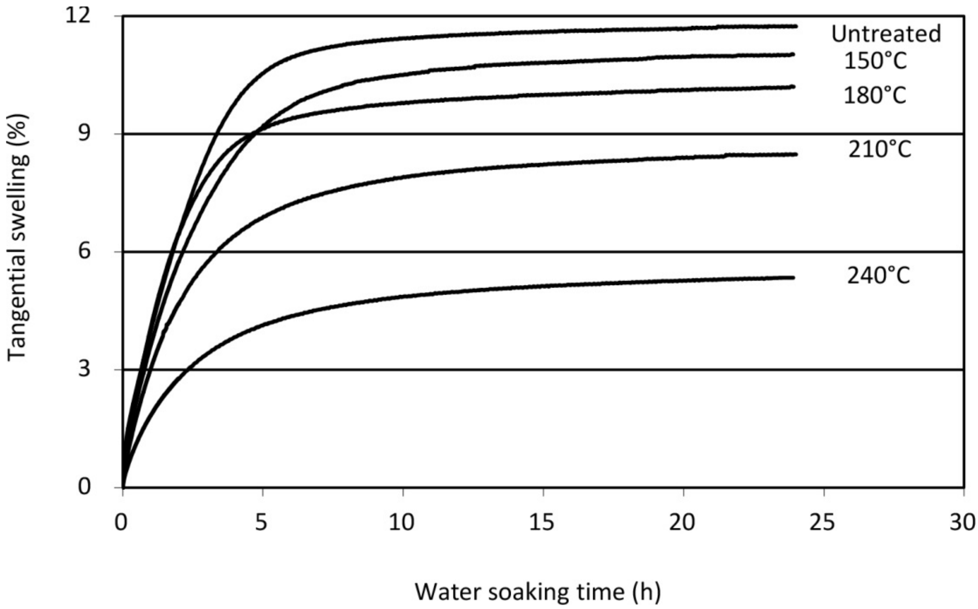


Figure 1: Real-time tangential swelling profile of heat treated *A. auriculiformis* wood.

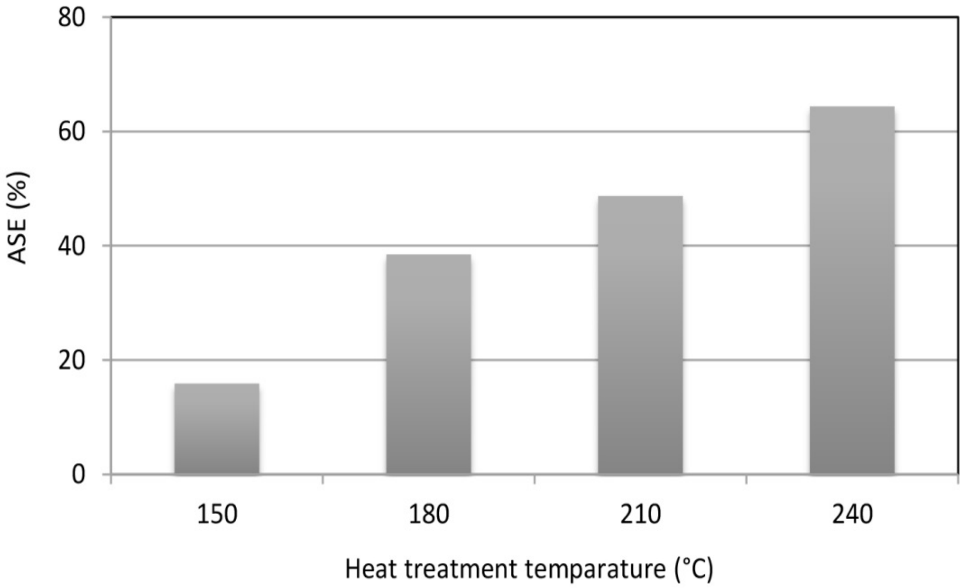


Figure 2: ASE of *A. auriculiformis* wood heat treated for 8h at different temperatures.

Surface roughness

Figure 3a and Figure 3b show the effect of heat treatment on surface roughness profiles of wood before and after thermal modification at 180ºC for 8 h. Heat treated wood showed lower value of R_a (=3,14μm) compared to untreated (R_a=4,54μm) wood samples. The results showed that surface roughness values decreased with increasing treatment temperature and duration. Figure 4a and Figure 4b depict average R_a and R_z values measured before and after heat treatments at different temperatures for 8 h along and across the grain on the surface of wood samples.

The average R_z values were much lower for both along and across the grain after thermal modification of wood samples. Similarly, surface profile parameters (R_a and R_z) of wood were found to be (5,72 and 39,8 µm) and (3,87 and 24,5 µm) respectively before and after heat treatment at 180°C for 8 h. These observations showed that roughness parameters of wood were much higher in the direction across the fibers compared to along the fiber. The wood surface turned smoother in both directions after heat treatments. Korkut and Akgul (2007) reported effect of high processing temperatures on surface roughness characteristics of wood veneers. It was concluded that these wood species may be utilized by using proper heat treatment techniques in areas where working, stability, and surface smoothness are important factors such as in floorings, furniture, window frames (Gunduz *et al.* 2008).

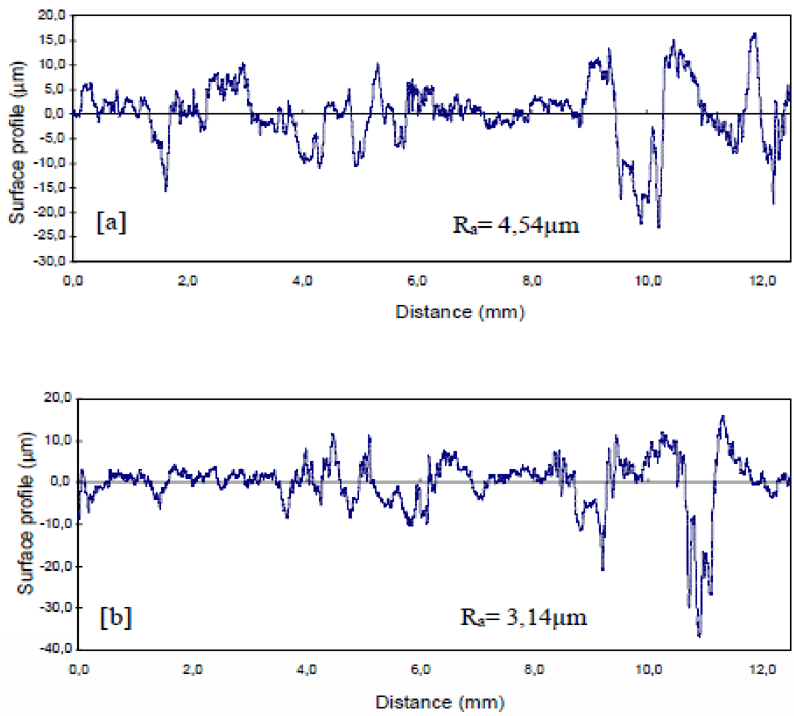
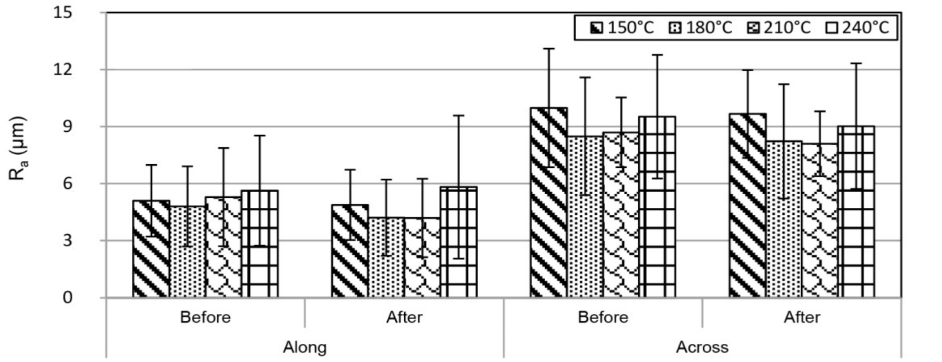


Figure 3: Surface profiles of *A. auriculiformis* wood before (a) and after (b) heat treatment at 180ºC for 8 h.

Colour changes

The colour variations were examined by means of amount of color difference before and after the thermal modification at different temperatures and durations under vacuum. Figure 5 shows the colour variations (ΔE) in wood heat treated at different temperatures for 8 h in vacuum. With increasing temperature of heat treatment, wood colour was seen dark brownish. The colour change was observed to be uniform though out the wood blocks. The mean colour values of wood heat treated at different temperatures were found to be significantly different ($F=53,87$; $P<0,001$). Pairwise multiple comparisons (Tukey test) showed no statistically significant difference in colour of wood surface heat treated at 150 and 180°C ($P=0,167$).



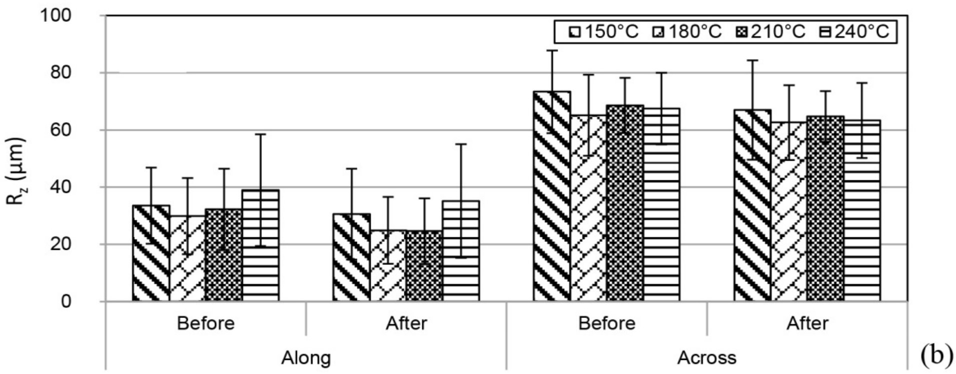


Figure 4: Average values of (a) R_a and (b) R_z of *A. auriculiformis* along and across the grain.

The observations on changes in colour are very important to evaluate the performances of wood towards colour acceptability, stability in various end-use applications. The colour of treated wood material was found to be uniformly changed throughout wood blocks. Increasing heat treatment temperatures have profound and variable effects on the colour changes of different wood species. With increasing treatment intensity, delta E-value was increased, showing that colour of wood surface became darker. However, no significant relationship between colour and other properties could be established. Depending on the severity of thermal modification process, the wood colour was changed from original to uniform dark brownish tones. Heat treated wood can therefore be successfully applied for wall paneling, siding, flooring tiles etc. due to its uniform colour change to darker, brownish colour, better moisture resistance and increased dimensional stability. It may be especially attractive to use heat treated *Acacia* wood for parquet flooring since it is possible to obtain different dark brownish colours of different shades by varying the process parameters (Emmler and Scheiding 2007).

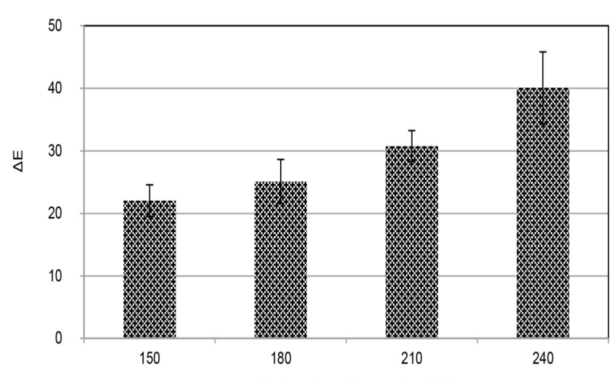


Figure 5: Colour variations (ΔE) in *A. auriculiformis* wood heat treated for 8 h.

Flexural properties (MOR and MOE)

Table 2 lists average values of flexural strength (MOR) and flexural stiffness (MOE) of *A. auriculiformis* wood heat treated at different temperatures along with standard deviations. Percentage of change compared to untreated wood is also given in the same table. Heat treatment temperature has significant effect on MOR (F=27,25; P<0,001). There was no significant difference between MOR of untreated and wood heat treated at 150°C (P=0,729) and 180°C (P=0,136). The moderate reduction in MOR was noticed up to 210°C temperature while higher temperature of 240°C was found to be detrimental to flexural strength and MOR was reduced drastically compared to untreated control (P<0,001). MOE of heat treated wood was not much affected with increasing temperatures. A slight enhancement in average values of MOE was observed in wood samples thermally modified at 150°C and 210°C. However, higher temperature of 240°C has affected the MOE significantly which was observed to be decreased by 14% compared to untreated control (P<0,001).

Variation of relative MOR of heat treated to untreated wood with weight loss (%) due to heating process at different temperatures is shown in Figure 6. Some of the changes in the wood properties due to heat treatment such as strength are linked with various processes parameters (Hill 2006). The increase in the strength loss with increasing heat treatment temperature while MOE found to be rarely affected is also reported in the literature (Kubojima *et al.* 2000). The reduction in strength properties is mainly attributed to decrease in viscosity and plasticity of material (Kubojima *et al.* 2000). The degradation in strength has also been associated with changes in wood acidity (Hodgin and Lee 2002) while both strength loss and durability increases are reported to be closely related with the temperature and duration of heat treatment (Kim *et al.*1998). In general increased treatment intensity was found to affect the flexural strength of heat treated wood. Since the intensity of the treatment correlates with the colour of the wood it also can be generally followed that the darker the wood the lower the flexural strength (Hill 2006, Niemz *et al.* 2010).

Table 2: MOR and MOE of *A. auriculiformis* wood heat treated for 8 h under vacuum.

Flexural properties	Untreated wood	Treatment temperatures			
		150°C	180°C	210°C	240°C
MOR (MPa)	111,6±10,7	116,8±13,9	100,9±13,1	97,7±7,8	44,3±6,5
% Change	-	4,7	-9,6	-12,5	-60,3
MOE (GPa)	10,65±1,08	11,21±1,70	11,15±0,84	12,11±1,39	9,14±1,36
% Change	-	5,3	4,7	13,7	-14,2

The changes in various properties are mostly influenced differently by the change of chemical parameters in different wood species (Windeisen *et al.* 2007, Windeisen *et al.* 2009). The bending strength is reported to be decreased in the hardwoods with increasing total phenol content. While heating up wood, the lignin is first softens, radicals are formed in the depolymerisation reactions that in turn are recombined to the chemical compounds of lower polarity. In this process, the hygroscopicity of lignin is found to decrease significantly (Tjeerdsma and Militz 2005, Windeisen and Wegener 2008). Transformation of lignin (i.e. increasing amounts on phenolic extractives in wood) seems to be closely correlated with decreased bending strength in hardwoods. A reduction in the hemicelluloses content is also found to be increased in total phenol concentration. During thermal degradation of hemicelluloses, the lignin-carbohydrate connections are also reported to be cleaved leading to the easier depolymerisation of this non-carbohydrate-bonded lignin fraction, yielding simple phenolic compounds. It seems that there is also a clear connection between a reduction in bending strength and hemicelluloses content. This establishes that in hardwoods, physical changes take place during degradation of hemicelluloses. Similarly, strong degradation of hemicelluloses through thermal treatment of wood has also been shown by several researchers (Pfriem and Wagenführ 2007). Understanding the varied behaviour of different types of wood elements during thermal treatment could therefore provide a basis for wood species dependent technology optimization in the future (Hofmann *et al.* 2008).

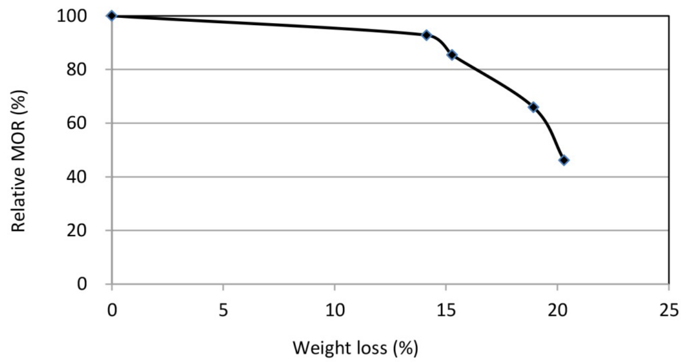


Figure 6: Variation of relative MOR of treated to untreated *A. auriculiformis* with weight loss.

Decay resistance against fungi

Unmodified and heat treated wood samples were degraded by white-rot (*Coriolus versicolor*) and brown-rot (*Polyporus meliae*) fungi. Weight loss (WL) due to white and brown rot decay in heat treated and untreated wood is shown in Figure 7. It may be seen that untreated samples exhibited higher amount of WL against both decay fungi compared to heat treated wood blocks. Increasing intensity of heating temperatures has shown significant effect on the WL of wood blocks due to decay fungi. WL less than 10% was recorded in the wood blocks heat treated at 180°C and above for both the decay fungi. Compared to brown rot, higher amount of WL (%) was recorded due to white rot decay in untreated wood samples. However, heat treated wood blocks exposed to brown rot showed lower amount of WL compared to white rot fungi. Wahab *et al*. (2012) also reported that oil-heat treatment was effective in reducing the attack of *Acacia* hybrid wood by *G. trabeum, P. sanguineus* and *C. versicolors* fungi. The percentage of weight loss was found to be decreased as temperature and duration increased.

Heat treatment of wood may be one of the most promising techniques to increase the decay resistance against decay fungi. It is well known that white rot of wood digest lignin rather than cellulose; while brown rot digests the cellulose, but leave lignin behind. Results showed different behaviour of resistance against white and brown rot fungi. Lignin is the least reactive wood component, but at high temperatures, bonds within the lignin complex will be cleaved, resulting in a higher concentration of phenolic groups (Kollmann and Fengel 1965). Some of the major reasons of improved durability of heat treated wood are: hydrophobic character of heat treated wood, generation of biocidal components, modification of wood polymers, degradation of hemicelluloses and reduction in cell wall porosity (Esteves and Pereira 2009, Kamdem *et al*. 2002, Niemz *et al.* 2010, Wahab *et al.* 2012). The reduction in average EMC contributes in retarding the rate of fungal attack (Metsa-Kortelainen and Viitanen 2010).

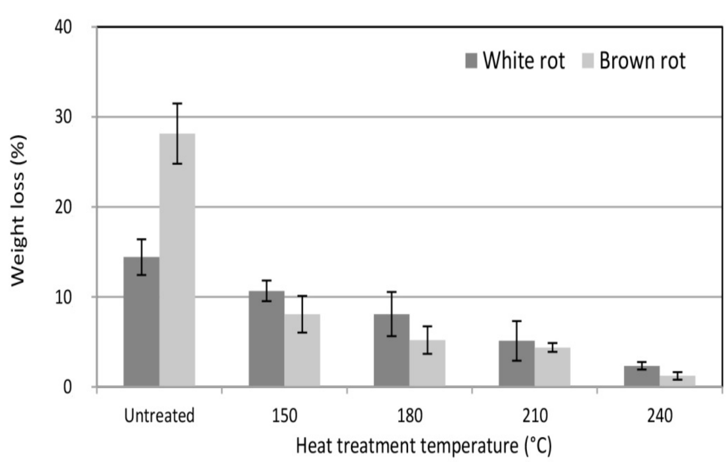


Figure 7: Weight loss due to white and brown rot fungi decay heat treated *A. auriculiformis.*

Various chemical changes during heat treatment invariably lead to modification of various properties of wood (Windeisen *et al*. 2007, Windeisen *et al*. 2009). It was found that thermal modification is an eco-friendly process that turns wood dimensionally stable and darker in colour without using any hazardous chemicals. Heat treatment process is also found suitable for improving the decay resistance of low durability wood (Gerardin 2016). Information on outdoor durability of heat treated *A. auriculiformis* wood against termite attack is being collected and would be reported elsewhere. This would certainly help in bringing awareness for better utility and value-addition to fast growing plantation species an alternate wood resources by using thermal processing technique.

CONCLUSIONS

Plantation grown *A. auriculiformis* wood was subjected to different heat treatments under vacuum and various physical, mechanical and biological properties were evaluated. Density and shrinkage of wood were found to be reduced significantly after thermal modification. The anti-shrinkage efficiency was increased up to 65%. Surface roughness parameters (R_a and R_z) were also observed to be reduced depending on thermal treatments. At different temperatures, R_a values measured along the grain were significantly lower compared to across the grain. Changes in colour due to heat treatment are measured with colorimeter and found to be darkening with higher temperatures. The colour change was also observed to be uniform throughout wood. Flexural strength was found to decrease slightly with increasing treatment temperature up to 210°C. Flexural stiffness (MOE) was not much affected by temperature up to 210°C while higher treatment temperatures were found to be deleterious for flexural strength and stiffness. Heat treated wood showed excellent decay resistance against brown and white rot fungi.Based on improved dimensional stability, colour, fungal decay resistance and certain other properties, *A. auriculiformis* wood may be used as an alternative to conventional timbers for various applications after moderate heat treatments below 210°C under vacuum. Thus, thermal modification provides an environmentally safe method of protecting sustainable timber species and offer a new generation of value-added wood material with enhanced stability and durability without using hazardous chemicals.

ACKNOWLEDGEMENTS

The author is grateful to the Director, IWST for his keen interest in this research work. Valuable help from technical staff in testing mechanical and biological properties is duly acknowledged. Author is also grateful to Indian Council of Forestry Research and Education (ICFRE), Dehradun for providing financial support in executing the research project.

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