Effect of Thermal Modification on Physical and Mechanical Properties of *Brachystegia spiciformis* and *Julbernardia globiflora* from Mozambique

Feliz Nhacila Jr1, Eunice Sitoe1, Ernesto Uetimane Jr1, Alberto Manhica2, Andrade Egas1, and Veikko Möttönen3*

[1]Eduardo Mondlane University
Faculty of Agronomy and Forest
Engineering, Maputo, 257,
Mozambique

[2]Agrarian National Research
Institute Ministry of Agriculture
Maputo, 3658, Mozambique

[3]Natural Resources Institute Finland,
Production systems, 80100 Joensuu,
Finland

*Corresponding author: E-mail veikko.mottonen@luke.fi, phone +358295325053

Abstract

Msasa (Brachystegia spiciformis Benth.) and red msasa (Julbernardia globiflora Benth. Troupin) are the most abundant tree species in the Miombo forests in Mozambique. However, they are hardly used for any high value added wood products due to the lack of knowledge about the properties of their wood. Furthermore, the timber of both species (especially the light coloured sapwood section) is characterised by very low resistance against fungal and insect attack. In this study, three different intensities of thermal modification were used to treat the sawn timber of both species and afterwards assess wood properties responses, namely mass loss, equilibrium moisture content, oven-dry density, colour change and selected mechanical properties. Both thermally modified and untreated specimens were prepared according to ISO standards.

The results shows that the untreated light coloured sapwood of both wood species darkened gradually as the thermal treatment intensity increased. The contrasting colour between sapwood and heartwood sections nearly disappeared and levelled for samples exposed to the highest treatment intensity. On average all tested wood properties changed significantly after the most intense treatment level was applied. Despite degradation of mechanical properties in both species, an optimal combination of temperature and treatment time was possible to achieve. The study concluded that the overall recorded changes of the tested wood properties in both species increase the range of applications including the new appealing colour resembling the most appreciated and sought after tropical hardwoods.

Keywords: Brachystegia spiciformis, Julbernadia globiflora, Thermal modification, colour changes, physico-mechanical properties,

BRIEF ORIGINAL

Mozambican msasa (*Brachystegia spiciformis*) and red msasa (*Julbernadia globiflora*) boards were heat treated using three different thermal modification temperature: 215, 230, and 245 °C. Changes in density, modulus of elasticity, modulus of rupture, Brinell hardness and compression strength between untreated and thermally modified wood were studied.

1. INTRODUCTION

The world's fast growing population and associated wood consumption is outpacing the natural forests' capacity to meet the demand, particularly in the tropics where in spite of high diversity of wood species, very few are selectively harvested in unprecedented alarming rates (Uetimane et al. 2018). A large number of tropical hardwood species is overlooked due to the poor knowledge on their timber properties including the local lack of cost effective technologies to process into competitive end products. This is particularly true for the group of light coloured and perishable timbers where toxic chemicals must be impregnated to ensure prolonged service life.

Therefore, environmental concerns on toxic chemicals impregnated in wood to enhance its properties have triggered research on alternative and environmental friendly wood processing methods such as thermal modification. This approach consists basically on exposing pre-kilned wood to high temperature ranges (180 - 250 °C) for relatively short periods resulting in changes to its natural structure. Typically, during thermal modification the wood is exposed to permanent changes in its colour, physico-mechanical properties and chemical structure. In general after thermal treatments, light coloured wood species tend to acquire darker tones resembling some natural dark coloured endangered and precious tropical hardwoods. Another typical acquired feature is improved resistance to biodegradation somewhat associated to acquired hydrophobicity compared to untreated solid wood (Hill 2006; Dubey 2010; Srinivas and Pandey 2012; Militz and Altgen 2014).

In Mozambique, wood thermal modification could be a suitable technology for processing non-durable lesser known/lesser used species such as Brachystegia spiciformis and Julbernadia globiflora. If successfully applied, this technology could potentially open new market opportunities as well as saving overexploited wood species (Sosef et al. 1998; Peres 2010).

Despite enjoying a large share of the Mozambique forest growing stocks (Marzolli 2007) both Brachystegia spiciformis (msasa) and Julbernardia globifora (red msasa) timbers are interchangeably mainly used for railway sleepers after pressure impregnation in creosote treatment plants. This decay resistive but toxic processing option restricts a wider range of uses. Therefore, this study is aimed at assessing wood properties responses induced by different thermal treatment levels of both B. spiciformis and J. globiflora. It is expected that a friendly environmental processing technology such as the thermal modification will ensure improved properties of a group of lesser used species which could enable their use for both indoor and outdoor applications and relieve pressure on the most sought after timbers across the country.

2. Materials and methods

2.1 Material and samples origin

The samples of Brachystegia spiciformis and Julbernadia globiflora were obtained from 10 mature undated dominant trees (five of each species) growing in humid miombo natural forests of Cheringoma district, Sofala province, Mozambique (S 18°45'21,9" E 034°55'27,1"). The identities of tree species were confirmed at the Eduardo Mondlane University Xylarium through vouchered reference specimens. A batch containing 121 planks of Brachystegia spiciformis and 64 planks of Julbernadia globiflora was transported to Luxhammar Ltd. (Mikkeli, Finland) where the thermal modification treatments were carried out. For the experiment, pre-kiln dried sapwood planks – nominal size (600 × 50 × 25mm3) (Long × Radial × Tang) of both species (average of 12% moisture content) – were exposed to three thermal treatment levels and distributed in the following sub-sets as shown on table 1. All sample lengths were shortened to length of 500mm to fit the thermal modification chamber.

2.2 METHODS

2.2.1 BRIEF DESCRIPTION OF THE THERMAL MODIFICATION METHOD

The wood specimens of both tree species were heat treated by the Luxhammar thermal modification process method developed by Luxhammar corporation (Luxhammar 2019). The entire thermal modification process consists of five different stages: Initial heating (temperature raised to 100°C), preconditioning and drying, actual thermal modification with high temperature up to 250°C, conditioning (restoration of moisture), and cooling. The processes in this study were carried out in an air tight stainless steel kiln chamber (research sized) using three temperature range intensities, 215°C (T1), 230°C (T2) and 245°C (T3), for 2 hours at saturated steam environment. Due to the shortage of wood material of Julbernardia globiflora, it was not included in the T3 treatment. However T3 treatment was used for Brachystegia spiciformis to enable also the further studies on the effects of different treatment processes on resistance to decay and termites of miombo wood species. The reference (untreated) specimens were separated after the pre-drying in convention drying kiln to the target moisture content of 10–12%.

2.2.2 ASSESSMENT OF WOOD PROPERTIES RESPONSES TO THERMAL MODIFICATION

For all subset of specimens the following wood properties listed in table 2 were tested before and after each thermal treatment level using untreated samples as reference control. Statistical differences between untreated samples and each treatment level within each wood species were calculated by mean of Tukey's multiply range test at $p < 0.005$. The mechanical tests were performed using the universal material testing machine Zwick Z050 (Germany) according to specific standards listed in the Table 2.

The mass loss (ML) of all specimens was calculated by weighing before and after each thermal treatment level and expressed in %. Specimens from each treatment were oven-dried to absolute dry weight and compared to monitor changes of the oven-dry density. Likewise, after each treatment the specimens were left in standard room climate (20, 65% relative humidity) until equilibrium moisture content (EMC) was achieved. Reflectance spectra of different treatments were measured using Konica Minolta CM-2600d portable spectrophotometer. Spectral data between 360 and 740 nm visible wavelength range was converted to CIEL*a*b* color coordinates using 2° standard observer and D65 light source. Lastly, the color difference (ΔE*ab) between the modified and unmodified specimens was calculated using CIE76 standard (Commission International de l'Eclairage, CIE), which corresponds to the distance between two points in the three-dimensional color coordinate system, and is calculated by the equation:

$$\Delta E^*_{ab}=((\Delta L^*)^2+(\Delta a^*)^2+(\Delta b^*)^2)^{1/2} \quad [-] \qquad (1)$$

where ΔL^*, Δa^* and Δb^* reflect the changes of lightness (L^*) and chromatic parameters redness (a^*) and yellowness (b^*) between the measurements on the treated samples.

Brinell hardness (HB) of wood was measured and calculated according to EN 1534 as follows:

$$HB = 2F/(\pi^*D^*(D-(D^2-d^2)^{1/2}) \quad [\mathrm{MPa}] \qquad (2)$$

where F is the nominal force, D is the diameter of the steel ball, and d is the diameter of the residual indentation. As a difference from EN 1534, the estimated value for the diameter of the residual indentation (d) was calculated from the depth of the residual indentation (h, mm) measured by the material testing machine as follows:

$$d = 2\times(10h - h^2)^{1/2} \quad [\mathrm{mm}] \qquad (3)$$

The tests for MOE (Ew) and MOR (σ b,W) were carried out according to standards ISO 13061-4 (2014) and ISO 13061-3 (2014), respectively, using 20×20×340mm, clearwood specimens as follows:

$$E_W = Pl^3/4bh^3f \quad [\mathrm{MPa}] \qquad (4)$$

where P is the load equal to the difference between the upper and lower limits of loading (N), l is the span (mm), b is the width of the test specimen (mm), h is the height of the test specimen (mm), f is the deflection at the upper and lower limits of loading (mm), and

$$\sigma_{b,W} = 3P_{max}l/2bh^2 \quad [\mathrm{MPa}] \qquad (5)$$

where P is the maximum load (N), l is the span (mm), b is the width of the test specimen (mm), h is the height of the test specimen (mm).

The figures describing the tested mechanical properties of MOE and MOR (before and after thermal treatments) were adjusted to 12% moisture content to address moisture variation amongst the subset of specimens modified in different thermal intensities, by using the following formulae, which are valid for moisture contents of 12±5%:

$$E_{12} = E_W/(1 - \alpha\times(W - 12)) \quad [\mathrm{MPa}] \qquad (6)$$

$$\sigma_{b,12} = \sigma_{b,W}\,[1 + \alpha\,(W - 12)] \quad [\mathrm{MPa}] \qquad (7)$$

where α is the correction factor for the moisture content, equal to 0,04, and W is the moisture content of wood.

3. RESULTS AND DISCUSSION

3.1 PHYSICAL PROPERTIES

3.1.1 COLOUR CHANGE

Thermally modified wood is widely known for inducing permanent structural changes on treated samples. Colour change in different shades of darkness is probably the most striking and recognized feature of thermally modified wood. Predictably, in this study, all thermal treatment levels produced visible change in colour as shown by the overall colour change parameter (ΔE*ab) (Table 3). In fact, ΔE*ab larger than 2 is visually perceived by naked human eye (Witzel et al. 1973; Hon and Minemura 2001).

Additionally, remarkable uniformity in colour was achieved as inferred by the negligible variations in all treatment levels for the two species. The acquired colours could potentially add value to both wood species due to similarities to expensive, rare, endangered precious tropical hardwoods. For consumers, the decorative look often prevails, and colour is in fact, a determining factor for the selection of a specific wood (Esteves and Pereira 2009; Dos Santos et al. 2014).

3.1.2 MASS LOSS, OVEN-DRY DENSITY AND EQUILIBRIUM MOISTURE CONTENT

The mass loss (ML) increased and the EMC and oven-dry density decreased as the thermal treatment level was increased (Table 4). One of the key structural changes in heat treated wood is improved hydrophobicity and lower oven-dry density due to progressive evaporation of extractives and thermal degradation of the main chemical components such as wood components, hemicelluloses, cellulose and lignin (Pockrandt et al. 2018).

The reduced EMC of thermally modified wood can be explained by several factors including degradation of the amorphous regions of cellulose triggering cross-linking reactions that potentially hinder moisture intake (Jermer et al. 2003; Mitani and Barboutis 2014; Adeyemi et al. 2017). Hydrophobicity and reduced density are improved wood features with potential for new applications where decay resistance and dimensional stability are critical. The ML of the thermally treated wood samples is indicative of degradation of wood polymers mainly by the hemicelluloses in this range of temperature, which are the most thermally-sensitive wood components (Mohebby and Sanaei 2005; Poncsak et al. 2006; Kocaefe et al. 2007).

3.2 Mechanical properties

3.2.1 BENDING STRENGTH

Thermal modification is known to induce permanent changes in the wood structure. The wood responses of B. spiciformis and J. globifora to thermal modification are shown below (Fig.1). There is a clear trend of decline in bending strength (MOE and MOR) for both species as the treatment intensity was increased. Similar trends were reported elsewhere for hardwoods (Korkut et al. 2008; Korkut 2012).

The MOR of both wood species decreased over 50 % of reference value, while the MOE dropped by 6% in B. spiciformis and beyond 6% in J. globiflora with the highest treatment intensity. According to Tukey multiple range test (at $p<0.05$) all induced changes are significantly different from the reference untreated samples since heat-treated samples turned brittle. According to Jämsa and Viitaniemi (2001), due to deterioration in mechanical properties, the use of thermal modified wood as load-bearing structural material should be restricted. However, a balance is needed to establish optimal treatment to allow a wide range of applications for the end product. For example, T2 treatment level seems suitable as no considerable gain is obtained by the very intense T3 applied to B. spiciformis timber.

3.2.2 BRINELL HARDNESS AND COMPRESSION STRENGTH PARALLEL TO GRAIN

Like in static bending (MOE and MOR), both compression strength and Brinell hardness suffered statistically significant decline as the thermal treatment intensity was increased (Fig. 2). All treatment levels caused decrease on Brinell hardness for B. spiciformis. Exceptionally, a slight increase was recorded for J. globiflora sample subjected to T1 treatment level, but a decrease for sample subjected to T2 level. Brinell hardness is a very important quality parameter for parquet and flooring materials as it measures the resistance against indentation. The resulting values of Brinell hardness after the T1 treatment for B. spiciformis (26.0 MPa) and T2 treatment for J. globiflora (32.4 MPa) are within range of most wood floorings. However, the Brinell hardness of B. Spiciformis samples subjected to T3 treatment level (20.2 MPa) was not comparable to Brinell hardness of untreated birch (23.4 MPa) or oak (30.5 MPa) wood (Heräjärvi 2004; Swaczyna et al. 2011), which typically are used for flooring materials in Europe.

For both species, thermal treatments led to 20% decrease of compression strength parallel to grain. Similar results were claimed by Korkut (2012), who studied wood responses of three thermally treated tropical hardwood species. As mentioned earlier mild thermal intensity treatment should be deployed if the decrease in strength properties is to be kept within critical limits.

4. SUMMARY

This study was aimed at testing wood properties responses by mean of thermal treatment of two low-value and abundant, but relatively lesser known/used native hardwoods from Mozambique. Based on measured parameters, it can be concluded that nearly all measured wood properties experienced statistically significant changes after all treatment levels. More specifically, from control reference samples to the highest treatment level, the results show that B. spiciformis's timber experienced a maximum ML of 27%, while the oven-dry density reduced from 0.65 g/cm3 to 0.56 g/cm3, the EMC dropped from 7% to 3%. With regard to J. globiflora, the ML induced by the highest treatment level was 23%, oven-dry density decreased from 0.81 g/cm3 to 0.74 g/cm3 and the EMC reduced from 8% to 3%. Changes in mechanical properties were also significant from reference samples to the highest treatment. For B. spiciformis, MOE reduced from 9150.48 to 8212.57 MPa, MOR from 43.88 to 21.60 MPa, compression strength parallel to grain decreased from 25129 to 17794 MPa and the Brinell hardness from 2.64 to 2.02 MPa. The samples from J. globiflora followed the same trend as its MOE reduced from 11037.46 to 10277.40 MPa, MOR from 50.02 to 23.39 MPa, compression strength parallel to grain from 29365.75 to 22935.08 MPa.

The study concluded that thermally modified wood of both species could potentially be used for flooring due to new appealing dark colour and low EMC associated with hydrophobicity. The overall assessment of the results suggest that thermal modification is potentially an effective method for processing low- value, but abundant wood species to relieve the current pool of overexploited tropical hardwoods.

5. ACKNOWLEDGEMENTS

The study was carried out in the framework of a project (FORECAS II project) financed by the Ministry for Foreign Affairs of Finland to which financial support is gratefully acknowledged. The authors also gratefully acknowledge LevasFlor Ltd. (Beira, Mozambique) for providing the sawn wood material for the tests and Luxhammar Ltd. (Mikkeli, Finland) for carrying out the thermal modification treatments.

REFERENCES

Adeyemi IE, Babatola O, Mayowa OJ, Adeola FJ (2017) Impact of Heat Treatment on Physico-Mechanical Properties of Thermally Modified Anthocleistha djalonensis Wood. Journal of Materials Sciences and Applications 3(2):28–34. Retrieved from http://www.aascit.org/journal/jmsa.

Dos Santos DVB, de Moura LF, Brito JO (2014) Effect of Heat Treatment on Color, Weight Loss, Specific Gravity and Equilibrium Moisture Content of Two Low Market Valued Tropical Woods. Wood Research 59(2):253–264.

Dubey MK (2010) Improvements in Stability, Durability and Mechanical Properties of Radiata Pine Wood after Heat-Treatment in a Vegetable Oil. PhD Thesis. University of Canterbury, New Zeland. 211 pp.

Esteves BM, Pereira HM (2009) Wood modification by heat treatment: A review. BioResources 4(1):370–404.

Heräjärvi H (2004) Variation of basic density and Brinell hardness within mature Finnish Betula pendula and B. pubescens stems. Wood and Fiber Sci. 36:216–227.

Hill CAS (2006) Wood Modification: Thermal and Other Process. John Wiley & Sons. 249 pp.

Hon DNS, Minemura N (2001) Color and discoloration. In: Hon, D.N.S., Shiraishi, N. (Eds.) Wood and Cellulosic Chemistry. Marcel Dekker, New York. pp. 385–442.

ISO/CIE 11664-6 (2014) Colorimetry - Part 6-CIEDE 2000-Colour difference formula. International Standards Organisation, Geneva.

ISO 13061-2 (2014) Wood-Determination of density for physical and mechanical tests. International Standards Organisation, Geneva.

ISO 13061-5 (1975) Wood-Test methods – Determination of ultimate stress in compression parallel to grain. International Standards Organisation, Geneva.

ISO 13061-3 (2014) Wood – Determination of modulus of elasticity in static bending. International Standards Organisation, Geneva.

ISO 13061-4 (2014) Wood – Determination of ultimate strength in static bending. International Standards Organisation, Geneva.

Jämsä S, Viitaniemi P (2001) Heat treatment of wood- Better durability without chemicals. In: Proceedings of special seminar held in Antibes, France, city, 68 p.

Jermer J, Bengtsson C, Brem F, Clang A, Ek-Olausson B, Edlund M (2003) Heat-treated wood – durability and technical properties Swedish Wood Association project 2001-025.

Kocaefe 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(3):355–361.

Korkut S (2012) Performance of three thermally treated tropical wood species commonly used in Turkey. Industrial Crops and Products 36(1):355–362.

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

Luxhammar 2019. Luxhammar thermal modification technology. Available at: http://www.luxhammar.com/index.php.

Marzolli A (2007) Inventário Florestal Nacional: Avaliação integrada das florestas de Moçambique. Direcção Nacional de Terra e Florestas, Ministério da Agricultura. Maputo. 92 pp.

Militz H, Altgen M (2014) Processes and Properties of Thermally Modified Wood Manufactured in Europe.

Mitani A, Barboutis I (2014) Changes Caused by Heat Treatment in Color and Dimensional Stability of Beech (Fagus sylvatica L.) Wood. Drvna Industrija, 65(3), 225–232.

Mohebby B, Sanaei I (2005) Influences of the hydro-thernal treatment on physical properties of beech Wood (Fagus orientalis). In: Annual Meeting Bangalore (36), New Delhi. Proceedings: Tarbiat Modarress University.

Peres CA (2010) Conservation Biology for All: Ovexploitation. Oxford 24 pp.

Pockrandt M, Jebrane M, Cuccui I, Allegretti O, Uetimane Jr E, Terziev N (2018) Industrial Thermowood® and Termovuoto thermal modification of two hardwoods from Mozambique. Holzforschung 72(8): pp. 701–709.

Poncsak S, Kocaefe D, Bouazara M, Pichette A (2006) Effect of high temperature treatment on the mechanical properties of birch (Betula papyrifera). Wood Science and Technology 40 (8): pp. 647–663.

Sosef MSM, Hong LT, Prawirohatmodjo S (1998) Plant Resources of South-East Asia No 5(3) Timber Trees: Lesser- Known timbers. Backhuys Publishers. 859 pp.

Srinivas K, Pandey KK (2012) Effect of Heat Treatment on Color Changes, Dimensional Stability, and Mechanical Properties of Wood. Journal of Wood Chemistry and Technology 32:304–316.

Swaczyna I, Kędzierski A, Tomusiak A, Cichy A, Różańska A (2011) Hardness and wear resistance tests of the wood species most frequently used in flooring panels. Ann. WULS-SGGW, Forestry and Wood Technology 76: 82–87.

Uetimane Jr E, Jebrane M, Terziev N, Daniel G (2018) Comparative wood anatomy and chemical composition of Millettia mossambicensis and Millettia stuhlmannii from Mozambique. Bioresouces 13(2):3335-3345.

Witzel RF, Burnham RW, Onley JW (1973) Threshold and supra threshold perceptual color differences. J. Optical Society of America 63(5):615–625.

Table 1. Number of wood samples for each tested thermal modification

Treatment	**Temperature, °C**	**Time, h**	***Brachystegia spiciformis***	***Julbernadia globiflora***
Untreated	-	-	9	7
T1	215	2	43	27
T2	230	2	40	29
T3	245	2	29	-

Table 2. Tested wood properties and specific standards

Tested wood properties	**Standard**
Equilibrium moisture content, mass loss and oven-dry density	ISO 13061-2:2014
Colour/spectral reflectance	ISO/CIE 11664-6:2014(E)
Bending strength: MOE & MOR*	ISO 13061-3:2014 & ISO 13061-4:2014
Brinell hardness	ISO 13061-12:2017
Compression strength	ISO/DIS 13061-5 & ISO 3132:1975

*MOE-Modulus of Elasticity; MOR-Modulus of Rupture; ISO-International Standards Organization

Table 3. Colour changes by treatment level and wood species

Wood species	**Treatment**	**Colour coordinate**			**Overall colour change**
		*L**	*a**	*b**	ΔE^*_{ab}
B. spiciformis	Untreated	77.09 (3.73)	6.20 (1.90)	23.32 (2.11)	-
	T1	44.54 (2.11)	8.98 (0.55)	19.75 (1.58)	33.33 (5.43)
	T2	36.11 (1.49)	7.26 (0.56)	13.19 (1.58)	42.37 (4.17)
	T3	33.26 (1.37)	6.22 (0.58)	10.90 (1.26)	45.19 (7.00)
J. globiflora	Untreated	75.35 (6.88)	6.59 (2.34)	23.41 (1.97)	-
	T1	42.12 (2.19)	10.40 (0.81)	18.13 (1.76)	34.49 (3.72)
	T2	34.00 (0.87)	7.44 (0.56)	11.28 (1.09)	42.87 (5.50)

Standard deviations in parenthesis

Table 4. Mass loss, EMC and oven-dry density changes after thermal modifications

Wood species	**Thermal treatment levels**	**ML (%)**	**EMC (%)**	**Oven-dry density (g/cm^3)**
B. spiciformis	Reference	-	7 (0.01)	0.65 (0.03)
	T1	15 (0.01)	4 (0.00)	0.61 (0.07)
	T2	24 (0.05)	3 (0.00)	0.58 (0.04)
	T3	27 (0.01)	3 (0.01)	0.55 (0.03)
J. globiflora	Reference	-	8 (0.02)	0.81 (0.10)
	T1	21 (0.02)	5 (0.02)	0.74 (0.07)
	T2	24 (0.01)	3 (0.00)	0.74 (0.04)

Standard deviation in parenthesis; ML-mass loss; EMC-Equilibrium moisture content

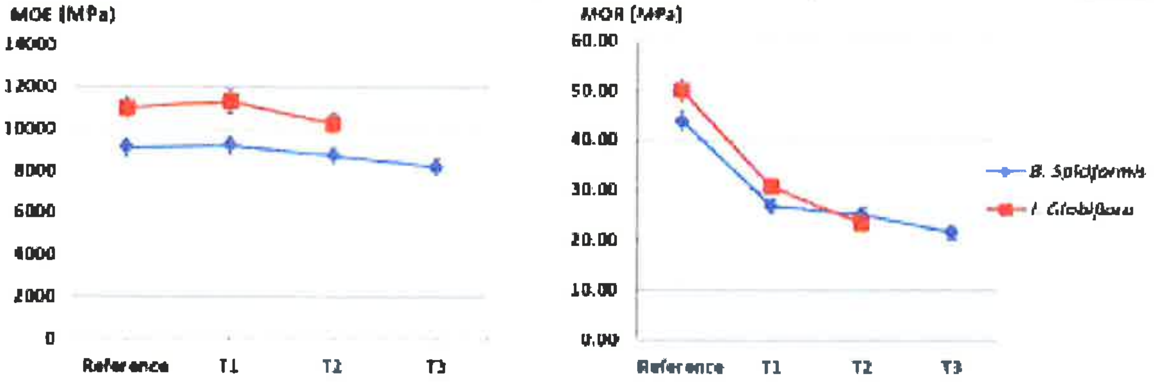

Fig.1. Bending stiffness and strength changes in timbers of *B. spiciformis* and *J. globiflora* after different thermal treatment

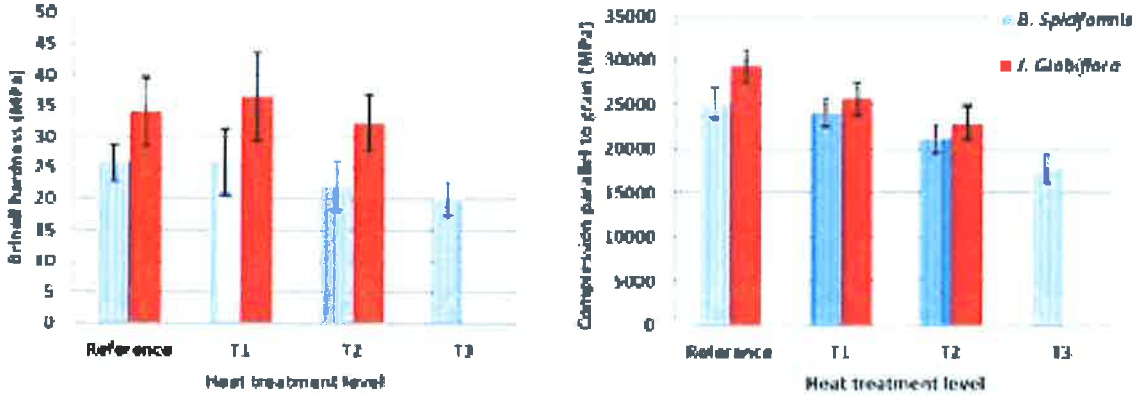

Fig. 2. Changes in Brinell hardness and compression strength of *B. spiciformis* and *J. globiflora* after thermal modification