Thermo-Vacuum Modification of Teak Wood from Fast-Growth Plantation

Ignazia Cuccui,[a,]* Francesco Negro,[b] Roberto Zanuttini,[b] Mario Espinoza,[c] and Ottaviano Allegretti [a]

Sawnwood of teak (*Tectona grandis* L. f.) from a Costa Rica plantation was thermally treated at different process conditions using thermo-vacuum technology. The main objectives of the study were to find the optimal combination of the process parameters, *i.e*. temperature (*T*), and duration (*t*), in order to minimise the colorimetric difference between sapwood and heartwood, and to evaluate the influence of the treatment on the modification pattern of physical properties of the material. The resulting mass loss (ML), hygroscopicity (*H*), dimensional stability (ASE), and lightness (*L*) were measured and compared. As expected, the temperature (*T*) is the main parameter influencing the extent of modification. The measured ML values turned out to be moderate even at high *T* values if compared with other hardwoods. The temperature range between 180 °C and 190 °C minimizes the colorimetric difference between treated sapwood and not treated heartwood.

Keywords: Teak; Sapwood; Heartwood; Thermal treatment; Colour

Contact information: a: Trees and Timber Institute CNR-IVALSA, via Biasi, 75 38010 San Michele A'A (TN) Italy; b: DISAFA, University of Turin, Largo Braccini, 2 I-10095 Grugliasco (TO) Italy; c: Novelteak Costa Rica S.A., P.O. Box 63-5000, Liberia, Guanacaste Costa Rica
** Corresponding author: cuccui@ivalsa.cnr.it*

INTRODUCTION

Teak (*Tectona grandis* L. f.) is a tropical hardwood species in the family Lamiaceae. It is a large, deciduous tree that grows mainly in mixed hardwood forests. Teak is native to south and southeastern Asia, and it is dominant in India, Sri Lanka, Indonesia, Malaysia, Thailand, Myanmar, and Bangladesh. Teak is naturalised and cultivated in many other countries of Africa and in the Caribbean and South America.

Teak wood is particularly valued for its durability and dimensional stability, and it is used for several applications such as boat building, exterior construction, veneers, furniture, carving, and turnings. The colour of teak-heartwood is brownish red, and teak-sapwood is whitish to pale yellowish-brown. The teak texture is a hard diffuse ring-porous wood. The average density is around 720 kg/m^{-3} (Bhat *et al*. 2003).

Teak wood from plantations can be very different from that grown in natural forests, as it is subjected to a great variability reflecting the growing conditions (Moya *et al*. 2014). The fast growing conditions related to the site determine the production of timber with wide rings and a large portion of sapwood, characterized by a clear colour (Richter *et al.* 2003; Moya and Berrocal 2010), and with strongest influence of juvenile wood.

Sapwood is less durable than heartwood (class 3 *vs.* class 1 according to EN 350-1 1994) (Wolfsmayr *et al*. 2008) and presents a lower dimensional stability. Furthermore, the appearance of the sawn boards is less attractive than natural teak because of the colour variability, which depends on the width of the rings and on the relevant presence of sapwood. These elements reduce the performance, the field of application, and the economic value of teak wood from various plantations. However, these factors should be valued in comparison to the reduced availability of teak coming from natural forests (Bermejo *et al*. 2004; Bhat and Indira 2005; Thulasidas and Bhat 2006).

Studies related to the control of teak wood colour are rather limited, although many techniques have been developed to standardize the colour in teak wood, such as drying schedules or heat treatment and application of chemicals (Basri *et al*. 2004). Some more specific studies on control of heartwood-sapwood colour difference by thermal modification was performed on other wood species such as Turkey oak which, as plantation teak, has a large portion of sapwood (Ferrari *et al*. 2013)

Thermal modification increases the durability and dimensional stability of the wood by darkening its colour homogenously across the thickness (Esteves and Pereira 2009). In particular, thermo-vacuum (TV) is a technology for the thermal modification of wood in which oxygen is removed by applying vacuum, and the heat transfer to the material is provided by convection. This determines its classification as a dry process in an open system (Hill 2006). These conditions can cause a milder degradation compared with other systems, with a lower mass loss (ML) and better residual mechanical properties (Allegretti *et al*. 2012; Candelier *et al*. 2014). The thermo-vacuum system combines an efficient drying process and a thermal treatment process; a more detailed description of this technology can be found in Sandak *et al.* (2015).

In the above context, the present paper explores the potential of the thermo-vacuum system as a possible means for improving the technological and aesthetical characteristics of plantation teak to increase its economic value in a wider range of end-uses in interior and exterior application. Pilot thermal modification tests were performed on plantation teak wood with the TV system. The influence of the process parameters on the modification of natural wood colour (especially sapwood) and the physical properties of the treated material were measured. Tests were here limited in a mild T range (T between 170 °C and 200 °C) according to the practical aim of this work which was to investigate possible new end-uses in interior design.

EXPERIMENTAL

Materials

Teak wood tested in this work came from plantations of the Novelteak company, located in northwestern Costa Rica near the city of Hojancha. The rotation was 17 to 23 years and resulted in logs with circumferences from 12 to 30 cm.

The tested material was composed of 290 sawn boards, with dimensions of 1000 mm x100 mm, equally distributed in three thickness values (28, 33, and 40 mm). Half of the boards were transversally cut in three portions: two external, 49 cm long, and a central, 2 cm long. The latter was used to measure the initial moisture content (MCi) using the gravimetric method. One other sample was treated (HT), while the remaining sample was used as a reference (NT).

The mass of every sample was measured at each treatment stage by weighing the samples, and the following parameters were calculated: initial MC (MC_i), final MC after drying (MC_f), oven-dry mass (M_o), mass loss after thermal modification (ML), and final MC after conditioning (MC_c).

The quality of the material after the treatment was assessed by means of a visual observation of the exterior appearance of the sawn board checking the presence of deformations and cracks. Presence of internal splits was assessed by means of the visual observation of the boards during the machining of samples.

The TV Process

The TV process was composed of three stages: vacuum drying, thermal treatment, and conditioning. Each stage was performed in the thermo-vacuum prototype plant previously described in Allegretti *et al.* (2012) and Sandak *et al*. (2015).

Drying

All the material was dried from the initial moisture content (MC_i) to a value of about 5%. The drying process involved the following steps: (1) warm-up at atmospheric pressure; (2) one drying phase, with constant pressure at 20 kPa and *T* varying as a function of MC from 55 °C to 75 °C.

Thermal treatment

In total five thermal treatments were performed; each one was done at a constant pressure of 25 kPa and at a heating phase that started from 100 °C up to the final temperature with a ΔT of 15 °C/h. Each batch was composed of 29 boards of 100 cm length, and 29 boards of 49 cm length, with the three thickness values equally distributed. A further explorative treatment was performed at 210 °C with a mixed batch of three boards only. For this test only the ML was measured. The parameters adopted for the thermal treatments are summarised in Table 1.

Table 1. Test Parameters

Parameter	Unit	Value					
Temperature (*T*)	°C	170	180	180	190	200	210
Time of exposure (*t*)	h	5		3			
Vacuum pressure (*p*)	kPa	25					
T increase (ΔT)	°C/h	15					

Final conditioning

In this final stage, the MC of treated wood was raised from 0% up to about 4%. Conditioning started when the *T* of the air was around 95 °C. It was performed in atmospheric pressure, keeping a constant *T* of 90 °C, and inletting spray water into the chamber for about 6 h. After this stage the wood was finally cooled down to a *T* not higher than 50 °C.

Laboratory Characterisation

The characterisation of the physical properties was performed on both boards modified by thermo-vacuum treatments and on the matched untreated samples, used as a reference. Tests have been carried out on clear, small (20 x 20 x 40 mm) specimens cut from treated (HT) and not-treated (NT) heartwoods of each sawn boards according to the specific standards of UNI CEN/TS 15629 (2008). Due to the small amount of available material it was only possible to cut a limited number of specimens from NT sapwood; consequently, all the statistics on physical characteristics of treated wood refer to the heartwood samples. The following physical characteristics were investigated in this study.

Density (ρ)

At 0% MC, the samples were equilibrated at 20 °C with RH 30%, 65%, for density measurements according to ISO 13061-2 (2014).

Equilibrium moisture content (EMC)

Samples were equilibrated at 20 °C with RH 30%, 65%.

Moisture exclusion efficiency (MEE)

The MEE of samples equilibrated at RH 65%, T 20 °C were estimated by Eq. 1,

$$MEE = (EMC_{NT} - EMC_{HT})/EMC_{NT} \quad (1)$$

where EMC_{NT} is the EMC of untreated reference samples (NT) and EMC_{HT} is the EMC of treated samples (HT). The MEE value expresses the relative variation of EMC of treated wood equilibrated at RH 65% (MEE = 0% means no EMC variation; MEE = 100% indicates an EMC value of 0%).

Swelling (β)

Swelling of samples in radial (R), tangential (T) and longitudinal (L) direction was measured according to ISO 4859 (1982) in NT and HT samples from MC = 0% to EMC of samples equilibrated at 20 °C and RH 30%, 65%, (cycle in adsorption).

Anti-swelling efficiency (ASE)

The anti-swelling efficiency in the radial (ASE_{R65}) and tangential direction (ASE_{T65}) of NT and HT samples equilibrated at 20°C and 65% RH was calculated using Eq. 2,

$$ASE_{65} = (\beta_{NT} - \beta_{HT})/ \beta_{NT} \quad (2)$$

where β_{NT} is the swelling of not-treated sample and β_{HT} is the swelling of the corresponding treated sample. ASE expresses the dimensional stability (ASE = 0% means no improvement of the stability after the treatment; ASE = 100% indicates a wood totally stable after the treatment).

Mass loss (ML)

The ML was determined by weighing the samples prior to the thermo-vacuum treatment (but after drying when the MC = 0%) and immediately after and is expressed in percent. The ML value was used as the main parameter for denoting the modification intensity of the treatment (Eq. 3),

$$ML = (M_0 - M_{HT})/(M_0) \quad (3)$$

where M_{HT} is the mass of the treated sample and M_0 is the oven-dry mass.

Colour coordinates (*CIE L*a*b** system).

Colour was measured using a Micro Flash 200D spectrophotometer (Data Color Int. Lawrenceville, NJ, USA) over a 6.5 mm diameter spot with a standard D65 light source at an observation angle of 10° according to ISO 11664-4 (2008). Additionally, pictures in calibrated light conditions were taken for each board before and after the treatment. From these pictures, the colour coordinates in several points of each board were sampled with the Adobe Photoshop software tool (Adobe Systems Software Ireland Ltd). The colour measurements were performed on planed surfaces of the boards before and after thermo-vacuum treatment, in sapwood and heartwood portions separately. Colour coordinates referred to the three dimensional CIE $L^*a^*b^*$ colour space, where L^* specifies the lightness in the range from black (0) to white (100), a^* is the red-green share, and b^* is the blue-yellow share. This data was used to calculate the colour distance and in particular, the lightness change (ΔL^*) and total colour change (ΔE^*) between two measurements, using Eqs. 4 and 5,

$$\Delta L^* = L_2^* - L_1^* \tag{4}$$

$$\Delta E = \sqrt{(L_2 - L_1)^2 + (a_2 - a_1)^2 + (b_2 - b_1)^2} \tag{5}$$

where measurement 1 and 2 can be refer to: the colour in the same point before (NT) and after the treatment (HT); the colour in two different point or portions such as sapwood and heartwood; and the colour between treated sapwood (sapHT) and untreated heartwood (heartNT) (particularly interesting for the purpose of this work).

RESULTS AND DISCUSSION

Process

The average (with standard deviation), initial MC, and final MC (after drying for processes named A and B) values are reported in Fig. 1. The most significant difference between the drying tests A and B was the application of a final conditioning phase after the drying process B, allowing equalization of existing MC differences of boards of different thickness values. About 48 h of drying resulted in a sufficient decrease of the MC from 16% to 6%, with some variation among different thickness values and a wide standard deviation.

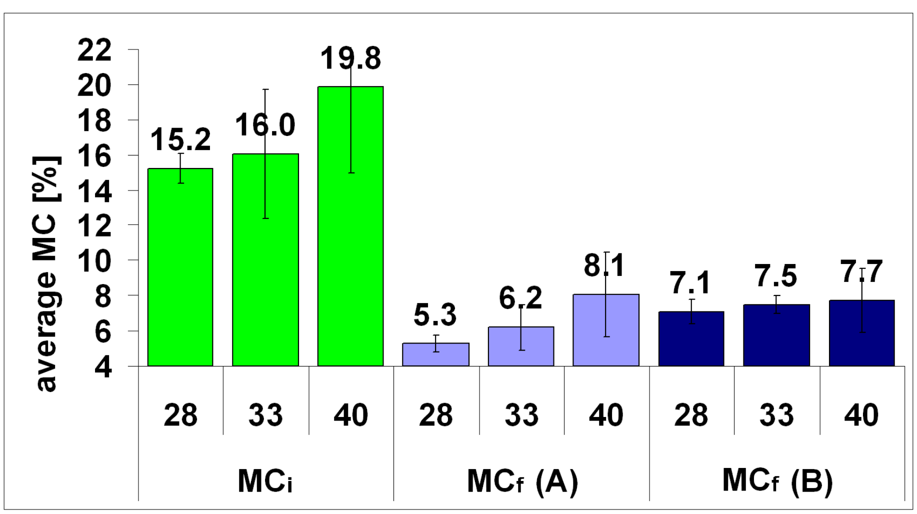

Fig. 1. Average and standard deviation for the initial and final MC at different thickness values

Product

The quality of the wood, assessed by a visual grading after the thermal treatment, was generally fair, with low incidence of warps and visible cracks, lack of collapse, and no internal cracks or residual internal tensions.

The measured (both average and standard deviation values) ML values for the tested processes are reported in Fig. 2. The ML was in the range of 1.5% to 6%. These values are rather low compared with other hardwoods treated with the same technology in similar process conditions (Ferrari *et al*. 2013). The ML was mostly influenced by *T*, with minor effects related to *t* (only weak differences were observed between 3 and 5 h).

The density of samples at 0% ML and conditioned at 20 °C, RH values of 0%, 30%, and 65% are illustrated in Table 2. Table 3 summarizes the measured physical properties.

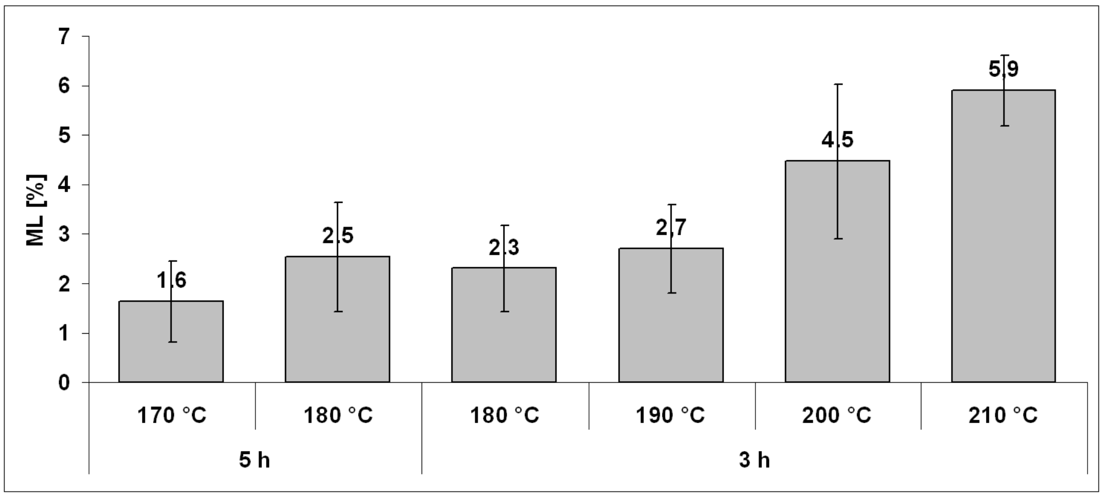

Fig. 2. The mass loss (ML) measured for the tested processes

Table 2. Sample Density

Sample	Density (kg/m^3)				
	T (°C)	*t* (h)	RH 0%	RH 30%	RH 65%
Sapwood	NT		584 ± 64	597 ± 66	610 ± 63
Heartwood	NT		597 ± 45	609 ± 44	623 ± 45
	170	5	585 ± 46	594 ± 46	603 ± 46
	180	5	595 ± 61	606 ± 62	616 ± 62
	180	3	594 ± 38	604 ± 39	613 ± 39
	190	3	581 ± 47	589 ± 47	597 ± 47
	200	3	596 ± 40	607 ± 44	615 ± 44

Note: Values shown are the average ± standard deviation

Table 3. Physical Properties of Samples Conditioned at RH 65%

T	*t*	ML	EMC	MEE	β_R	ASE $_R$	β_T	ASE $_T$	β_V	ASE $_V$
S	NT		8.7 ± 0.6		1.6 ± 0.1		2.2 ± 0.4		4.0 ± 0.4	
H	NT		7.2 ± 0.5		1.0 ± 0.2		1.6 ± 0.3		2.7 ± 0.4	
170	5	1.6 ± 0.8	5.2 ± 1.3	-28.3%	0.7 ± 0.2	-23.9%	1.1 ± 0.4	-26.5%	2 ± 0.5	-24.8%
180	5	2.5 ±1.1	5.8 ± 0.8	-20.0%	0.8 ± 0.3	-23.7%	1.2 ± 0.3	-20.0%	2.1 ± 0.6	-21.5%
180	3	1.8 ± 0.9	5.6 ± 0.8	-22.6%	0.8 ± 0.3	-17.4%	1.2 ± 0.4	-23.8%	2.2 ± 0.8	-20.7%
190	3	2.7 ± 0.9	4.4 ± 0.6	-38.3%	0.6 ± 0.1	-38.1%	0.8 ± 0.1	-46.3%	1.6 ± 0.2	-42.2%
200	3	4.5 ± 1.6	4.6 ± 0.9	-35.8%	0.5 ± 0.1	-45.6%	0.8 ± 0.2	-51.7%	1.4 ± 0.2	-48.4%

Note: Values shown are the average ± standard deviation. S, sapwood; H, heartwood.

Figure 3 shows the linear correlation between MEE and ASE *vs.* ML. A treatment time (t) longer than 3 h produced no remarkable changes in the physical characteristics. The density of NT sapwood was lower than the density of NT heartwood. The thermal modification slightly decreased the density. The hygroscopicity and swelling values of NT sapwood resulted in higher values than those measured on NT heartwood. The thermal treatment increased the dimensional stability of the wood tested in a range from 20% to 50%. Increasing in MEE and ASE values was proportional to the intensity of the modification process, *i.e.*, with the ML (Fig. 4). ASE_T was higher than ASE_R, indicating that the thermal modification reduced the shrinkage ratio, $\boldsymbol{N} = (\beta_T / \beta_R)$ of wood, which is an indicator of the cupping predisposition of tangential boards (in not treated wood N ranges between 1.5 and 2.5).

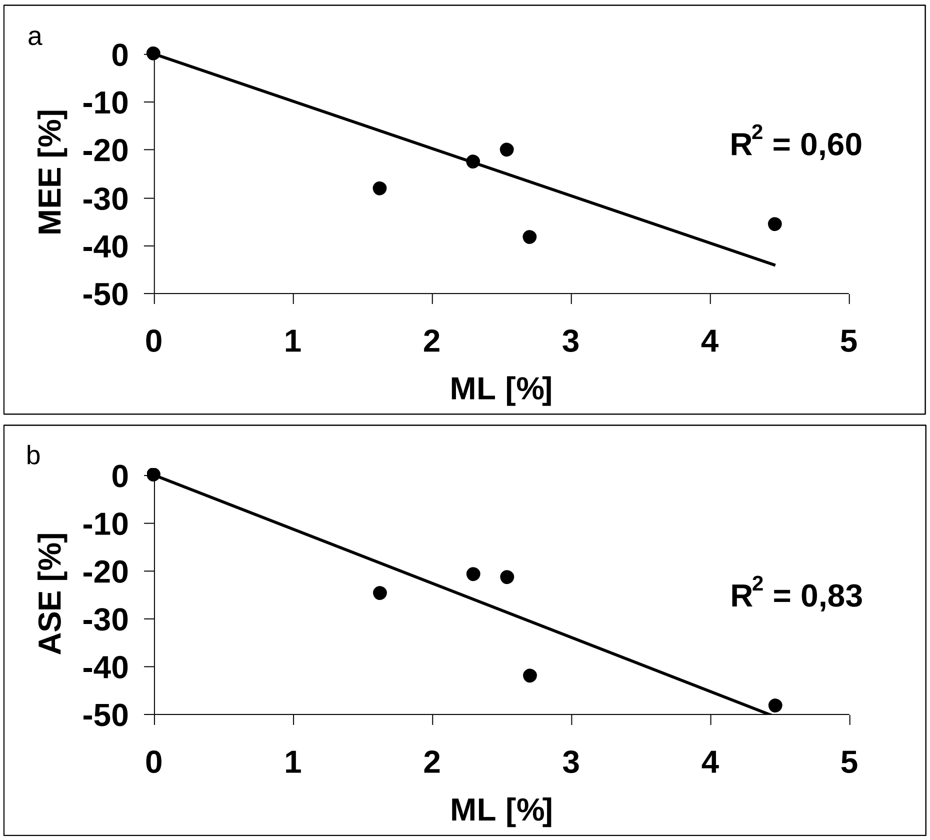

Fig. 3. Moisture exclusion efficiency (MEE) (a) and anti–swelling efficiency (ASE) (b) *vs.* mass loss (ML)

The measured colour coordinates are shown in Fig. 5 while Fig. 6 reports the lightness difference (ΔL) between the treated sapwood and untreated heartwood (sapHT - heartNT). In the first column (grey bar) the original difference of untreated sapwood and heartwood was reported. When $\Delta L = 0$ there was no difference in lightness, whereas $\Delta L < 0$ indicates that the sapHT had darker colour than the heartNT. A photographic representation of the colour variation is reported in Fig. 7.

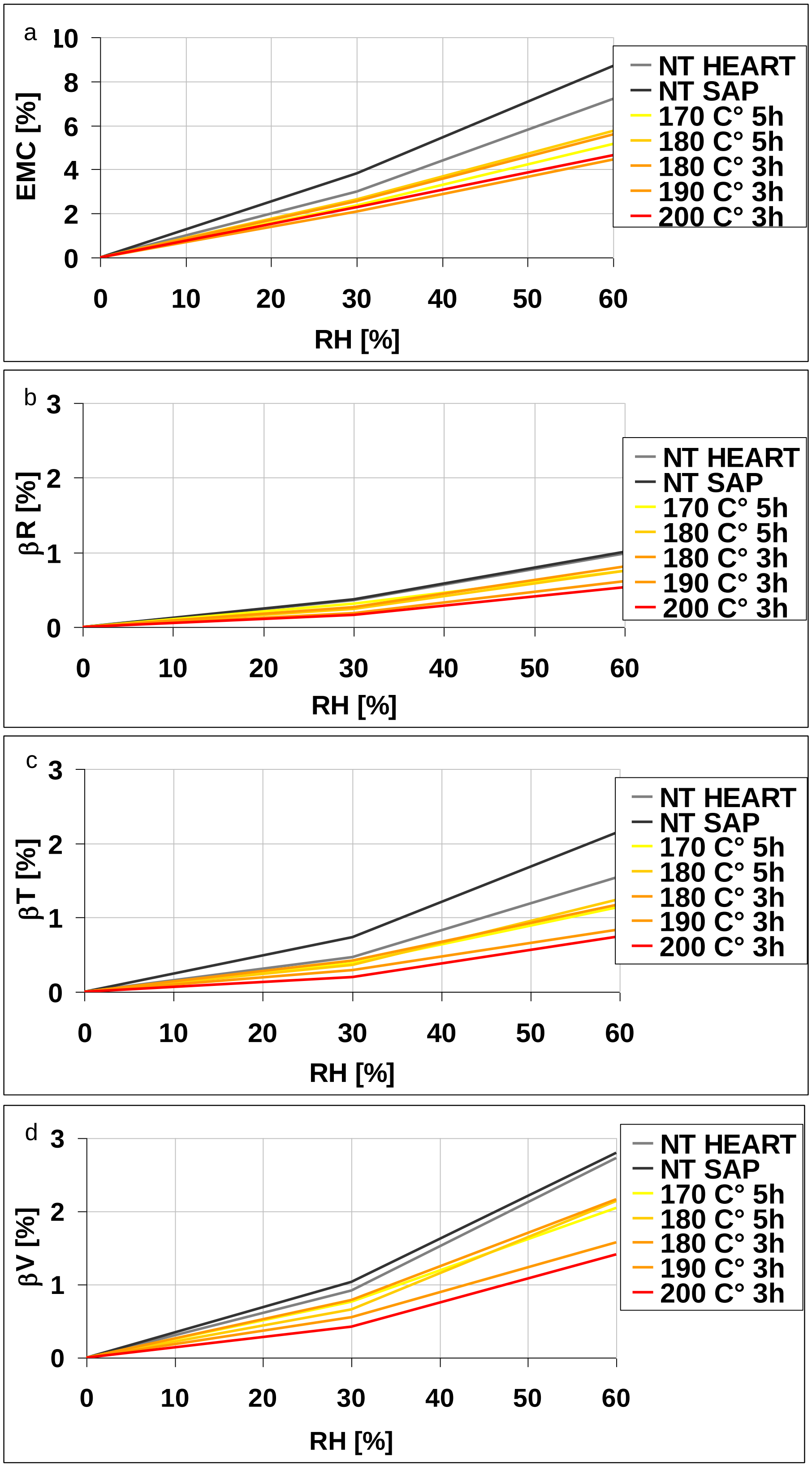

Fig. 4. Equilibrium moisture content EMC (a), radial βR (b), tangential βT (c), and volumetric swelling βV(d) *vs.* RH

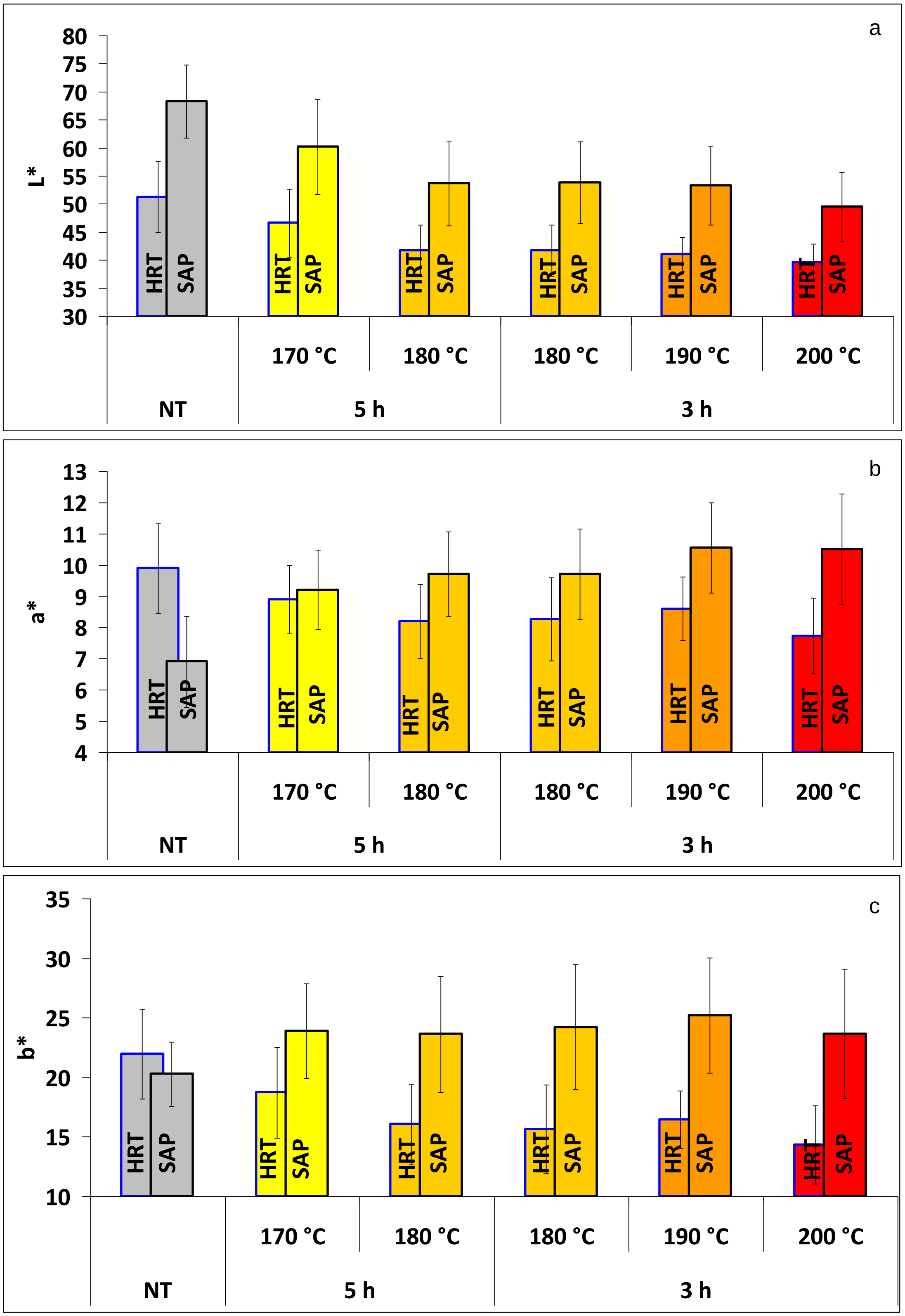

Fig. 5. Colour coordinates *L** (a), *a**(b), and *b**(c) of sapwood and heartwood of untreated and treated wood at different process conditions.

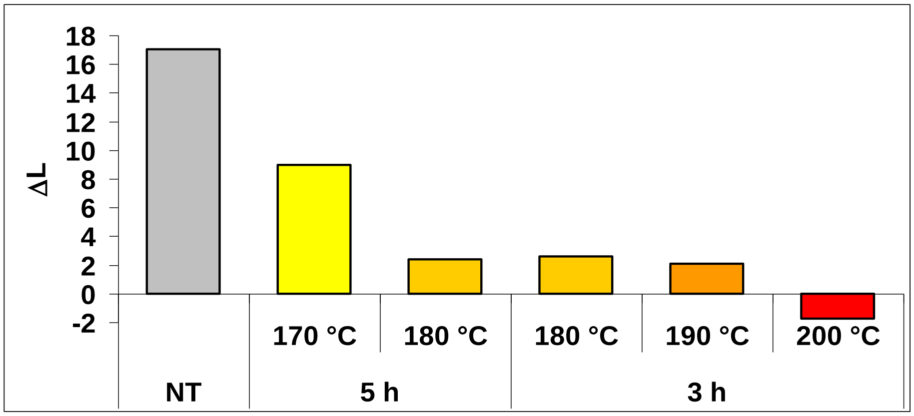

Fig. 6. Lightness difference (ΔL) between treated sapwood and untreated heartwood (sapHT - heartNT)

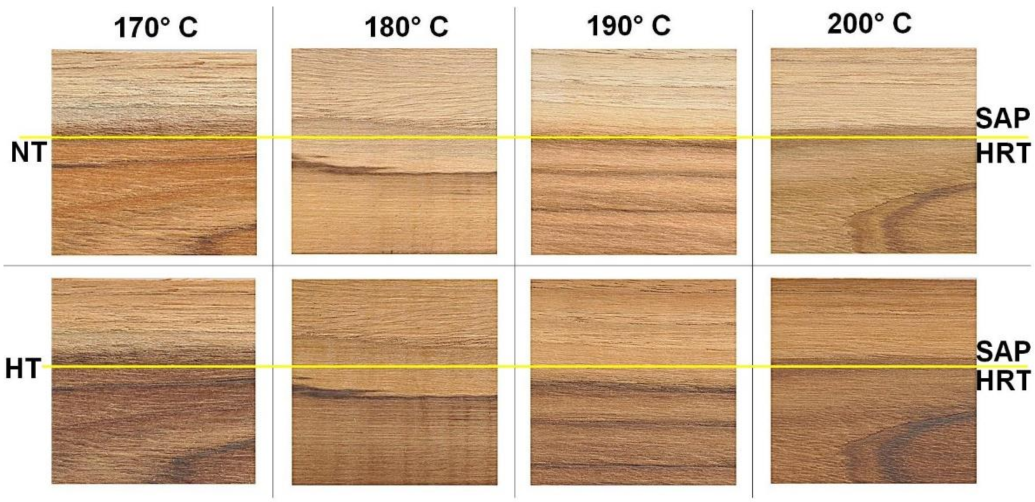

Fig. 7. Pictures of boards in calibrated light conditions containing both sapwood (SAP) and heartwood (HRT) before and after the treatments at different conditions

Figure 8 reports the ΔL and ΔE values plotted as a function of ML. The coordinate of lightness L^* decreased from 70 to 50 (sapwood) and from 50 to 40 (heartwood) depending on the ML, indicating the darkening of the wood. The coordinates a^* and b^* increased in sapwood and decreased in heartwood (Fig. 5). However, the most relevant colour variation related to the thermal treatment was due to the change in lightness (L^*).

The thermal treatment caused darkening of both sapwood and heartwood. For this reason, after treatment there was little change in the colour coordinate distance between sapwood and heartwood. Nevertheless, the thermal treatment reduced the distance sapHT – heartNT. In other words, it made the appearance of treated sapwood more similar to that of the natural heartwood.

Treatment at 170 °C for 5 h produced the smallest sapHT - heartNT difference, while treatments at T between 180 °C and 210 °C also exhibited a similar difference. Treatment at 200 °C for 3 h produced a negative ΔL value, meaning that the treated sapwood became darker than natural heartwood. A greater uniformity in wood teak pieces containing heartwood and sapwood, was observed by Lopes *et al.* (2014) after the thermal rectifier treatments under two temperature conditions, 180 and 200 °C, with the treatment at 200 °C being the most effective.

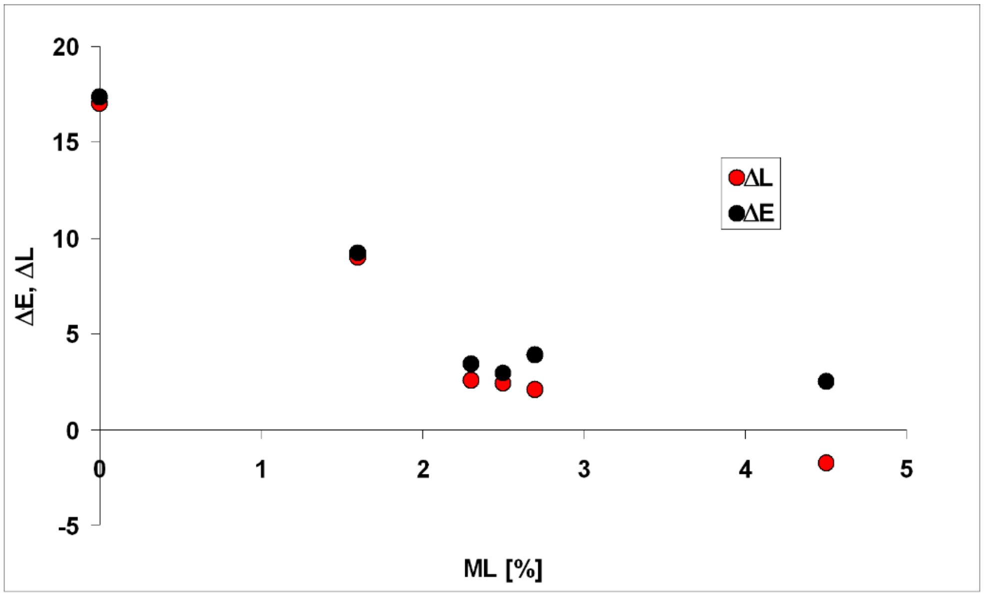

Fig. 8. Lightness change (Δ*L*) and total colour change (Δ*E*) *vs.* mass loss (ML)

CONCLUSIONS

1. The quality of the wood after the thermal treatment was generally fair, with low incidence of warps and visible cracks, lack of collapse, and no internal cracks or residual internal tensions. This is a relevant point considering that due to the high value of teak wood it is particularly important to minimize the losses arising during the processing phases.
2. In the untreated material, the sapwood was more hygroscopic and prone to deformation than heartwood (resulting for instance in $\beta_{V65\%}$ 4.0 compared to 2.7, respectively). The thermal modification reduced the hygroscopicity and increased the dimensional stability of the specimens in the range of 20% to 50% (depending on the level of ML reached).
3. Thermal modification reduced the difference of colour between treated sapwood and not treated heartwood. The shorter colour distance was obtained with treatments producing a ML higher than 2%, in the approximate range around 2.5% to 4% (180° < T < 200 °C). In this range, the Δ*E* varied from 18 for untreated wood to about 4. Based on this, it can be concluded that process producing ML > 4% (*T* > 200 °C) are probably not convenient.
4. The findings noted above suggest that, in the context of production, the thermo-vacuum process could be applied only to sapwood sawn boards pre-sorted according to the sapwood content. Later, treated sapwood and not treated heartwood could be machined and combined together in the final product with reduced problem of homogeneity. In this way it could be possible to increase the yield and quality of plantation teak and make its value closer to the teak from natural forests.

5. A characterisation of durability and mechanical properties is needed to refine and complete this work and to achieve a better identification of potential uses for plantation teak. Durability is expected to increase for *T* higher than 200-210 °C, which is out of the range of the present work. The reduction of mechanical properties is in general proportional to *T*.

ACKNOWLEDGMENTS

This work was carried out within the framework of scientific collaboration between Ivalsa CNR (Italy) and Novelteak S.A (Costa Rica). The authors would like to thank Dominique Y. Leuba (Novelteak) and Alessandro Calcaterra (Legnonord S.p.A.) for their technical support.

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Article submitted: November 17, 2016; Peer review completed: January 7, 2017; Revised version received and accepted: January 20, 2017; Published: January 26, 2017.
DOI: 10.15376/biores.12.1.1903-1915