

Heat Treatment of *Paulownia tomentosa* Steud. Wood

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Heat treatment of *Paulownia tomentosa* wood was studied relative to the physical and mechanical properties, with a view to expanding the potential fields of use of this species. Several physical properties (density, water absorption after 2 and 24 h, thickness swelling) and mechanical ones (strength and modulus of elasticity in static bending, tensile strength parallel to the grain and Brinell hardness) were evaluated. Most physical and mechanical properties of *Paulownia* wood were superior in the radial direction, with the exception of tensile strength, regardless of whether the samples were subjected to torrefaction treatment or not. In addition, the water affinity of heat-treated wood decreased significantly, with water absorption after 2 h of immersion reduced by 21% and tangential thickness swelling after 2 h of immersion reduced by 36.6%. The static flexural modulus of elasticity decreased by 12.1% at temperature of 160 °C treatment, by 39.9% for the 180 °C treatment and by 52.8% for the at temperature of 20 °C treatment.

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INTRODUCTION

Paulownia plantations have been known in China for nearly 3000 years, in the United States since 1800, and in Japan since 1970, when the exploitation of this tree's timber became a billion-dollar export business. *Paulownia* spp. is a deciduous species with typically ring-porous wood. It is a fast growing species, reaching maturity after only 8 to 10 years. The species *Paulownia tomentosa* was named in honour of Queen Anna Pavlovna of the Netherlands. Initially cultivated as an ornamental species, it was also called the princess tree, Kiri or the royal tree. It is appreciated for its remarkable spring blossoms and its very large leaves. Over time, it became a valuable timber species used by the wood-processing industry for furniture, panelling, decorative elements, indoor staircases and musical instruments (ISO 13061-4 2014). Today, *Paulownia* plantations represent a highly profitable business, capable of generating an annual income of up to 30.000 Euro/hectare. There are several *paulownia* species, including *Paulownia tomentosa*, *Paulownia fortune* and *Paulownia elongate*, as well as many clones adapted to different growing environments. Generally, *Paulownia* trees requires high air humidity and soil moisture levels and as much sunlight as possible throughout the year. These conditions ensure a rapid growth and early maturity of *Paulownia* trees.

The physical and mechanical properties of *Paulownia tomentosa* depend on the age

conditions of growth, as well as on the management of the stand. Figure 1 shows the microscopic structure of *Paulownia* wood, a hardwood species, which has pores typically arranged in rings in the early wood.

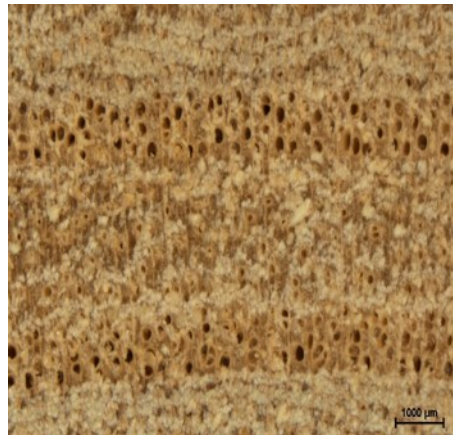


Fig. 1. Microscopic image of *Paulownia* wood

Paulownia is a lightweight species, having a density around 220 to 350 kg/m³, which is not much higher than that of balsa wood, the benchmark for the lowest density timber. The density of balsa wood is 160 kg/m³ (Gafiadas-Lopez *et al.* 2019).

Paulownia grows very quickly, reaching maturity in only 10 to 15 years when high-quality lumber is desired. Otherwise, the life cycle of *Paulownia* is 7 to 10 years. Its mechanical properties can be compared to those of many species that are moderately hard. Among all *Paulownia* species, *Paulownia tomentosa* is the most versatile. It is able to adapt and grow in high-altitude areas and even at a temperature as low as -20 °C (EN 1534 2000).

From an ecological perspective, due to its rapid growth, *Paulownia* spp. is environmentally friendly, capturing over 22 to 28 kg of carbon dioxide per year, while an average tree does not exceed 20 kg of carbon dioxide per year (Suri *et al.* 2021). Thus, over a life cycle of about 15 years for a *Paulownia* tree and 100 years for other deciduous tree and 100 years for other deciduous trees, each tree could absorb approximately 1000 kg of carbon dioxide through photosynthesis. In contrast, human activity has released about 40 billion tons of carbon dioxide into the atmosphere each year (Esteves *et al.* 2021).

Considering that there are roughly three trillion trees worldwide, each person on Earth has approximately 420 mature trees allocated to them (Pasztory *et al.* 2020). Even so, the global emission of 40 billion tons of carbon dioxide is offset by only about 30 billion tons through the world's existing forests (Akyildiz *et al.* 2010; Kaymakci *et al.* 2013; Koman and Feher 2017). Therefore, around 10 billion tons of carbon dioxide remain in the atmosphere, contributing to global warming through the greenhouse effect. To offset this deficit, an additional one thousand billion trees would be needed or, considering a planting density of 5,000 trees per hectare, an area of about 500 million hectares (Akhtary *et al.* 2012). From this perspective, FAO statistics indicate that global reforestation is not only stagnating but also declining, with approximately 5% of forested land lost annually due to deforestation and the conversion of forestland to agricultural use in poorer regions of the world. *Paulownia* production in Europe is increasing, especially in Romania, where there are large producers of seedlings and plantations. The crop is attractive to farmers due to the potential for timber.

The high demand for wood species has contributed to increased interest in alternative raw materials used in the processing industry. Many studies have used Paulownia wood in design projects due to its favorable qualities (Liese *et al.* 1987; Wagenfuhr 2000; Kaymakci 2010; Akyildiz *et al.* 2014).

Paulownia trees have gained significant global interest due to their relatively fast growth rate. This tree can produce a large amount of wood in a short period of time and can be used as construction timber within 5 to 20 years after planting and in good condition of air humidity (Ates *et al.* 2008; Ashori and Nourbakhsh 2009; ASTM D 1102-01; Caceres-Hidalgo 2016). *Paulownia* wood plays an important role in reducing the imbalance between wood supply and demand. Paulownia trees are fast-growing and have large leaves. For many years, *Paulownia* clones have been selected using direct selection related to growth rate, stem form, and wood color (Kaygin *et al.* 2015).

The heat-treatment process has been used for a long time, its main purpose being to improve certain wood properties, such as moisture behavior, durability and dimensional stability. This is a thermal process involving temperatures above 170 °C under low oxygen supply. When an inert nitrogen atmosphere is used, the temperatures can rise above 260 °C, eliminating the risk of self-ignition of the wood. During heat treatments the temperature acts on the hemicelluloses in the wood, these being the components most prone to absorbing water. The heat treatment degrades them and reduces their affinity for moisture content. Torrefaction as one of the main thermal treatments of wood can be performed at 180 to 210 °C under saturated steam in autoclaves and is called Thermo-Wood process. When the thermal treatment is realized in an oil bath its name is Thermo-Dyn process, the process would be realized by direct heating in chambers with hot air and a nitrogen atmosphere (Candan *et al.* 2013; Clapa *et al.* 2014; Jo *et al.* 2024). In the above case, the heat treatment was done in the Memmert laboratory oven at temperatures of 160, 180, and 200 °C, for 1, 2, and 3 h, respectively. As a result of the heat treatments, modification on the bending strength properties decreased slightly (Plistil *et al.* 2005).

Fan *et al.* (2015) examined the effect of thermal treatment on some properties of *Paulownia* wood panels. The results showed that some properties decreased with increasing pressing temperature. For instance, Gao (2019) reported that if the initial moisture content of the samples was 13%, after thermal treatments at 170 °C the moisture content decreased to 9%. The average density of the panels also decreased, while thickness swelling and water absorption values increased after thermal treatment. The above study suggests that thermal processes may not yield improvements in the density of *Paulownia* wood (Kaygin and Gunduz 2009; Chang *et al.* 2013; Icka and Damo 2016; Dogu *et al.* 2017; Feng *et al.* 2020). By analyzing the information provided by the authors mentioned above, it can be concluded that *Paulownia* wood exhibits a diameter growth of up to 90 mm/year while linden wood (*Tilia cordata*), for example shows an annual growth rate approximately ten times lower (Jey 1998; Khanjanzadeh *et al.* 2012; Jo *et al.* 2016; Owfi 2017; Nelis *et al.* 2018). The diameter of the *Paulownia* logs was 30 cm. Thus, the possibility of forestation of this wood species can be considered, both for soil stabilization and especially for using *Paulownia* wood as a substitute material to reduce pressure on traditional wood forests (Tang *et al.* 1980; Lawson 2010; Shtereva *et al.* 2014; Popescu and Sabau 2016; Qi *et al.* 2016; San *et al.* 2016; Esteves *et al.* 2021).

The main purpose of this study was to heat-treat *Paulownia tomentosa* wood and to determine the influence of this thermal process on the physical and mechanical properties. The main properties considered were: wood density, water absorption after 2

and 24 h of immersion, thickness swelling, static bending as strength and elasticity, tensile strength parallel to the grains, and Brinell hardness.

EXPERIMENTAL

Mass Loss Through Torrefaction

For this thermal treatment, 10 specimens with dimensions of $100 \times 20 \times 20$ mm were used. As a reference, non-torrefied *Paulownia tomentosa* wood was used. The samples were cut from clean timber, without knots or other defects that would influence the properties. These specimens were dried in a Memmert laboratory oven at 105°C to a constant mass and the initial mass was determined using a Kern-type analytical balance (Kaiser Kraft, Stuttgart, Germany). Afterwards, the thermal process was carried out at three successive temperatures, 160, 180, and 200°C . First, a temperature of 160°C was applied using the same oven, with the air intake valve closed. We are referring to equilibrium moisture content. The duration of the sample exposure was 2 h. Subsequent weighing was performed, and the mass loss was calculated using the following equations,

$$ML1 = \frac{m_i - m_{f160}}{m_i} \times 100 [\%] \quad (1)$$

$$ML2 = \frac{m_i - m_{f180}}{m_i} \times 100 [\%] \quad (2)$$

$$ML3 = \frac{m_i - m_{f200}}{m_i} \times 100 [\%] \quad (3)$$

where m_i is the initial mass of the specimen (g), and m_{f160} , m_{f180} , and m_{f200} are the final mass of the specimen after torrefaction at 160, 180, or 200°C , respectively (g).



Fig. 2. Samples of *Paulownia tomentosa* torrefied at 160°C , 180°C , and 200°C

Figure 2 shows wood samples for thermal treatment. Equations 1 to 3 show the mass loss of the samples. The equations were applied successively for each temperature to all 10 specimens. After torrefaction at a temperature of 160°C , the same samples were placed again in the oven, set at 180°C . At the end of the 2-h torrefaction period, the specimens were removed, weighed again and then reintroduced into the oven, set at a

temperature of 200 °C. After this final treatment, they were weighed once more. In this way, the influence of samples variability and individual characteristics on mass loss was eliminated.

Wood Density of the Samples

Wood density was determined before thermal treatment using 10 prismatic samples with a cross-section of 20 × 20 mm and a length of 100 mm, all free of defects. The samples were conditioned in a drying kiln to reach an average moisture content of 12%. After removal from the conditioning chamber, the samples were weighed using a Kern analytical balance and their three dimensions were measured. Based on these data, the wood density of the samples (D) was calculated.

Water Absorption of the Samples

Water absorption represents the amount of water that wood samples absorbed after being completely immersed in water, approximately 20 mm below the surface. The determination was performed after 2 h or 24 h of immersion. For the test, an immersion tank filled with clean water was used, equipped with two support bars that kept the samples 20 mm below the water level. Before testing, the samples were dried at a temperature of 105 °C to constant mass in order to determine the amount of water absorbed over the entire absorption field. A total of 10 samples of each type (torrefied and non-torrefied) were used. The test was performed successively, namely the samples were kept immersed for 2 h and were weighed before and after immersion. They remained immersed until 24 h, after which a final weighing was performed. After each immersion period, the samples were gently blotted with absorbent paper to remove excess surface water adhering to the samples. For the calculations, the initial mass of the samples was used as the reference value, and the following equations were applied,

$$A_{2h} = \frac{m_{2h} - m_0}{m_0} \cdot 100 [\%] \quad (4)$$

$$A_{24} = \frac{m_{24h} - m_0}{m_0} \cdot 100 [\%] \quad (5)$$

where A_{2h} is the water absorption after 2 h of immersion (%), m_{2h} is the mass of the samples after 2 h of immersion in water, m_0 is the mass of samples at the initial moment of immersion, A_{24h} is the water absorption after 24 h of immersion (g), and m_{24h} is the mass of the samples after 2 h of immersion in water.

Thickness Swelling of the Sample

Thickness swelling was measured in both the radial and tangential directions. For this purpose, samples (with dimensions of 100 x 20 x 20 mm) were selected so that the structural directions relative to the grain orientation (longitudinal direction) could be clearly identified during cutting. Swelling in the longitudinal direction was not determined, as it was extremely small-well below 0.1 %. The test procedure was similar to the water absorption test, but in this case the dimensions of the samples were measured using a digital caliper with an accuracy of two decimal places. The following calculations were used,

$$S_{r2h} = \frac{t_{r2h} - t_{r0}}{t_{r0}} \cdot 100 [\%] \quad (6)$$

$$S_{r24h} = \frac{t_{r24h} - t_{r0}}{t_{r0}} \cdot 100 [\%] \quad (7)$$

$$S_{t2h} = \frac{t_{t2h} - t_{t0}}{t_{t0}} \cdot 100 [\%] \quad (8)$$

$$S_{t24h} = \frac{t_{t24h} - t_{t0}}{t_{t0}} \cdot 100 [\%] \quad (9)$$

where S_{r2h} is the radial swelling after 2 h of immersion (%), S_{r24h} is the radial thickness swelling after 24 h of immersion (%), S_{t2h} is the tangential thickness swelling after 2 h of immersion (%), S_{t24h} is the tangential thickness after 24 h in immersion (%), t_{r2h} is the thickness radial direction after 2 h of immersion (%), t_{r0} is the initial thickness in the radial direction, t_{r24h} is the thickness in the radial direction after 24 h of immersion in water (mm), t_{t2h} is the thickness in the radial direction after 2 h of immersion in water (mm), t_{t0} is the initial thickness in the tangential direction (mm), and t_{t24h} is the thickness in the tangential direction after 24 h of immersion.

Because the longitudinal swelling was negligible, the volumetric swelling was calculated as the sum of the radial and tangential thickness swellings.

Static Bending Strength and Modulus of Elasticity of the Samples

Among the mechanical properties of wood, static bending strength is the most important, as it classifies wood species into high-strength, medium-strength, and low-strength categories. The bending strength machine type WA (China) was used. The distance between supports was set to 240 mm, meaning that the total length of the samples was 300 mm, with 30 mm extending beyond each support point during testing. The cross-sectional dimensions of the bending samples were 20 x 20 mm, and the loading speed during the test was 10 mm/min (Fig. 3).



Fig. 3. Torrefied bending testing specimens after testing

The formulas used were the following,

$$\sigma_i = \frac{3 \cdot F_{\max} \cdot l}{2 \cdot b \cdot t^2} \text{ [N/mm}^2\text{]} \quad (10)$$

$$E_m = \frac{l_1^3 \cdot (F_1 - F_2)}{4 \cdot b \cdot t^3 \cdot (a_2 - a_1)} \text{ [N/mm}^2\text{]} \quad (11)$$

where σ_i is the static bending strength (N/mm²), $F_{\max}$ is the maximum breaking force of the specimen (mm), l is the distance between supports (mm), b is the width of the specimen (mm), t is the average thickness of the specimen (mm), E_m is the modulus of elasticity in static bending (N/mm²), F_2 is the force corresponding to 40% of the total breaking force

(N), F_1 is the force corresponding to 10% of the maximum breaking force (N), a_2 is the deformation corresponding to force F_2 (N), and a_1 is the deformation corresponding to force F_1 (N).

Tensile Strength Parallel to the Grain of the Samples

Tensile strength is characterized by special-dimension samples, having a milled central section, designed to weaken the cross-section, so that failure can occur in that region. This is necessary because the tensile strength of wood is lower than its compressive strength, and during testing the samples have significant compression in the gripping zone between the machine jaws. Additionally, to avoid introducing stress concentrators, the ends of the milled section were rounded with a radius of 30 mm (Fig. 4).



Fig. 4. Tensile strength parallel to the grain of the samples

Brinell Hardness

Brinell hardness aims to determine the resistance of the wood surface to indentation, obtained by a steel indenter with a constant diameter of 10 mm, which compresses or crushes the surface. The penetration force is constant and depends on the density of the wood species. Due to the low density of *Paulownia* wood, a force of 200 daN was selected. Immediately after applying the force of 200 daN, it was maintained for 25 seconds to allow the indentation to be stabilized on each of the samples. The Brinell hardness value was then determined using the following calculation,

$$HB = \frac{2 \cdot P}{\pi \cdot D(D - \sqrt{D^2 - d^2})} \text{ [N/mm}^2\text{]} \quad (12)$$

where HB is the Brinell hardness (N/mm²), P is the applied force (N), D is the diameter of the steel ball indenter (m), and d is the diameter of the indentation left on the samples, measuring that use carbon paper for a good visualizing of trash (mm).

Compressive Strength Parallel to the Grain of the Samples

The strength was determined using 10 samples with dimensions of 20 × 20 × 100 mm, with the force applied parallel to the wood grain using two flat loading plates. During the test, the force decreased noticeably and then remained constant, when shearing occurred along the transverse cross-section of the samples. The compression strength was calculated as the ratio between the maximum breaking force and the cross-section area of the samples, using the following relationship,

$$\sigma_c = \frac{F_{max}}{b \cdot t} \text{ [N/mm}^2\text{]} \quad (13)$$

where σ_c is the compressive strength (N/mm²), F_{max} is the maximum applied force (N), b is the width of the samples (mm), and t is the thickness of the samples (mm).

Statistical Analysis

The test results for each experiment were cumulated in the tables, first using Microsoft Excel, where the arithmetic mean, sample median, standard deviation and coefficient of variation were calculated. Variation graphs were also created to visually observe differences, using either the same software or the Minitab program, which also provides additional statistical parameters.

RESULTS AND DISCUSSION

After the statistical values were analysed for each test, the visualisation graphs were created in order to illustrate the differences between torrefied and non-torrefied *Paulownia* wood, as well as other interdependencies between them.

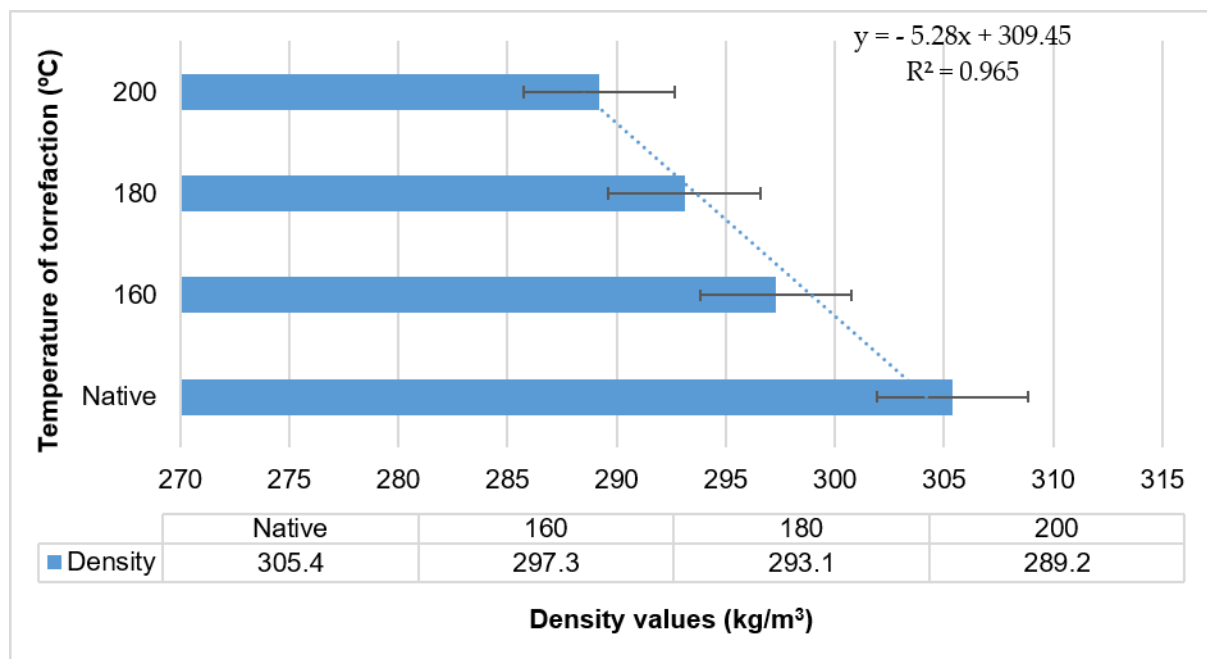


Fig. 5. Decrease in Paulownia wood density during torrefaction treatment

Density of Paulownia Wood

The density of non-torrefied wood was 305.4 kg/m³, while the density of torrefied wood decreased depending on the torrefaction level, reaching 289.2 kg/m³ at the maximum temperature of 200 °C (Fig. 5).

Degree of Torrefaction

Initially, it was assumed that the factors influencing the degree of torrefaction were temperature and treatment duration. During the thermal treatment, treatment duration had

little influence, which led to reducing the thermal treatment time to only 2 h. Thus, the treatment temperature remained the main factor affecting the torrefaction of *Paulownia* wood, as shown in Fig. 6. For example, if the temperature had been 180 °C, the predicted mass loss would have been 4.06%; and if the temperature had reached 200 °C, the mass loss would have increased to 5.31%. These values were obtained both by reading the graph and by using the linear dependency equation presented there. Furthermore, the mass losses were very close to the density losses (Fig. 5), because during torrefaction the samples volume did not change significantly, the main change being their mass.

Taking the mass loss at a temperature of 160 °C as the reference point, at the next temperature of at a temperature of 180 °C, the increase in mass loss was 53.2%. At the next increase at 200 °C, the increase relative to the previous temperature was 30.7%, and the total increase relative to at a temperature of 160 °C reached 100.3%, *i.e.*, the mass loss was doubled compared to the initial temperature.

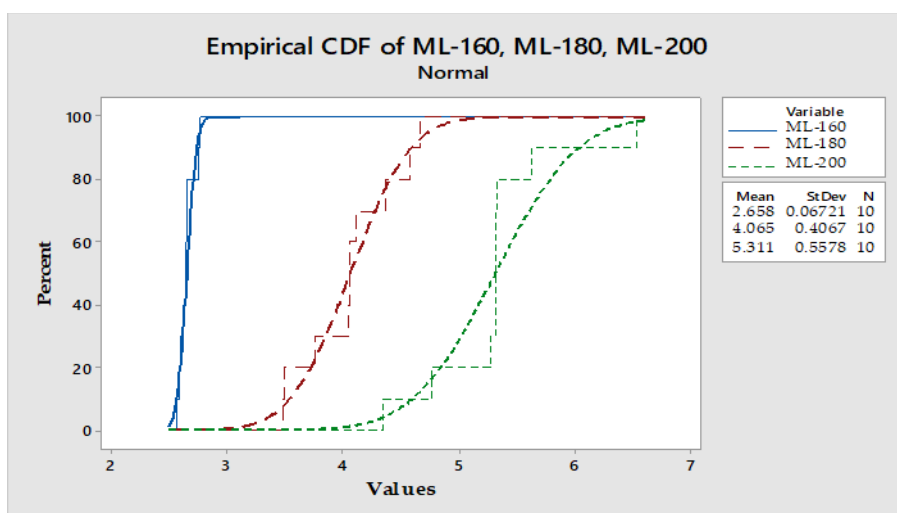


Fig. 6. Empirical CDF for mass losses during torrefaction of *Paulownia* wood: ML-160 is the mass loss at the temperature of 160 °C; ML-180 is the mass loss at the temperature of 180 °C; ML-200 is the mass loss at the temperature of 200 °C.

Water Absorption after 2 h and 24 h

The amount of absorbed water varied depending on the immersion duration of 2 or 24 h, but especially on whether the *Paulownia* wood was torrefied or non-torrefied. For the torrefied category, the wood treated at a temperature of 200 °C was selected for comparison, since the degrees of torrefaction at the other temperatures were already known, as shown in Fig. 7.

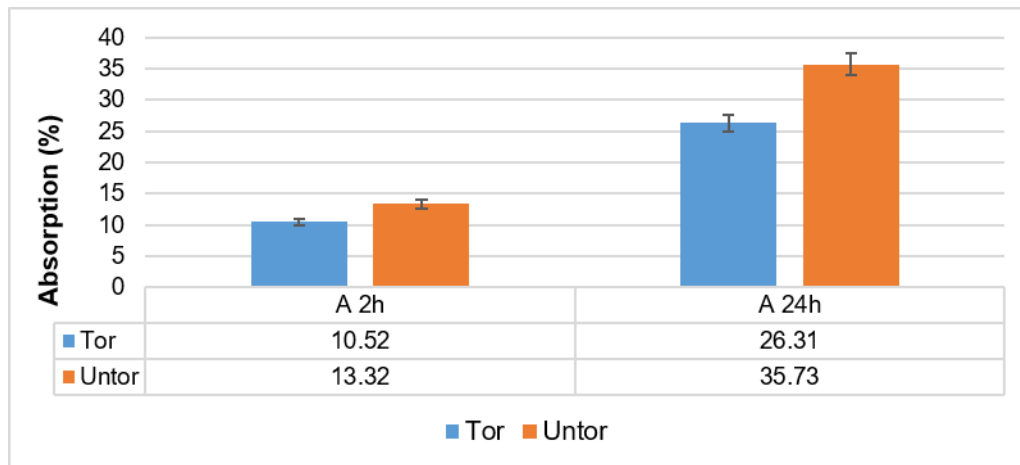


Fig. 7. Water absorption of torrefied and non-torrefied *Paulownia* wood: A2h –absorption after 2 h, A24h-absorption after 24 h; Tor-torrefied wood; Untor-non-torrefied wood

Figure 8 presents the samples used for the bending test.



Fig. 8. Samples used for the bending test

Thickness Swelling

The thickness swelling of *Paulownia* wood differed between the two main structural directions (tangential and radial) for both torrefied wood at a temperature of 200 °C and non-torrefied wood. Thus, for torrefied wood after 2 h of immersion, tangential swelling was 80% higher than radial swelling and by 63% higher after 24 h of immersion as shown in Fig. 9.

The thickness swelling of *Paulownia* wood differed between the two main structural directions (tangential and radial) for both torrefied wood at a temperature of 200 °C and non-torrefied wood. For non-torrefied wood after 2 h of immersion, tangential swelling was 70% higher than radial swelling and by 79% higher than radial swelling after 24 h of immersion.

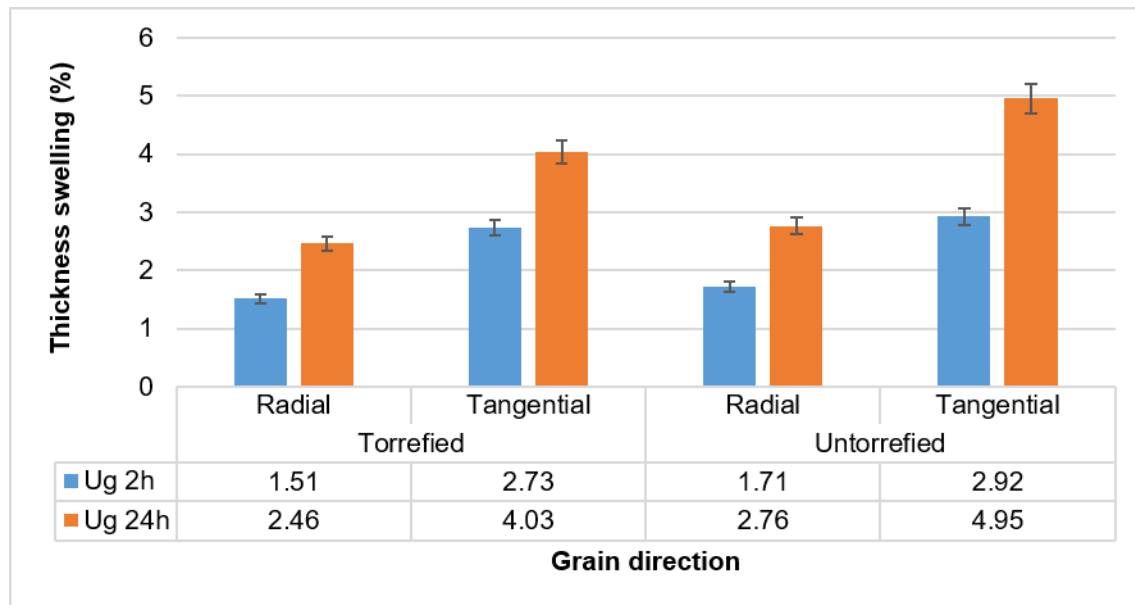


Fig. 9. Thickness swelling in tangential and radial directions

Brinell Hardness

A slight surface degradation of the torrefied wood was observed. The outer surface was dark because the hemicellulose degraded in time of the torrefaction processes. The eliminated volatile compounds and temperatures give to the wood surface a dark colour. As a result, during the Brinell test, the indentation diameters increased slightly and the Brinell hardness decreased accordingly. Because the diameter differences were very small, two perpendicular measurements of each indentation were taken, and the precise diameter was determined using a Brinell microscope. The results are shown in Fig. 10.

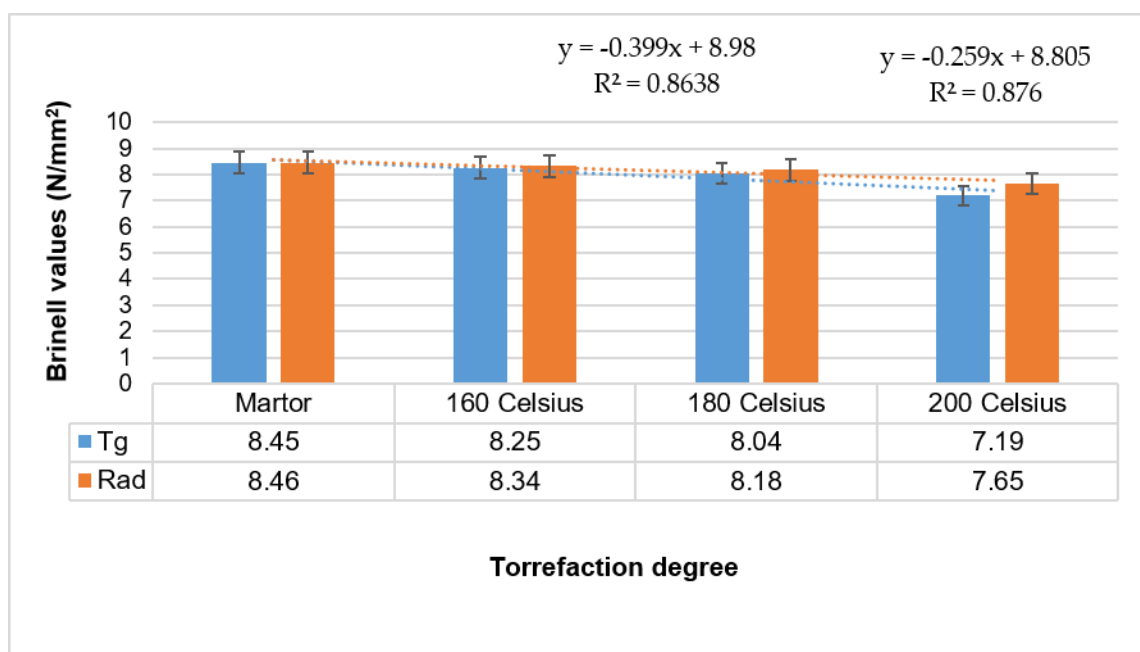


Fig. 10. Brinell hardness: Tg. - tangential; Rad - radial

Brinell hardness was determined on both torrefied and non-torrefied samples, in the radial and tangential grain directions. Compared to the non-torrefied control samples, Brinell hardness decreased as follows: at a temperature of 160 °C, by 2.3% in the tangential direction and 1.4% in the radial direction; at a temperature of 180 °C, by 4.8% in the tangential direction and 3.3% in the radial direction; at a temperature of 200 °C, by 14.9% in the tangential direction and 9.5% in the radial direction.

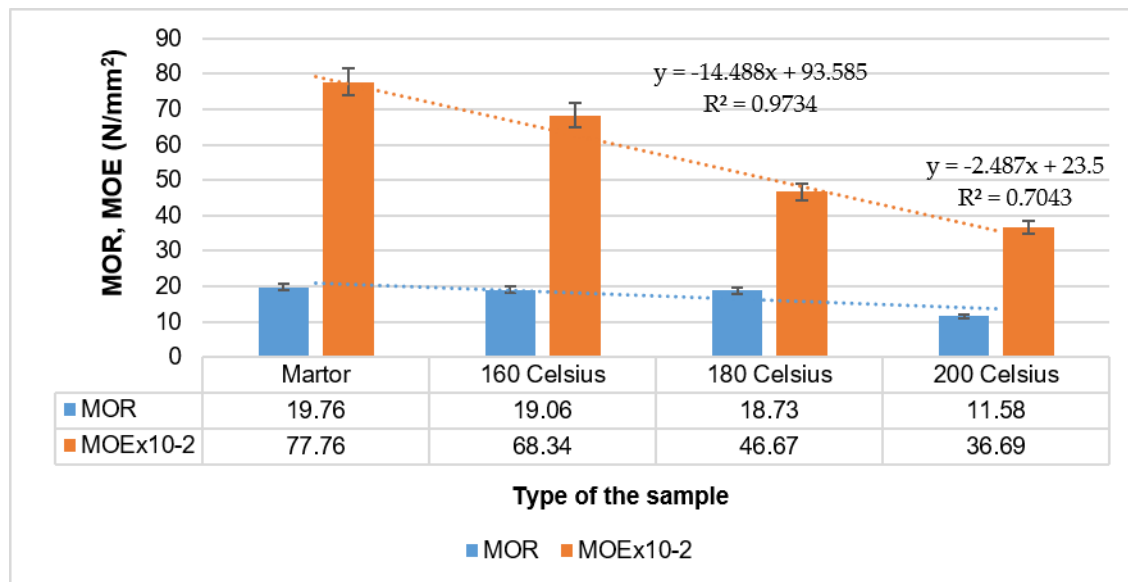


Fig. 11. Static bending strength and modulus of elasticity: MOR-static bending modulus of rupture; MOE- static bending modulus of elasticity

Bending Strength Results Modulus of Rupture (MOR) and Modulus of Elasticity (MOE)

As shown in Fig. 11, the static flexural modulus of elasticity decreased by 12.1% at temperature of 160 °C treatment, by 39.9% for the 180 °C treatment and by 52.8% for the at temperature of 200 °C treatment.

Tensile Strength Parallel to the Grain

The tensile strength parallel to the wood grain decreased during the torrefaction process, by 45.2% in the radial direction and by 34.5% in the tangential direction. It was observed that the strength values decreased by 3.5% for the treatment at 160 °C, by 5.2% for the treatment at a temperature of 180 °C, and by 41.3% for the treatment at a temperature of 200 °C. The modulus of elasticity in static bending decreased by 12.1% for the treatment at a temperature of 160 °C, by 39.9% for the treatment at a temperature of 200 °C. Tensile strength also has differed within each type of specimen, being lower in the radial direction by 19.9% for the torrefied specimens and by 4.3% for the non-torrefied samples. Thus, the non-torrefied samples are more homogeneous from this point of the tensile strength parallel to the wood grain, compared to the torrefied ones.

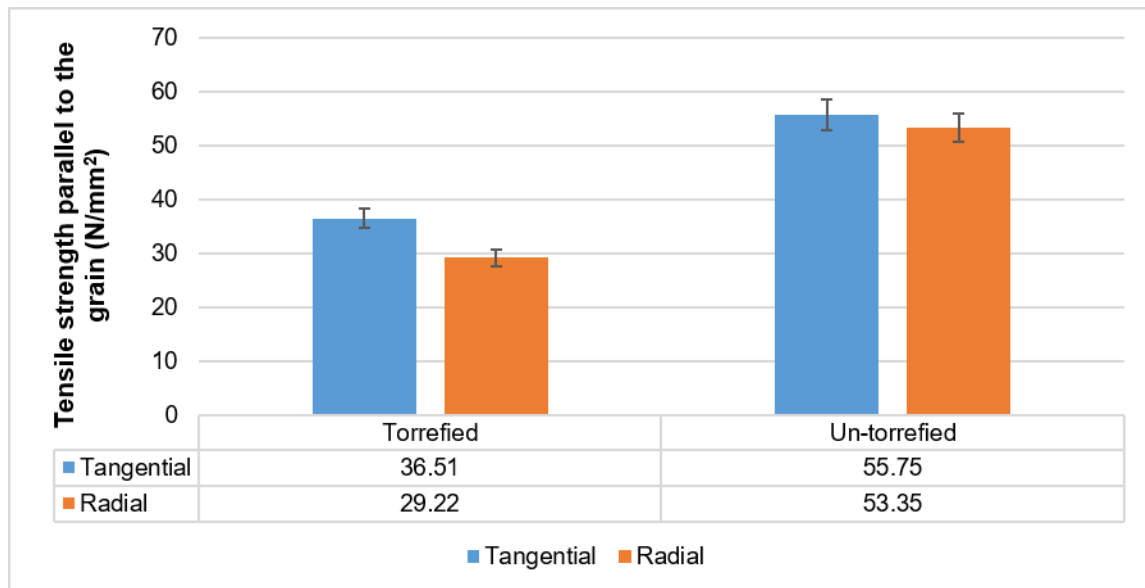


Fig. 12. Tensile strength parallel to the grain



Fig. 13. The samples for tensile strength parallel to the wooden fibers

Figure 13 presents the samples for tensile strength parallel to the wood grain. Most of the fractures occurred in the central area of the specimens, where the milling to weaken the sections was performed.

This research started from the hypothesis that the torrefaction treatment will have improvements in dimensional stability and some deficiencies in mechanical properties. The results obtained demonstrated the viability of the two hypotheses, namely good results were obtained in terms of water absorption and swelling of the torrefied samples, and the mechanical properties decreased slightly. In addition, the density of the torrefied wood decreased slightly, which may be beneficial for some certain uses of it (Table 1).

Table 1. Centralized Results

No.	Property	Value for torrefied	Value for un-torrefied
1	Water absorption (2h), %	10.5	13.3
2	Thickness swelling (tang), %	2.7	2.9*
3	Brinell hardness (tang), N/mm ²	7.1	8.4
4	MOR (0-200 °C), N/mm ²	11.5	19.7
5	MOE (0-200 °C), N/mm ²	3,650	7,770
6	Tensile parallel (tang), N/mm ²	36.5	55.7
* This value is not significant as standard deviation			

The decrease in density cannot be separated from the significant reduction in the mechanical properties. The decrease in density is primarily due to the degradation of hemicelluloses and the evaporation of extractive substances (Caceres-Hidalgo 2016). Density decreased both with increasing treatment temperature, but not with treatment duration (Candan *et al.* 2013; Kaigin *et al.* 2015). Calculations showed that the wood density decreased steadily during torrefaction by 2.6% at a temperature of 160 °C, by 4.0% at a temperature of 180 °C and by 5.3% at a temperature of 200 °C. Hemicelluloses are responsible for the flexibility of wood. Therefore, the significant reduction in hemicellulose content may be one of the main reasons for the decrease in bending elasticity. The increase in lignin content may be responsible for the higher stiffness of the wood.

Most studies employed experimental designs testing with multiple temperature values. Treatment temperatures ranged from 150 °C up to a temperature of 220 °C across studies. Notable methodological variation included the use of mechanical restraint through clamping in two studies, and thermal treatment techniques at elevated pressures (Kaygin and Gunduz 2009; Icka and Damo 2016). In the present study the mass losses at different torrefaction temperatures by 2.65%, 4.06%, and 5.31% were proportional, and the coefficient $R^2 = 0.99$ shows that the linear approximation of this proportionality is accurate. This indicates that for other temperature values, the linear equation shown in Fig. 6 can be used reliably in 99% of cases. Usually, mass loss increased systematically with treatment intensity. At a temperature of 200 °C for 7 h, maximum mass loss reached 9.78% (Jey 1998). Density decreased by 5.6% at 180 °C, 8.9% at a temperature of 200 °C, and 14.1% at a temperature of 220 °C. The relationship between temperature and mass loss was consistent across all studies, because higher temperatures produce greater material degradation (Hidayat *et al.* 2017; Owfi 2017).

The mechanical property reductions showed dose-response relationships. At the most severe treatment condition (200 °C, 7 h), bending strength decreased by 78% and impact strength by 88%, representing near-complete loss of these properties. In contrast, more moderate conditions (212 °C Thermo-Wood process) resulted in a 50% reduction in bending strength, suggesting a threshold effect where extreme conditions produce disproportionate damage. The static flexural modulus of rupture (MOR) and static flexural modulus of elasticity were determined simultaneously on the same testing machine, and the values decreased significantly during torrefaction, as shown in Fig. 11. It was observed that the resistance values decreased by 3.5% at a temperature of 160 °C, by 5.2% at a temperature of 180 °C treatment, and by 41.3% at a temperature of 200 °C treatment. Differences in Brinell hardness were also observed solely due to grain direction:

- For the control sample, an increase of 0.5% in the tangential direction compared to the radial direction;
- For the samples treated at a temperature of 160 °C, an increase of 0.01% in the

- tangential direction compared to the radial direction;
- For the samples treated at a temperature of 180 °C, an increase of 0.1% in the tangential direction compared to the radial direction;
- For the samples treated at a temperature of 200 °C, an increase of 6.3% in the tangential direction compared to the radial direction

Statistical analysis confirmed that changes were significant, and a high correlation (1% significance level) existed between modulus of elasticity and modulus of rupture.

Dimensional stability is one of the most important properties of wood, as dimensional changes between dry and humid states lead to the formation of cracks and consequently to some mechanical degradation. If the swelling of torrefied wood is compared with that of non-torrefied wood, the following 4 conclusions can be drawn:

- When immersion lasted 2 h and the direction was radial, thickness swelling was 13.4% lower in torrefied wood compared to non-torrefied wood.
- When immersion lasted 2 h and the direction was tangential, thickness swelling was 6.9% lower in torrefied wood compared to non-torrefied wood.
- When immersion lasted 24 h and the direction was tangential, thickness swelling was 22.8% lower in torrefied wood compared to non-torrefied wood.
- When immersion lasted 24 h and the direction was radial, thickness swelling was 12.1% lower in torrefied wood compared to non-torrefied wood.

CONCLUSIONS

1. This study aimed to determine the properties of *Paulownia tomentosa* wood subjected to thermal treatment, with the purpose of evaluating its potential as an alternative material for exterior facades with variation of air humidity and temperature.
2. The thermal treatment process decreased density of *Paulownia* wood in a manner similar to the decrease in bending strength or for other mechanical strength. A higher treatment temperature would improve dimensional stability (thickness swelling and water absorption). Thus, for torrefied wood after 2 h of immersion, tangential swelling was 80% higher than radial swelling and by 63% higher after 24 h of immersion.
3. As the main conclusion of the work, it can be summarized that the heat-treatment of *Paulownia* wood improved some properties in terms of its relationship with water. The treatment makes it possible to use the wood in new ways in exterior spaces, where high of different humidity and temperatures may be encountered.

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