The Influence of Thermal Treatment on the Compressive Strength and Density of Bamboo (*Guadua angustifolia* Kunth)

Ricardo Acosta,[a,]* Jorge A. Montoya,[b] and Carlos A. Londoño [c]

Lignocellulosic materials that are thermally treated *via* hydrolysis react chemically, modifying their internal structure, which in turn modifies their physical and mechanical properties, as well as their dimensional stability. Bamboo (*Guadua angustifolia* Kunth) samples 3 years old, without nodes and without skin, obtained from their basal area were subjected to thermal treatment with temperatures between 160 and 200 °C and duration times between 1 h and 4 h. The severity of the thermal treatment affects the modulus of rupture and modulus of elasticity in compression. The modulus of rupture increased at temperatures up to 180 °C with treatment times of 2 h, *i.e.*, the severity, defined as the product of the temperature and the time varied between 320 (°C*h) and 360 (°C*h). An inflection point was obtained at a temperature of 180 °C after 2 h with a maximum value of 115.1 MPa. The modulus of elasticity increased as the temperature and time increased. The modulus of rupture and the modulus of elasticity of the treated samples increased up to 14.7% and 36.1%, respectively, compared to the not thermal treated samples. Additionally, when the density increased, the resistance and the compression stiffness also increased.

Keywords: Bamboo; Guadua angustifolia Kunth; Compression test; Density analysis; Physical properties; Mechanical properties; Thermal treatment

Contact information: a: Facultad de Tecnología, Universidad Tecnológica de Pereira, Pereira 660003 Colombia; b: Facultad de Ciencias Ambientales, Universidad Tecnológica de Pereira, Pereira, Colombia; c: Facultad de Ciencias Básicas, Universidad Tecnológica de Pereira, Pereira 660003 Colombia;
** Corresponding author: ricosta@utp.edu.co*

INTRODUCTION

The need of people to adapt to demanding, accelerating, and changing living conditions has led them to make improvements in production processes and consequently make improvements in the raw materials used during these processes to further increase effectiveness. Technological materials, *e.g.* steel and natural materials, *e.g.* wood, have been the subject of study in terms of improving their chemical, physical, and mechanical properties, as well as achieving standardized processes and finding a suitable alternative in thermal treatments (TT).

Wood, through its transformation, can offer competitive advantages over other materials in terms of construction. Ramage *et al.* (2017) presented multiple options for the use of this natural material. Out of these options, TT stands out, *i.e.*, a controlled processes of the addition and extraction of heat that use different means and conditions to modify the microstructure of the material and improve its properties (Mbamu *et al.* 2020). Thermal modification is a promising ecological technique to increase the water repellency and decay resistance of wood-based products (Yang *et al.* 2016; Ghadge and Pandey 2017; Barnes *et* *al.* 2018). Therefore, thermally modified wood is considered a new material for different applications (Sahin 2017).

Thermal treatments are carried out *via* pyrolysis or hydrolysis. For pyrolysis, it is necessary to dry the wood prior to treatment, the system is open, and works at atmospheric pressure with high temperatures. However, the process takes a long time and therefore has a high energy consumption and emission generation. For hydrolysis, it is not necessary to dry the wood prior to treatment, the system is closed, and high pressures and relatively low temperatures are applied. Heat is added to the material until a value close to the pyrolysis temperature is obtained, in an oxygen-free environment to avoid combustion. Subsequently, the temperature is kept constant for a period of time (duration of the TT), and finally a controlled cooling process is carried out so that the modified material is conditioned. Therefore, the process requires less time and has a lower energy consumption and emission generation when compared to pyrolysis (Klaas 2019).

Thermal treatments in wood change its chemical composition, its color, cause a loss of mass, lower its equilibrium moisture content (EMC), as well as improve its dimensional stability and its biological durability, without adding external chemicals or biocides (Tjeerdsma and Militz 2005; Yang *et al.* 2016). Although physical properties improve, some mechanical properties of wood decrease during TT at high temperatures, due to the degradation of hemicelluloses (Esteves *et al.* 2013; Sahin 2017). A variation of these processes are hydrothermal treatments, which produce a major change in the composition of hemicelluloses (decrease) and lignins (increase); the polycondensation reactions of lignins result in greater resistance in the longitudinal direction, in addition to increased compressive strength and stiffness (Boonstra *et al.* 2007).

Bamboo is a natural material like wood, as well as being abundant, widely studied, with demonstrated substitute capacity for wood, and potential as a structural material. However, little work has been performed studying the effects of technological processes on the properties of bamboo and even less have been performed related to its TT (Sharma *et al.* 2014, 2015a,b; Yang *et al.* 2016; Yun *et al.* 2016; Xu *et al.* 2019; Mbamu *et al.* 2020). For these reasons, it is important to obtain reliable technical information to establish the benefits and their applicable implications in the processing, transformation, and commercialization of bamboo. Studies carried out have obtained reinforced composites (Zakikhani *et al.* 2014), laminated bamboo, (Xiao *et al.* 2013; Sharma *et al.* 2014; Takeuchi 2014; Archila 2015; Brito *et al.* 2018; Yang and Lee 2018; Xu 2019) and compacted bamboo (Sharma *et al.* 2015a; Shangguan *et al.* 2016; Zhong *et al.* 2016); these studies made it possible to improve the usage of this natural resource. However, a deeper understanding of the behavior of bamboo subjected to TT is needed to broaden its range of application.

Thermal treatments in bamboo change their chemical composition and their color; the EMC gradually decreases due to the degradation of hemicelluloses, and the cellulose and lignin content increases (Wang *et al.* 2020a). This lower moisture absorption can positively contribute to improving the dimensional stability and the durability of bamboo stems (Yang *et al.* 2016; Meng *et al.* 2016; Yang and Lee 2018; Wang *et al.* 2020b). In addition, with TT, the resistance to decomposition increases when the bamboo is exposed to severe environmental conditions (Brito *et al.* 2020). With increasing temperature and duration of the TT, the mass loss increases and the density decreases (Nguyen *et al.* 2012; Shangguan *et al.* 2016; Yang *et al.* 2016; Ghadge and Pandey 2017). Research has determined that the thermal processing method influences the mechanical properties of bamboo (Sharma *et al.* 2015b; Yang *et al.* 2016; Yun *et al.* 2016; Ghadge and Pandey 2017;

Magalhães *et al.* 2017; Brito *et al.* 2018; Yang and Lee 2018; Mbamu *et al.* 2020; Wang *et al.* 2020a). It affects the bending behavior and properties, its resistance to compression and shear forces parallel to the grain increases, while the perpendicular resistance to compression and tension parallel to the grain decreases (Sharma *et al.* 2015b). The specific effect of TT on the mechanical properties, specifically the resistance to compression of Colombian *Guadua angustifolia*, should be further investigated.

One of the important parameters of TT is the severity, considering that it affects the mechanical properties of bamboo, as well as increases the anti-inflammatory efficacy and anti-swelling efficiency (Ghadge and Pandey 2017; Wang *et al.* 2020b). Some authors propose evaluating the severity by considering the color or the change in density of the material (Nguyen *et al.* 2012), while other authors propose evaluating the area under the curve after the temperature exceeds 100 °C, there is a certain weight loss, or there is a certain amount of heat supplied. The severity depends on the modification conditions, *i.e.*, the temperature and duration of the modification, where the temperature has greater influence compared to the duration (Ghadge and Pandey 2017). For this work, it was defined as the product of temperature and time.

Investigations into TT, resistance testing in terms of compression, and the modulus of elasticity (MOE) of different bamboo species have discovered the following: Guarín (2004) found for the basal section of *Guadua angustifolia* Kunth (*G*aK), the peripheral zone and transition without node, with a height (h) to thickness (t) ratio equal four (h / t = 4), moisture content (MC) of 10%, had a modulus of rupture (MOR) of 137.6 MPa and a MOE of 118.3 MPa in samples without TT. González *et al.* (2008) evaluated *G*aK bamboo specimens without TT and found an average compressive stress of 28.8 MPa. This test was carried out following the ISO standard 22157-1 (2004) and ISO standard 22157-2 (2004). Díaz (2012) investigated the mechanical properties of *Ga*K bamboo that had not undergone TT and found an average basal compression stress of 36.3 MPa and a MOE of 3582 MPa. This test was carried out according to NTC standard 5525 (2007).

Takeuchi and González (2007) used *Ga*K bamboo samples that had not undergone TT and obtained an average compressive strength parallel to the basal fiber of 56.4 MPa and a MOE of 18130 MPa. This test was carried out according to ISO standard 22156 (2004), ISO standard 22157-1 (2004), and ISO standard 165 (1999). Later Takeuchi (2014) tested specimens of *Ga*K bamboo sheets (relationship h/t = 2), with no nodes and that had not undergone TT, at a relative humidity (RH) of 65%, a temperature of 20 °C, and a moisture content (MC) of 12%. These specimens had a MOR of 69.2 MPa and a MOE of 19559 MPa. This test was carried out following the NTC standard 5525 (2007). Correal and Arbelaez (2010) investigated the mechanical properties of *Ga*K bamboo that had not undergone TT and found an average basal area compression stress of 36.6 MPa and a MOE of 16.8 MPa. This test was carried out following the NTC standard 5525 (2007) and ISO standard 22157-1 (2004).

Shangguan *et al.* (2016) used scrimber bamboo samples that had been thermally treated at temperatures between 50 °C to 230 °C for 2 h and the samples were placed at room temperature for 24 h. The compressive strength reached a maximum when the fiber bundles were cleanly fractured at a temperature of 170 °C, which was a turning point for the physical, mechanical, and chemical properties under these TT conditions. The compressive strength parallel to the fiber was determined according to GB standard 1935 (2009). Zhong *et al.* (2016) evaluated scrimber bamboo samples that had been thermally treated at temperatures between 20 °C to 225 °C. The samples were conditioned at a RH of 65%, a temperature of 20 °C, and a MC of 8.2%. The influence of the temperature on the compressive strength parallel to the fiber was determined and the average compressive strength parallel to the fiber was found to be 133 MPa at a temperature of 20 °C, 61.4 MPa during firing, and 115 MPa after firing (a temperature of 225 °C). The results showed that 175 °C was a key tipping point, at which the cellulose in the bamboo and the phenolic compounds in the resin were thermally decomposed. This test was carried out in accordance with GB standard 1935 (2009).

Magalhães *et al.* (2017) used *Dendrocalamus asper* bamboo samples that had been thermally modified under standard atmospheric conditions, in a conventional muffle furnace (Jung, model 10010) and an adapted microwave oven. The working temperatures were 120 °C, 140 °C, and 160 °C, with a heating rate of 1 °C/min and an isotherm of 10 min. The study found a similar MOR after TT in a microwave oven and muffle furnace at 120 °C (77.4 and 83.2 MPa) with an MOE of 4.6 and 4.7 GPa, respectively. The thermally treated bamboo increased in stiffness and resistance after undergoing treatment (a MOE of 3.4 GPa and a MOR of 73.6 MPa) when compared with the untreated bamboo samples. The study by Magalhães *et al.* (2017) was based on the NBR standard 7190 (1996). Wang *et al.* (2020a) used natural moso bamboo samples (*Phyllostachys pubescens* L). The TT had the following conditions: a temperature of 180 °C, a duration of 10 min, 20 min, 30 min, 40 min, and 50 min, and a moisture content of 25%, 30%, 40%, 50% and 65%. In the first 20 min during the saturated steam TT (VS), the compressive strength with an initial moisture content of 65% increased, reaching a maximum of 100.5 MPa. The resistance along the bamboo fibers in samples with a lower initial moisture content (25% and 30%) decreased. The tests were carried out according to GB/T standard 15780 (1995).

Wang *et al.* (2020b) subjected samples of moso bamboo (*Phyllostachys heterocycle* (Carr.) Mitford cv. *pubescens*) to TT with VS at temperatures of 140 °C, 160 °C, and 180 °C for 10 min to 30 min, under VS at a temperature of 140 °C; the density, flexural strength, and elastic modulus of these samples increased slightly. However, the trend was opposite when the VS temperature was higher than 160 °C. A TT with a high temperature VS (30 min at 160 °C or 10 min at 180 °C) was found to be the best conditions for bamboo. The tests were carried out in accordance with ASTM standard D1037 (2012). Mbamu *et al.* (2020) used various bamboo samples (*Phyllostachys aurea* and *Bambusa tuldoides*) and subjected them to TT at temperatures of 160 °C, 180 °C, and 200 °C with durations of 15 min, 30 min, and 45 min, respectively. The TT did not affect the compressive strength of either bamboo species (*Phyllostachys aurea* or *Bambusa tuldoides*).

In this study, *Guadua angustifolia* Kunth (*Ga*K) bamboo skinless strips were thermal treated *via* hydrolysis in a closed pressurized system at temperatures between 160 and 200 °C and at durations between 1 to 4 h. No additional densification was performed. The results of MOR, MOE and density of the thermally treated bamboo were analyzed. The severity was recorded.

EXPERIMENTAL

Three-year-old bamboo (*Guadua angustifolia* Kunth) was obtained from the botanical garden of the Technological University of Pereira (Pereira, Colombia). It is located at latitude 4.791959, longitude -75.68896, at 1450 m above sea level. Its environmental conditions are an average temperature of 20 °C and an annual rainfall of 2600 mm.

The basal section of the green culms were processed as indicated in Fig. 1. They were cut into segments of internodes and marked in ascending order (20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, and 42) according to the position of each internode. The stems were divided into strips from which the skin was removed.

The TT was carried out in a four-compartment batch reactor (Fig. 2), where the processed material is located at the indicated temperature and time (as shown in Table 1).

The TT was performed in a pressurized saturated steam (VS) atmosphere (hydrolysis). The VS was obtained by adding a specific amount of water to each of the compartments and sealing them until the end of the process.

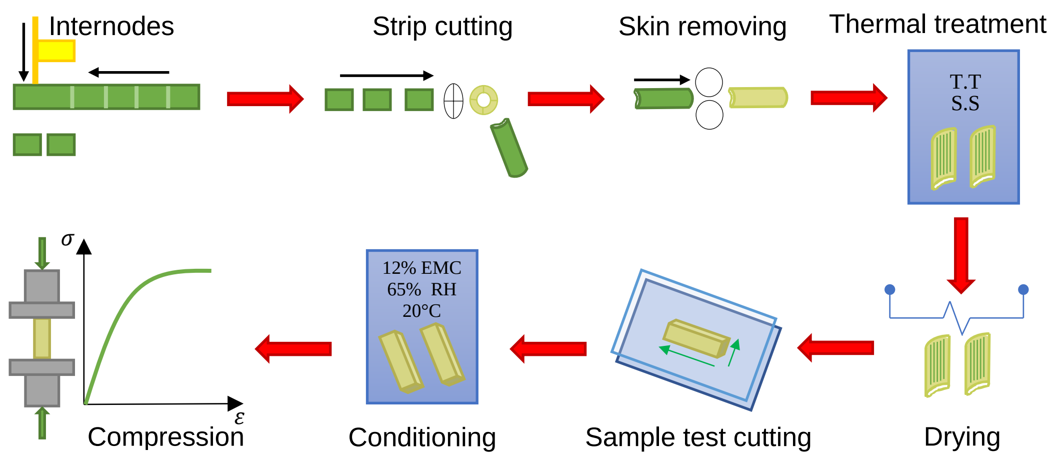


Fig. 1. Experimental methodology

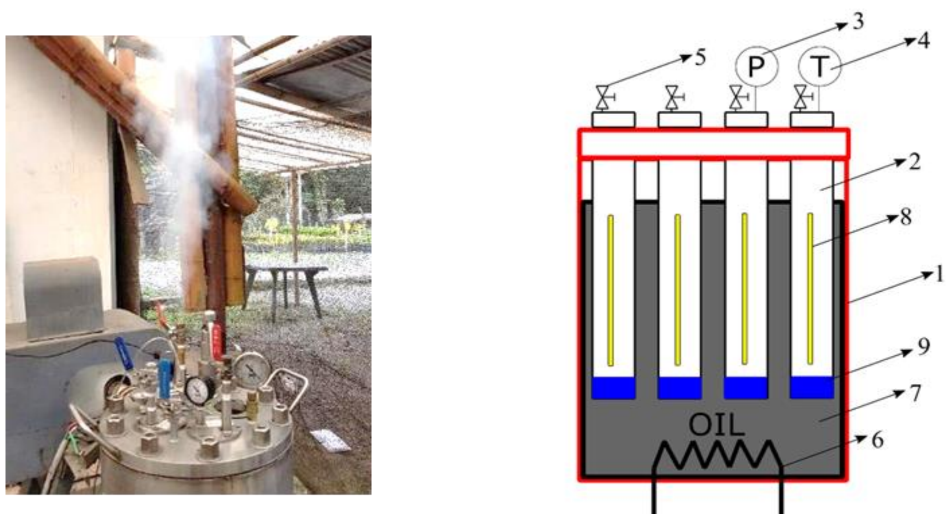


Fig. 2. Four-compartment reactor: 1. Main tank; 2. Compartments; 3. Pressure gauges; 4. Thermocouple; 5. Steam escape valves; 6. Electrical resistor; 7. Thermal fluid; 8. Samples; and 9. Added water

The reactor had a main tank (1) which contained the heating fluid (7), which was heated by an electrical resistor (6). This fluid was responsible for heating four compartments (2), in which each one of the bamboo samples was located and a quantity of water was added to generate the VS. Once the TT time had elapsed, the respective compartment was depressurized *via* opening the steam exhaust valves (5). Then the gates were opened, and the samples (8) were removed. The thermocouple (4) sensed the temperature and interacted with the control system to maintain the temperature. The manometers (3) measured the pressure in each of the compartments (2).

At the end of each TT, the steam release valve was activated, the compartment was opened, and the samples were withdrawn. The samples were left in the open air until they reached room temperature and then dried in an oven at a temperature of 103 °C ± 2 °C for 24 h, before being sanded and sized.

Rectangular solid specimens from the basal mid zone of the *Ga*K were used with a width (b) to thickness (t) ratio of approximately one (t / b = 1) (as shown in Fig. 3). The critical length (L_{cr}) of the specimen was calculated *via* means of the Euler equation, as shown in Eq. 1,

$$P_{cr} = \frac{\pi^2 EI}{kL^2} \quad (1)$$

where P_{cr} is the critical force (MPa), E is the modulus of elasticity of the material (MPa), I is the moment of inertia (mm^4), L is the length of the column (mm), and k is the fixing factor (1 = recessed-recessed, 0.7 = articulated-recessed, 1 = articulated-articulated, 2 = free-recessed). The L_{cr} was calculated to guarantee failures in compression and not failures due to local buckling. The test was assumed as an ideal column with articulated ends, axial compression load, and a square section specimen of 5 mm on each side as the most critical value.

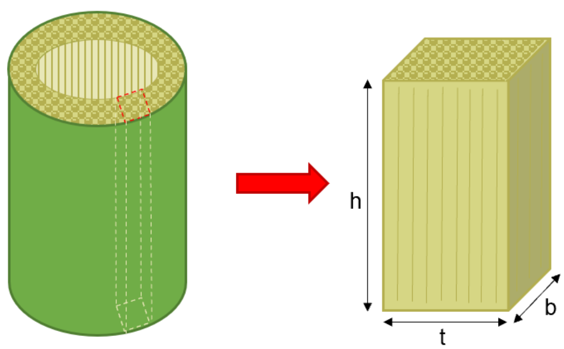


Fig. 3. Compression specimen for *Ga*K

To find this equation in terms of the critical stress (σ_{cr}), an articulated-articulated column $k = 1$ was assumed, which was divided by the cross-sectional area A of the column and the Euler critical stress equation was obtained, as shown in Eq. 2,

$$\sigma_{cr} = \frac{P_{cr}}{A} = \frac{\pi^2 EI}{L^2 A} \quad (2)$$

In previous compression tests for *G*aK, a MOR of 82.7 MPa and an MOE of 1241.4 MPa (control samples), a safety factor N of 2.5 was applied to find the allowable stress σ_{adm}, as shown in Eq. 3,

$$\sigma_{adm} = \frac{\sigma_u}{N} = \frac{82.7\ MPa}{2.5} = 33.08\ MPa \quad (3)$$

and the critical length (L_{cr}) of the specimen, as shown in Eq. 4,

$$L_{cr} = \pi . \sqrt{\frac{EI}{\sigma_{cr}A}} = \pi . \sqrt{\frac{(1241{,}3MPa)\left({5^4}/{12}mm^4\right)}{(33{,}08\,MPa)(5^2mm^2)}} \rightarrow L_{cr} \leq 27.7\,mm \qquad (4)$$

This means that the specimens must have a height (h) less than the critical length (L_{cr}), so that the failure is not due to local buckling.

To manufacture the compression specimens, cuts were made on the longitudinal sections using a disk specimen cutter to guarantee parallel and flat faces. Later the skin was removed, and the final sizing was carried out with the help of a blade. The final dimensions of the specimens varied between 5 mm and 8 mm on side b, and 17 mm to 20 mm of height (h) (as shown in Fig. 4).

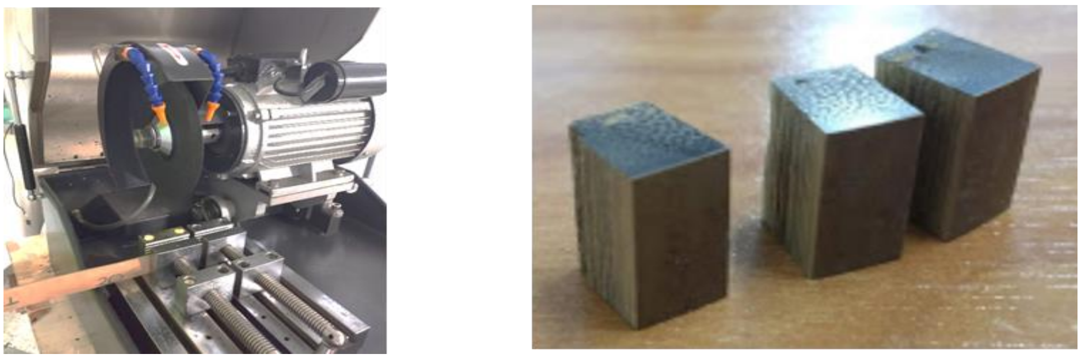


Fig. 4. Longitudinal cutting and compression specimens

The specimens were weighed, and the external measurements of the specimen were taken to obtain the density of the specimen to be able to contrast it with its mechanical properties.

Compression testing on wood and bamboo is standardized by ASTM standard 143 (2014) and ISO standards 22157-1 (2004) and 22157 (2019), respectively. ASTM standard 143 (2014) establishes dimensions for wood in square sections, while ISO standards 22157-1 (2004) and 22157 (2019) establish culm height as a function of the diameter and leave other geometries and dimensions free for scientific research. The compression test was carried out on a Mark-10 universal testing machine (Model ESM1500) with fixed parallel plates (as shown in Fig. 5) with a preload of 100 N and a speed of 0.01 mm/s.

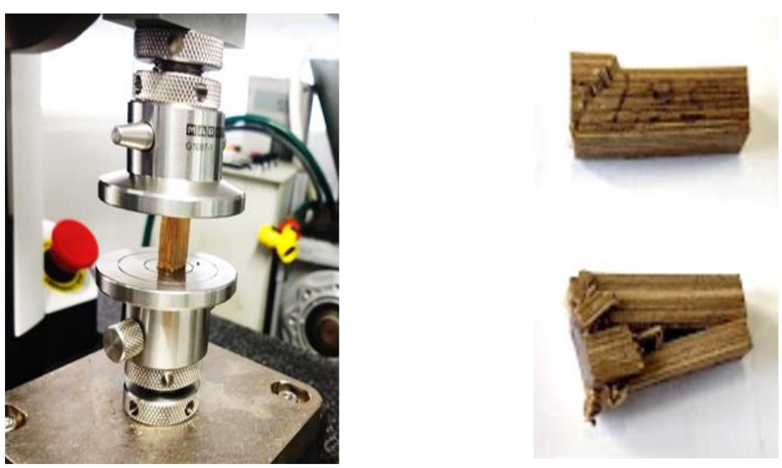


Fig. 5. Compression discs and failures in the compression specimens

The force was obtained with a load cell with a capacity of 6.7 kN, the displacement was obtained by means of an encoder coupled to the screw-drive of the machine and the manufacturers MESUR®gauge Plus software (V1510-05). The MOE value was obtained for values between 10% and 80 % of the MOR, according to the criteria of Arce (1993).

Twenty-four control samples and eight samples were caused to fail for each of the internodes 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, and 42 thermally treated at different temperatures and times; the severity values were recorded, as well as the density, MOR, and MOE with their respective coefficients of variation (COV). Values per internode and total test were averaged to identify the relationships between the different parameters. The samples of each internode were weighed before and after the TT, as well as after drying in the oven to perform a general mass removal analysis of the process.

RESULTS AND DISCUSSION

The TT performed on the material shows a variable mass removal for each of the internodes (as shown in Fig. 6); this is due to the difference in conditions to which they were subjected, including the differences in the moisture content of each treatment. It cannot be ensured that the mass removal due to TT is entirely water since there are chemical reactions induced at high temperatures in the material that yield volatile elements that are lost in the form of vapor as well as soluble elements that remain inside the reactor in a liquid state at the end of the process.

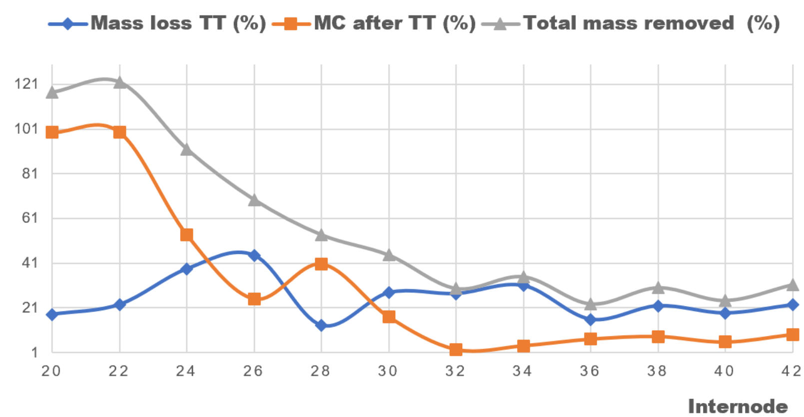


Fig. 6. Weight loss before and after TT

The mechanical and physical properties, *i.e.*, the density, modulus of rupture, and modulus of elasticity, were dependent on the temperature and duration of the TT, *i.e.*, the severity of the TT, and were related. Table 1 summarizes the results for all TT parameters and the average density, MOR, and MOE of the control samples were 724 (kg/m^3), 100.3 MPa, and 1448.9 MPa, respectively. The results of the compression tests in bamboo differed according to the species, the configuration of the test, the geometry of the specimen, the section, the area, nodes or not nodes, and whether the sample had skin or no skin. In the case of *Ga*K bamboo that did not undergo TT, the MOR and the MOE from the following studies were: Guarín (2004) 137.6 MPa and 118.3 MPa, respectively; González *et al.* (2008) MOR 28.8 MPa and 1947 MPa, respectively; Diaz (2012) 36.3 MPa and 3582 MPa, respectively; Correal and Arbelaez (2010) 36.6 MPa and 16.8 MPa, respectively; and Takeuchi (2014) 69.2 MPa and 19559 MPa. The average results for the control samples with respect to González *et al.* (2008), Diaz (2012), and Correal and Arbelaez (2010), showed an approximate difference for the MOR of 68% and with respect to González *et al.* (2008) showed an approximate difference for the MOE of 34%.

Table 1. Compression Test Results of *Ga*K With and Without TT

Inter-node	*N*	*T* (°C)	*t* (h)	Severity (°C*h)	Density (kg/m³)	COV (%)	MOR (MPa)	COV (%)	MOE (MPa)	COV (%)	MC (%)
20	8	160	1	160	556.4	3.1	88.5	4.2	1228.9	10.6	12.5
22	8	160	2	320	619.5	5.3	103.0	9.6	1499.8	11.8	13.5
24	8	160	3	480	665.1	9.4	96.1	8.3	1515.6	13.2	14.2
26	8	160	4	640	649.2	4.1	94.3	6.4	1560.4	8.0	14.7
28	8	180	1	180	620.7	4.2	105.1	6.9	1509.7	12.1	13.8
30	8	180	2	360	668.4	3.8	115.1	6.5	1740.8	10.5	14
32	8	180	3	540	622.1	3.4	103.4	4.9	1825.6	6.9	13.8
34	8	180	4	720	608.9	2.4	101.1	3.2	1763.2	8.1	13.5
36	8	200	1	200	651.5	1.7	105.3	2.7	1755.6	7.1	14
38	8	200	2	400	600.6	4.6	93.7	10.3	1730.6	7.8	12.7
40	8	200	3	600	661.6	2.4	101.5	3.3	1810.3	4.6	13
42	8	200	4	800	699.7	4.0	107.6	9.2	1972.8	7.9	10.5
Control	24	n.a	n.a	n.a	724.4	9.3	100.3	12.8	1448.9	17.7	12.5

The data for the density, MOR, and MOE were highly grouped, which was reflected in the results of the coefficients of variation (COV), which were below 20% for this type of materials.

In the case of *Ga*K bamboo that underwent TT, as stated by Wang *et al.* (2020b), the severity of the TT affects the MOR and MOE in terms of compression. The MOR increased under TT temperatures of up to 180 °C with treatment times of 2 h, *i.e.*, at severities between 320 °C*h and 360 °C*h. An inflection point was obtained at a temperature of 180 °C and a 2 h duration, with a maximum value of 115.1 MPa; these results coincided in behavior with what was proposed by Shangguan *et al.* (2016), Zhong *et al.* (2016), and Wang *et al.* (2020b). The MOE showed an increasing behavior as temperature and time increased according to what was indicated by Magalhães *et al.* (2017) (as shown in Table 1).

The MOR and the MOE of the treated samples increased up to 14.7% and 36.1%, respectively, compared to the not thermal treated samples. The change in the mechanical and physical properties of thermally treated *Ga*K bamboo was caused by an alteration in its chemical composition due to the modification of cellulose, hemicellulose, and lignin (Wang *et al.* 2020a).

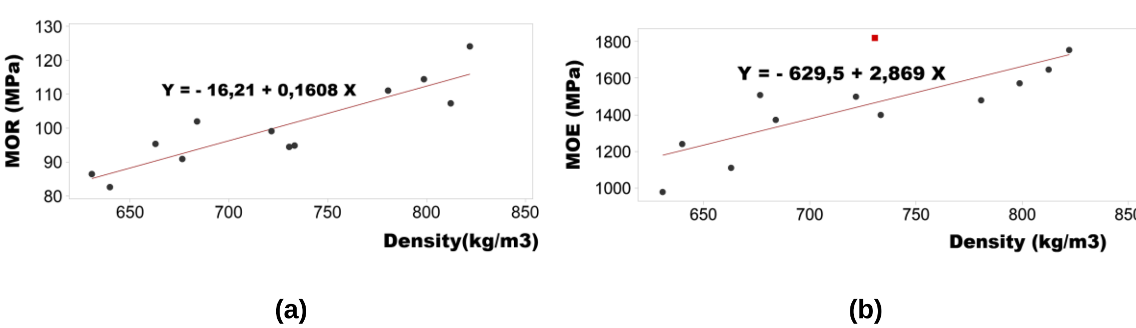


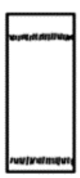
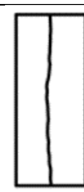
Fig. 7. (a) Linear regression for density and MOR; (b) Linear regression for the density and MOE

The equation for the linear model that describes the relationship between the density and the MOR of the material that did not undergo TT had a proper fit (as shown in Fig. 7a). The positive correlation (R = 0.89) indicated that when the density increases the MOR also increases, and this linear regression model explained 79.2% of the results for the variation of the MOR. The relationship between the density and MOR was statistically significant (*p*-value was less than 0.05).

The equation for the linear model that describes the relationship between the density and MOE of the material that did not undergo TT had a proper fit (as shown in Fig. 7b). The positive correlation (R = 0.78) indicated that when the density increases the MOE also increases, and this linear regression model explained 60.2% of the results for the variation of the MOE. The relationship between the density and MOE was statistically significant (*p*-value was less than 0.05).

The failures of the *G*aK subjected to compression can be described by three individual or combined factors, *i.e.*, shear, crushing, and buckling. Eight samples were subjected to failure for each of the TT conditions and the failures were characterized as established by the ASTM standard D143 standard (as shown in Table 2).

Table 2. Typical Compression Failures in Wood according to ASTM143:2014 (ASTM 143 (2014))

Flattening (A)	Split Wedge (B)	Shearing (C)	Crack (D)	Compression and Shear Parallel to the Fiber (E)	Rounded Frayed (F)
					
This term should be used when the plane of rupture is completely horizontal	A radial division or tangency should be noted	This term should be used when the plane of rupture forms an angle of more than 45° with the top of the specimen.	This type of failure usually occurs when the specimen has a previous internal defect, and the specimen must be discarded.	This failure usually occurs in pieces with transverse grains and the specimen should be discarded.	This type of failure is associated with an excess of moisture content at the ends of the specimen, an improper cut of the specimen, or both. This type of failure is not accepted and is associated with low loads. You must make the considerations to solve this type of failure.

The characterization of the failures is shown in Table 3, and the unwanted failures D was removed from the analysis for each of the TT conditions.

Table 3. Frequency of Various Compression Failure Modes

Failure mode	A	B	C	D	E	F	Total
Frequency	85	1	6	4	0	0	96
%	88.5	1.0	6.3	4.2	0.0	0.0	100.0

The results obtained for the MOR under different TT conditions showed a considerable influence on the density of the material as well as the severity (Fig. 8). Some areas were seen in the surface and contour diagrams that did not correspond to a defined behavior; this is probably due to the variable behavior of this type of materials.

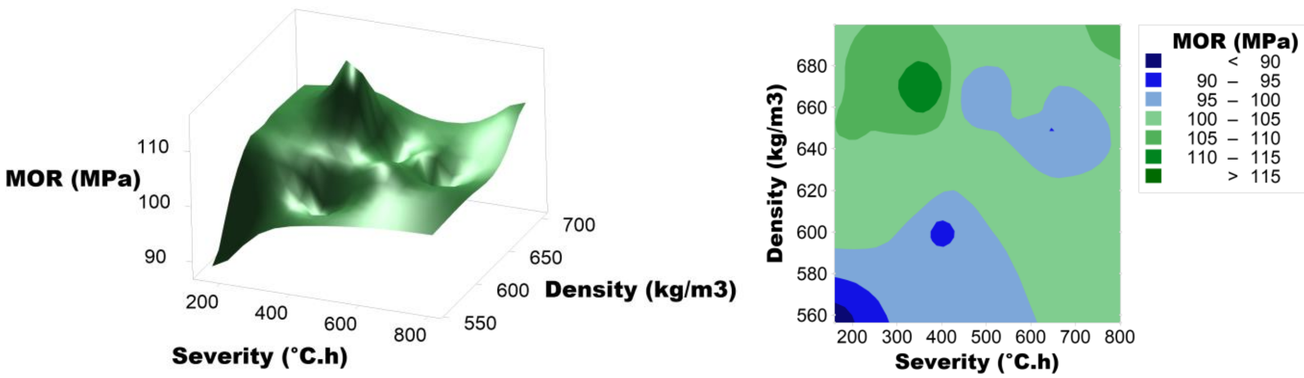


Fig. 8. Surface and contour plot for MOR

The results obtained for the MOE (Fig. 9) and the MOR from different TT conditions showed a considerably strong influence on the density of the material as well as the severity. Some areas were seen in the surface and contour diagrams that did not correspond to a defined behavior; this is probably due to the variable behavior of this type of material.

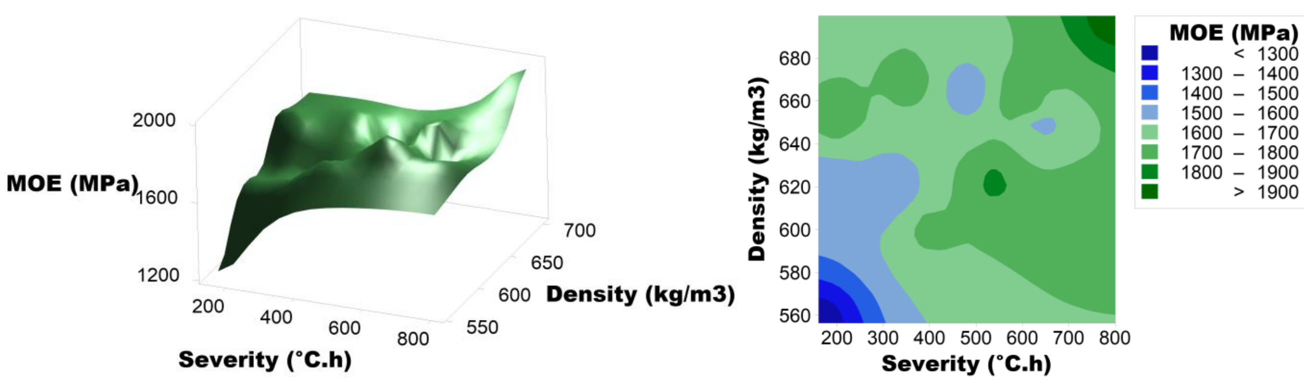


Fig. 9. Surface and contour plot for MOE

CONCLUSIONS

1. The thermal treatment (TT) performed on the bamboo showed a variable mass removal amount for each of the internodes. The average modulus of rupture (MOR) and modulus of elasticity (MOE) of the samples that had not been thermally treated were 100.3 and 1448.9 MPa, respectively.
2. The severity of the TT affected MOR and MOE in compression tests. The MOR showed a maximum value of 115.1 MPa, and an inflection point was obtained with severities between 320 and 360 °C*h. The MOE showed increasing behavior as the temperature and time increased.
3. The MOR and the MOE of the treated samples increased up to 14.7% and 36.1%, respectively, compared to the not thermally treated samples.
4. When the density increased, the MOR also increased. The relationship between the density and MOR was statistically significant (*p*-value was less than 0.05).
5. When the density increased, the MOE also increased. The relationship between the density and MOE was statistically significant (*p*-value was less than 0.05).
6. The data for the density, MOR, and MOE were highly grouped, which was reflected in the results of the coefficients of variation (COV), which were below 20% for this type of materials.
7. The results obtained for the MOR and MOE from samples subjected to different thermal treatment conditions showed a considerable influence on the density of the material as well as the severity.

ACKNOWLEDGMENTS

The authors are grateful for the support of the Technological University of Pereira, Colombia (Research 9-17-7) and to the model laboratory of the Mechanical Technology Program of the UTP.

REFERENCES CITED

ABNT NBR 7190 (1996). "Projeto de estruturas de madeira [design of wooden structures]," Asociación Brasilera de Normas Técnicas, Rio de Janeiro, Brasil.

Arce, O. A. (1993). *Fundamentals of the Design of Bamboo Structures*, Ph.D. Dissertation, Eindhoven University of Technology, Eindhoven, Netherlands.

Archila, S. H. F. (2015). *Thermo-Hydro-Mechanically Modified Cross-Laminated Guadua-Bamboo Panels*, Ph.D. Dissertation, University of Bath, Bath, United Kingdom.

ASTM D1037 (2012). "Standard test methods for evaluating properties of wood-base fiber and particle panel materials," ASTM International, West Conshohocken, PA.

ASTM D143 (2014). "Standard test methods for small clear specimens of timber," ASTM International, West Conshohocken, PA.

Barnes, H. M., Aro, M. D., and Rowlen, A. (2018). “Thermally modified engineered wood products durability,” *Forest Products Journal* 68(2), 99-104. DOI: 10.13073/FPJ-D-17-00060

Boonstra, M. J., Acker, J. V., Tjeerdsma, B. F., and Kegel, E. (2007). “Strength properties of thermally modified softwoods and its relation to polymeric structural wood constituents,” *Annals of Forest Science* 64, 679-690. DOI: 10.1051/forest:2007048

Brito, F. M. S., Paes, J. B., Oliveira, J. T. d. S., Arantes, M. D. C., and Dudecki, L. (2020). “Chemical characterization and biological resistance of thermally treated bamboo,” *Construction and Building Materials* 262, DOI: 10.1016/j.conbuildmat.2020.120033

Brito, F. M. S., Paes, J. B., Oliveira, J. T. d. S., Arantes, M. D. C.., Vidaure, G. B., and Brocco, V. F. (2018). “Physico-mechanical characterization of heat-treated glued laminated bamboo,” *Construction and Building Materials* 190, 719-727. DOI: 10.1016/j.conbuildmat.2018.09.057

Correal, J. F., and Arbelaez, J. (2010). “Influence of age and height position on colombian *Guadua angustifolia* bamboo mechanical properties,” *Maderas. Ciencia y Tecnologia* 12(2), 105-113. DOI: 10.4067/S0718-221X2010000200005

Diaz, G. A. R. (2012). *Influencia de la Densidad Aparente de Fibras Sobre la Resistencia a Esfuerzos de Compresión, Tensión y Flexión de la Guadua angustifolia Kunth* [Influence of the apparent density of the fiber in the resistance to compression, tension and flexion of *Guadua angustifolia* Kunth], Master’s Thesis, Universidad Industrial de Santander, Bucaramanga, Colombia.

Esteves, B., Velez, M., A., Domingos, I., and Pereira, H. (2013). “Chemical changes of heat treated pine and eucalypt wood monitored by FTIR,” *Maderas. Ciencia y Tecnología* 15(2), 245-258. DOI: 10.4067/S0718-221X2013005000020

GB 1935 (2009). “Method of testing in compressive strength parallel to grain of wood,” Standardization Administration of China, Beijing, China.

GB/T 15780 (1995). “Testing methods for physical and mechanical properties of bamboo,” Standardization Administration of China, Beijing, China.

Ghadge, K., and Pandey, K. K. (2017). “Effect of thermal modification on physical properties of *Bambusa nutans*,” in: *Wood is Good*, K. K. Pandey, V. Ramakantha, S. S. Chauhan, and A. N. A. Kumar (eds.), Springer Nature Singapore, Singapore, pp. 287-295.

González, H. A., Montoya, J. A., and Bedoya, J. R. (2008). “Comportamiento de muestras de *Guadua angustifolia* Kunth con diafragma y sin diafragma sometidas a esfuerzo de compresión [Guadua – Bamboo samples behavior with diaphragm and without diaphragm submitted to compression strain],” *Scientia et Technica* 38(2), 449-454.

Guarín, G. W. G. (2004). “Resistencia de la sección transversal de la guadua sometida a compresión[Resistance of the cross section of guadua under compression],” Master’s Thesis, Universidad Nacional de Colombia, Bogota, Colombia.

ISO 22156 (2004). “Bamboo structural design,” International Organization for Standardization, Geneva, Switzerland.

ISO 22157-1 (2004). "Bamboo - Determination of physical and mechanical properties - Part 1: Requirements," International Organization for Standardization, Geneva, Switzerland.

ISO 22157-2 (2004). "Bamboo - Determination of physical and mechanical properties - Part 2: Laboratory manual," International Organization for Standardization, Geneva, Switzerland.

ISO 22157 (2019). "Bamboo structures - Determination of physical and mechanical properties of bamboo culms - Test methods," International Organization for Standardization, Geneva, Switzerland.

ISO 165 (1999). "Laboratory manual on testing methods for determination of physical and mechanical properties of bamboo," International Organization for Standardization, Geneva, Switzerland.

Klaas, P. (n.d.). "Wood treatment technology," (https://wtt.global/wp-content/uploads/2018/01/ThermoTreat-2.0_Product-Presentation.pdf)) Accessed 12 de Nov 2019.

Magalhães, T., Santos, V., Gauss, C., and Savastano J., H. (2017). "Conventional and microwave-assisted thermal treatment of *Dendrocalamus asper* bamboo," in: *Proceedings of the 2nd International Conference on Bio-based Building Materials & 1st Conference on ECOlogical Valorisation of GRAnular and Fibrious Materials,* 21-23 June, Clermont-Ferrand, France. pp. 1-5.

Mbamu, M. F. A. d. O., Nascimento, A. M. d., García, R. A., and Souza, d. J. D. (2020). "Propriedades mecânicas em duas espécies de bambu submetidas a tratamentos térmicos[Mechanical properties in bamboo species subjected to thermal treatments]," *Cadernos de Ciência & Tecnologia* 37(1), 1-8. DOI: 10.35977/0104-1096.cct2020.v37.26547

Meng, F., Yu, Y., Zhang, Y., Yu, W., and Gao, J. (2016). "Surface chemical composition analysis of heat-treated bamboo," *Applied Surface Science* 371, 383-390. DOI: 10.1016/j.apsusc.2016.03.015

Nguyen, C. T., Wagenführ, A., Phuong, L. X., Dai, V. H., Bremer, M., and Fischer, S. (2012). "The effects of thermal modification on the propiertioes of two vietnamese bamboo species, Part I: Effect on physical propierties," *BioResources* 7(4), 5355-5366. DOI: 10.15376/biores.7.4.5355-5366

NTC 5525 (2007). "Métodos de ensayo para determinar las propiedades físicas y mecánicas de la *Guadua angustifolia* Kunth[Test methods to determine the physical and mechanical properties of *Guadua angustifolia* Kunth]," Instituto Colombiano de Normas Técnicas (ICONTEC), Bogotá, Colombia.

Ramage, M. H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D. U., Wu, G., Yu, L., Fleming, P., Densley-Tingley, D., *et al.* (2017). "The wood from the trees: The use of timber in construction," *Renewable and Sustainable Energy Reviews* 68(Part 1), 333-359. DOI: 10.1016/j.rser.2016.09.107

Şahin, H. İ. (2017). "Heat treatment application methods and effects of heat treatment on some wood properties," in: *Proceedings of the 3rd International Confernece on Engineering and Natural Sciences*, 3-7 May, Budapest, Hungary, pp. 540-546.

Shangguan, W., Gong, Y., Zhao, R., and Ren, H. (2016). "Effects of heat treatment on the properties of bamboo scrimber," *Journal of Wood Science* 62, 383-391. DOI: 10.1007/s10086-016-1574-3

Sharma, B., Gatóo, A., and Ramage, M. (2015b). "Effect of processing methods on the mechanical properties of engineered bamboo," *Construction and Building Materials* 83, 95-101. DOI: 10.1016/j.conbuildmat.2015.02.048

Sharma, B., Gatóo, A., Bock, M., and Ramage, M. (2015a). "Engineered bamboo for structural applications," *Construction and Building Materials* 81, 66-73. DOI:

10.1016/j.conbuildmat.2015.01.077

Sharma, B., Gatóo, A., Bock, M., Mulligan, H., and Ramage, M. (2014). "Engineered bamboo: State of the art," *Construction Materials* 168(2), 57-67. DOI: 10.1680/coma.14.00020

Takeuchi, C. P. (2014). *Caracterización Mecánica del Bambú Guadua Laminado Para uso Estructural* [Mechanical Characterization of Laminated Guadua Bamboo for Structural Use], Ph.D. Disseration, Universidad Nacional de Colombia, Bogotá, Colombia.

Takeuchi, C. P., and González, C. E. (2007). "Resistencia a la compresión paralela a la fibra de la *Guadua angustifolia* y determinación del módulo de elasticidad[Resistance to compression parallel to the fiber of *Guadua angustifolia* and determination of the modulus of elasticity]," *Ingniería y Universidad* 11(1), 89-103.

Tjeerdsma, B. F., and Militz, H. (2005). "Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood," *Holz Roh Werkst* 63, 102-111. DOI: 10.1007/s00107-004-0532-8

Wang, Q., Wu, X., Yuan, C., Lou, Z., and Li, Y. (2020a). "Effect of saturated steam heat treatment on physical and chemical properties of bamboo," *Molecules* 25(8), 1-11. DOI: 10.3390/molecules25081999

Wang, X., Cheng, D., Huang, X., Song, L., Gu, W., Liang, X., Li, Y., and Xu, B. (2020b). "Effect of high-temperature saturated steam treatment on the physical, chemical, and mechanical properties of moso bamboo," *Journal of Wood Science* 66(1), 1-9. DOI: 10.1186/s10086-020-01899-8

Xiao, Y., Yang, R. Z., and Shan, B. (2013). "Production, environmental impact and mechanical properties of glubam," *Construction and Building Materials* 44, 765-773. DOI: 10.1016/j.conbuildmat.2013.03.087

Xu, M., Cui, Z., Tu, L., Xia, Q., and Chen, Z. (2019). "The effect of elevated temperatures on the mechanical properties of laminated bamboo," *Construction and Building Materials* 226, 32-43. DOI: 10.1016/j.conbuildmat.2019.07.274

Yang, T.-C., and Lee, T.-Y. (2018). "Effects of density and heat treatment on the physico-mechanical properties of unidirectional round bamboo stick boards (UBSBs) made of Makino bamboo (*Phyllostachys makinoi*)," *Construction and Building Materials* 187, 406-413. DOI: 10.1016/j.conbuildmat.2018.07.182

Yang, T.-H., Lee, C.-H., Lee, C.-J., and Cheng, Y.-W. (2016). "Effects of different thermal modification media on physical and mechanical properties of moso bamboo," *Construction and Building Materials* 119, 251-259. DOI: 10.1016/j.conbuildmat.2016.04.156

Yun, H., Li, K., Tu, D., and Hu, C. (2016). "Effect of heat treatment on bamboo fiber morphology crystallinity and mechanical properties," *Wood Research* 61(2), 227-234.

Zakikhani, P., Zahari, R., Sultan, M. T. H., and Majid, D. L. (2014). "Extraction and preparation of bamboo fibre-reinforced composites," *Materials & Design* 63, 820-828. DOI: 10.1016/j.matdes.2014.06.058

Zhong, Y., Ren, H.-Q., and Jiang, Z. H. (2016). "Effects of temperature on the compressive strength parallel to the grain of bamboo scrimbe," *Materials* 9(6), 436-444. DOI: 10.3390/ma9060436

Article submitted: May 9, 2021; Peer review completed: June 26, 2021; Revised version received and accepted: August 23, 2021; Published: September 2, 2021.
DOI: 10.15376/biores.16.4.7006-7020