Influence of a Thermal Treatment on the Tensile Strength and Equilibrium Moisture Content of Bamboo (*Guadua angustifolia* Kunth)

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Thermal treatments applied to lignocellulosic materials were found to induce internal chemical reactions, which modified the physical and mechanical properties and dimensional stability of the material. A 3-year-old basal section of bamboo (*Guadua angustifolia* Kunth), with no nodes and no skin, was subjected to a thermal treatment at temperatures which ranged from 160 to 200 °C for 1 to 4 h. The tensile stiffness showed a slight increase with temperature and time, while the tensile strength showed a notable increase at 160 °C for 2 h. There was a 5% difference in the equilibrium moisture content at 80% relative humidity between the untreated samples and the 200 °C, 4 h treatment.

Keywords: Bamboo; Guadua angustifolia Kunth; Tension test; Moisture sorption analysis; Physical properties; Mechanical properties; Thermal treatment

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INTRODUCTION

Thermal treatments (TT) can be defined as the application of heat to wood to achieve the desired performance improvement (Hill 2006). Thermal treatments induce internal chemical reactions and can be used to change the color, reduce the hygroscopicity (EMC), and increase the dimensional stability. The color change is considered as an aesthetic aspect and is considered a correlating indicator for the intensity of thermal modification as well. However, the major loss of mass at higher temperatures is seen as a problem (Nguyen *et al.* 2012; Bremer *et al.* 2013). Moreover, TT weakens the mechanical performance of wood (Sandberg and Navi 2007) and thus limits its application range.

A similar challenge for bamboo is the weakening of strength properties (Leithoff and Peek 2001) and its brittle behavior after TT. Thermal treatment in common temperature ranges can decrease the strength by 30%, reduce density by up to 20%, and increase the fragility of the material (Majano 2014). Many bamboo species have been investigated for their mechanical behavior after thermal modification. Investigations were done for commercial species from Vietnam (Nguyen *et al.* 2012), Ethiopia (Starke *et al.* 2016), Brazil (Colla *et al.* 2011), China (Zhang 2013), and Colombia (Archila *et al.* 2014). Colla *et al.* (2011) treated Asian *Dendrocalamus giganteus* in inert and non-inert atmospheres for several hours, resulting in improved thickness swelling and stable mechanical properties. Yun *et al.* (2016) investigated Chinese moso *Phyllostachys pubescens* bamboo and explained the mechanical weakness with changes in crystallinity of bamboo cellulose. Zhang *et al.* (2013) showed the negative effects on mechanical properties for the same Asian bamboo species. Starke *et al.* (2016) used nitrogen as treatment medium and recommended temperature for African highland bamboo *Yushania alpina* treatment from 140 to 220 °C. Comparable results were presented by Schmidt *et al.* (2020, 2016). Archila *et al.* (2014) thermally treated *Guadua angustifolia* but also combined it with a severe densification for use in panel products. The sole effect of thermal treatment on mechanical properties, especially tensile strength for the Colombian *Guadua angustifolia*, has not been well studied yet.

Moreover, the extent of property change depends on process temperature, process gas, time, and whether a closed or open system is applied (Tjeerdsma *et al.* 2002). Thermal treatments can be performed *via* either pyrolysis or hydrolysis processes. For the pyrolysis process, the wood must be dried previously, the systems are open and are maintained at atmospheric pressure with high temperatures; the cycles are long-running, generate emissions, and consume a lot of energy. For the hydrolysis process, the wood does not need to be dried previously, the systems are closed and are subjected to high pressures and relatively low temperatures. The material is heated up close to the pyrolysis temperature an inert environment to prevent combustion. Then the temperature remains constant for a certain time (treatment time) and a controlled cooling is carried out for conditioning the modified material. Hence, the cycles are short, and the emissions generated and total energy consumption are both lower than pyrolysis (Klaas 2019). A possible drawback might be a higher brittleness and variability in closed systems, as shown for eucalypt wood (Wentzel *et al*. 2019).

Velásquez *et al.* (2005) used the basal section of bamboo, with no nodes and without thermal treatment, according to ISO TC-165 INBAR (1999) and measured a MOR value of 190.7 MPa. González *et al.* (2006) used the basal section of bamboo, with no nodes and without thermal treatment, and at 65% RH, 20 °C, and a moisture content (MC) of 12%, had a MOR value of 191.6 MPa and a MOE value of 17139.2 MPa for the basal section. This test was done following the recommendations of standards ISO 22157-1 (2004) and ISO 22157-2 (2004). Takeuchi (2014) used the basal section of bamboo, with no nodes and without thermal treatment, and at 65% RH, 20 °C, and a moisture content (MC) of 12%, had a MOE value of 21150 MPa. This test was carried out following standards ASTM D143 (2014) and NTC 5525 (2007).

Archila *et al.* (2014) combined TT at 150 °C and densification at 6.2 MPa, and achieved results of 16210 MPa, 22800 MPa, and 31040 MPa for the MOE values of the untreated sample, the densified dry sample and the densified moist sample respectively. All samples contained nodes and were conditioning beforehand at 70% ± 5% RH and a temperature of 27 °C ± 2 °C. This test was carried out following the recommendations established in the standards ISO 22157-1 (2004), ISO 22157-2 (2004), and NTC 5525 (2007).

In this study, bamboo *Guadua angustifolia* Kunth skinless strips, were thermally treated by hydrolysis in a closed pressurized system with temperatures between 160 to 200 ° C and times between 1 to 4 hours. No additional densification was done. The results of MOR, MOE and EMC of the thermally treated bamboo were analyzed.

EXPERIMENTAL

Three-year-old bamboo (*Guadua angustifolia* Kunth) was harvested a natural plantation located in the botanical garden of the Technological University of Pereira (Pereira, Colombia). Located at a latitude of 4.791959, a longitude of -75.68896, a height above sea level of 1450 m, an average temperature of 20 °C, and an annual rainfall of 2600 mm. The material was processed according to Fig. 1. The green bamboo culm was cut into internode sections and marked from bottom up (20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, and 42, basal section) according to each internode. The culms were split into strips, and the skin was removed.

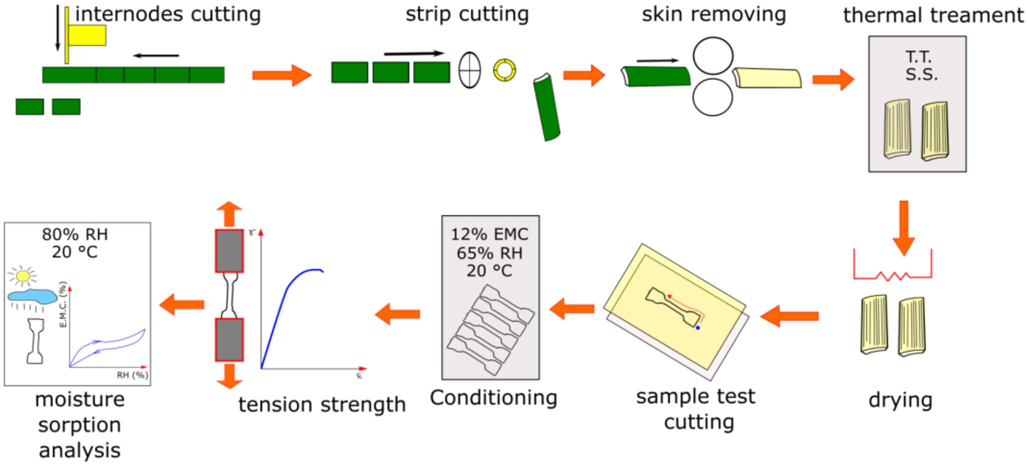

Fig. 1. Experiment methodology

The TT was carried out in a batch reactor of four compartments (Fig. 2), where the processed material is located at the temperature and time indicated (Fig. 3).

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

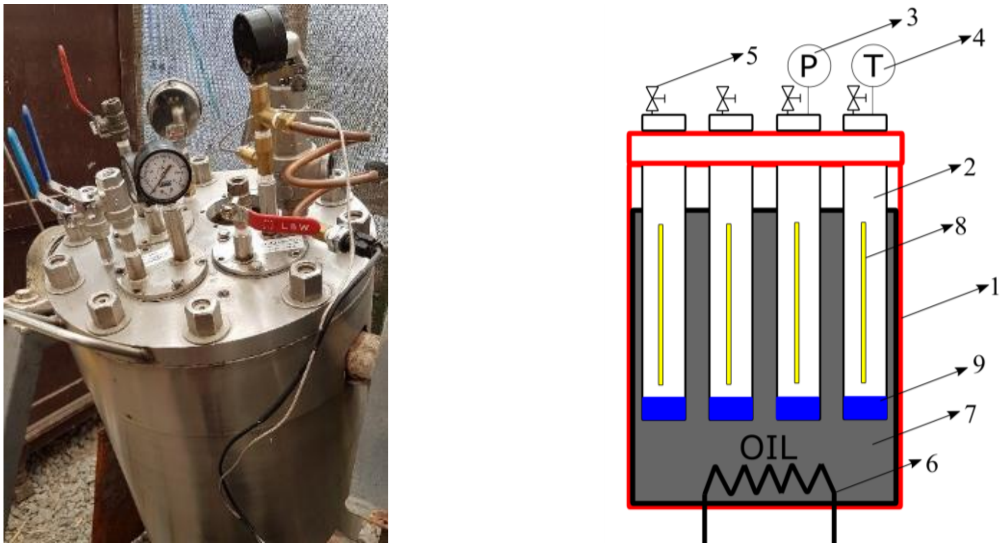

Fig. 2. Four compartment reactor, 1. Main deposit, 2. Compartments, 3. Pressure gauges, 4. Thermocouple, 5. Steam exhaust valves, 6. Electric resistance, 7. Heat fluid, 8. Samples, 9. Water added

The reactor had a main tank (1) containing the heating fluid (7), which was heated by means of an electric resistor (6). This fluid was responsible for heating four compartments (2) in which each of the bamboo samples was located and an amount of water was added to generate SS. Once the heat treatment time had elapsed, the respective compartment was depressurized by opening the steam exhaust valves (5). Then, the gates were opened and the samples (8) were withdrawn. The thermocouple (4) sensed the temperature and interacted with the control system to sustain the temperature. Pressure gauges (3) allowed to measure the pressure in each of the compartments (2).

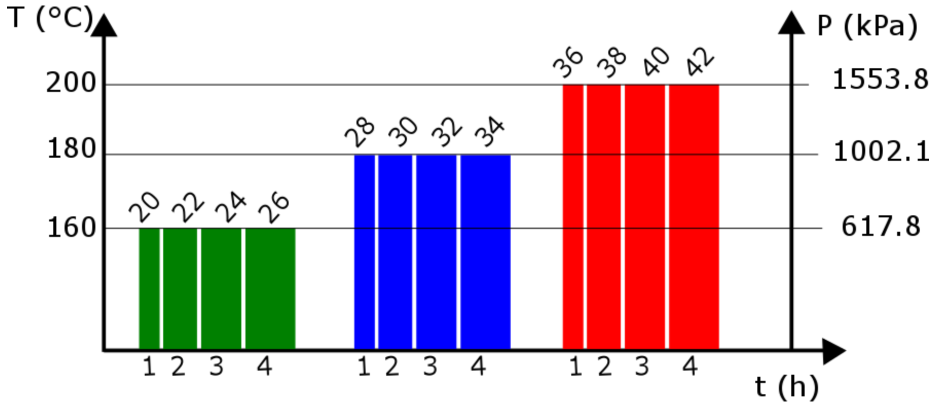

Fig. 3 . Thermal treatment program number, culm section, temperature, and time

At the end of each TT, the steam exhaust valve was activated, the compartment was opened, and the samples were removed. The samples were left outdoors until they reached ambient temperature and then dried in an oven at 103 °C ± 2 °C for 24 h, before being sanded and sized with a bench router, sample template, and milling cutter.

Figure 4 illustrated the final dimensions, as follows: width (a) = 10 mm, thickness (b) = 5 mm, clamping width (c) = 20 mm, equivalent clamping height (h) = 30 mm, total length of the specimen (l) = 140 mm, and radius of curvature (r) = 50 mm.

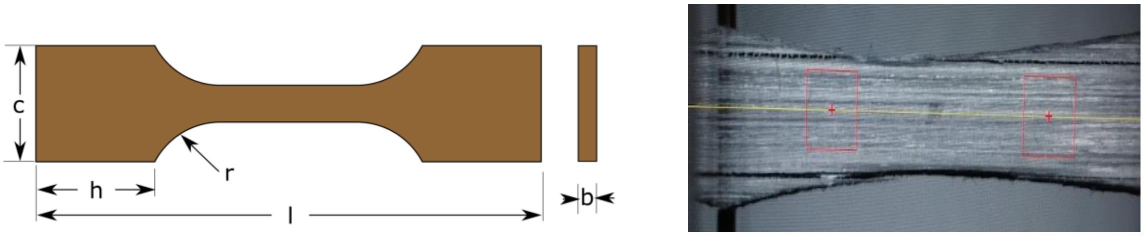

Fig. 4. Measurement of the test specimen and Video extens axial strain

The tension strength test was carried out using a universal testing machine (ZwickRoell Z050, Zwick GmbH & Co. KG, Ulm, Germany) with fixed grips and a 100 N preload. Axial strain was measured with a contact-free method using video monitoring (VideoExtens). The actual strain gauge length was set at 40 mm and the specimen strain was measured continuously until ultimate stress was reached. The configuration of the test was carried out following the recommendations established in the standards ISO 22157-1 (2004) and ISO 22157-2 (2004). Eight specimens were loaded for each treatments.

Fig. 5. Universal tension test machine and grips

Flaked bamboo (Fig. 6) was analyzed with a multisample dynamic moisture sorption balance (SPSx-1µ Advance, ProUmid GmbH & Co. KG, Ulm, Germany) following the recommendations established in the standard ASTM D4442-16 (2016). Before performing the tensile strength test and moisture sorption analysis, the samples were subjected to conditioning at 20 °C and 65% relative humidity (RH) for 15 d. Moisture sorption analysis was performed once for each thermal treatment.

Fig. 6. Flaked bamboo samples and moisture sorption analysis equipment

RESULTS AND DISCUSSION

The mechanical and physical properties, modulus of elasticity (MOE), modulus of rupture (MOR) and EMC, were dependent on the thermal treatment, temperature, and time and were interconnected. Table 1 summarized the results for all treatment parameters. The MOR, MOE, and EMC of the control samples were 191 MPa, 16960 MPa, and 15.0%, respectively. The EMC at 80% RH and 20 °C showed that there was an approximately 5% difference between the control samples and the 200 °C, 4 h treatment. This was caused by a modification of the structural polymers, cellulose, hemicellulose, and lignin. This modification is greater in hemicellulose, since it has a greater number of accessible hydroxyl groups (Bremer *et al.* 2013) and is thermally less stable than lignin and cellulose.

Table 1. Results of the MOR, MOE, and EMC for the Thermally Treated Bamboo (*Guadua angustifolia* Kunth)

Inter-node	T (°C)	p (kPa)	t (h)	Mass Loss (%)	MOR (MPa)			MOE (MPa)			EMC (%) at 20 °C/80% RH
					Mean	S^2	CV	Mean	S^2	CV	
untreated	-	-	-	-	190.6	895.6	15.7	16982	6676754	15.2	15.0
20	160	617.8	1	18.0	234.3	2331.0	20.6	19338	15254891	20.2	12.5
22	160	617.8	2	22.5	263.6	439.3	7,9	14795	903662	6.4	13.7
24	160	617.8	3	38.5	255.3	257.72	6.2	14957	14067640	25.0	14.2
26	160	617.8	4	44.4	270.1	126.28	4.1	17470	2896825	9.7	14.7
28	180	1002.1	1	13.1	215.4	1193.6	16.0	17956	4492444	11.8	13.8
30	180	1002.1	2	27.8	225.0	541.8	10.3	14792	6111199	16.7	14.0
32	180	1002.1	3	27.4	180.7	259.17	8.9	18695	9370226	16.3	13.8
34	180	1002.1	4	30.9	203.4	1894.1	21.4	20226	10723100	16.1	13.5
36	200	1553.8	1	15.9	177.0	834.0	16.3	16866	3136342	10.5	14.0
38	200	1553.8	2	21.9	246.8	459.9	8.6	18225	15330739	21.4	12.7
40	200	1553.8	3	18.7	154.7	848.0	18.8	20597	283505	2.5	13.2
42	200	1553.8	4	22.4	109.0	177.29	12.2	16296	3487459	11.4	10.7

Figure 7 shows the surface and contour plots for the MOR as a function of temperature and time. A substantial decrease was observed for treatments with a temperature of 180 °C or higher and a time longer than or equal to 3 h. The MOR increased by 38% for the thermal treatment at 160 ° C and 2 h compared to the untreated sample.

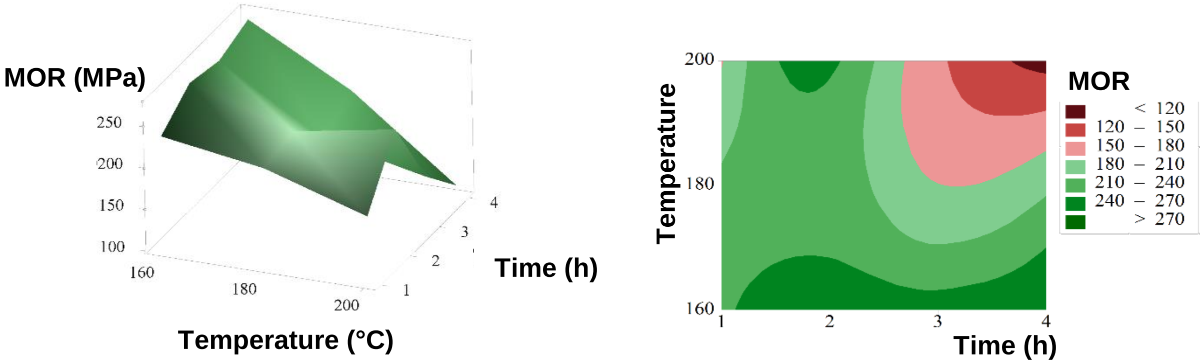

Fig. 7. Surface and contour plot MOR (MPa) *vs.* *T* (°C) and *t* (h)

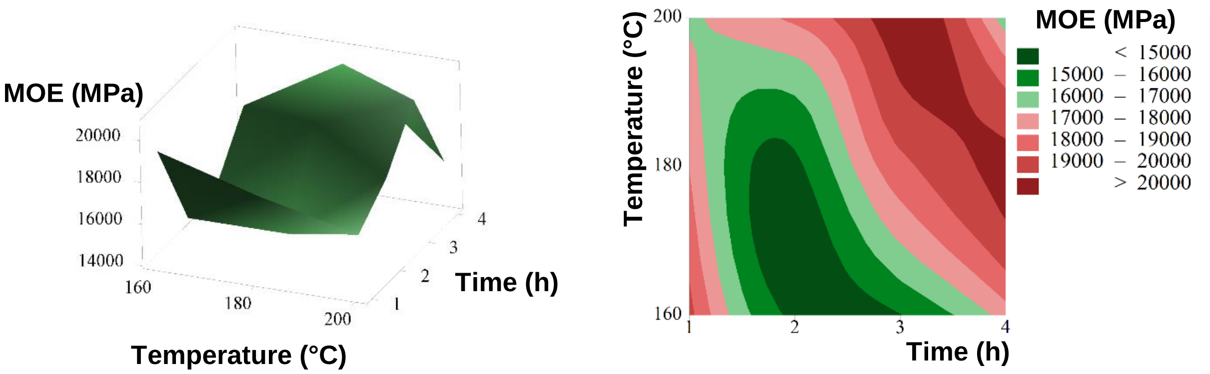

Fig. 8. Surface and contour plot MOE (MPa) *vs.* *T* (°C) and *t* (h)

Figure 8 shows the surface and contour graphs of the MOE as a function of temperature and time. There was neither a notable change in the MOE for temperatures from of 160 to 180 °C and treatment times of 2 to 3 h. The MOE increased at a treatment time greater than 3 h for 180 to 200 °C temperatures. This might have been cause by a lower EMC in the treated samples.

EMC showed noticeable decrease at a temperature of 200 °C and for a time of 4 h. A slight variation was also observed for temperatures between 160 and 180 °C and a time of 2 to 4 h.

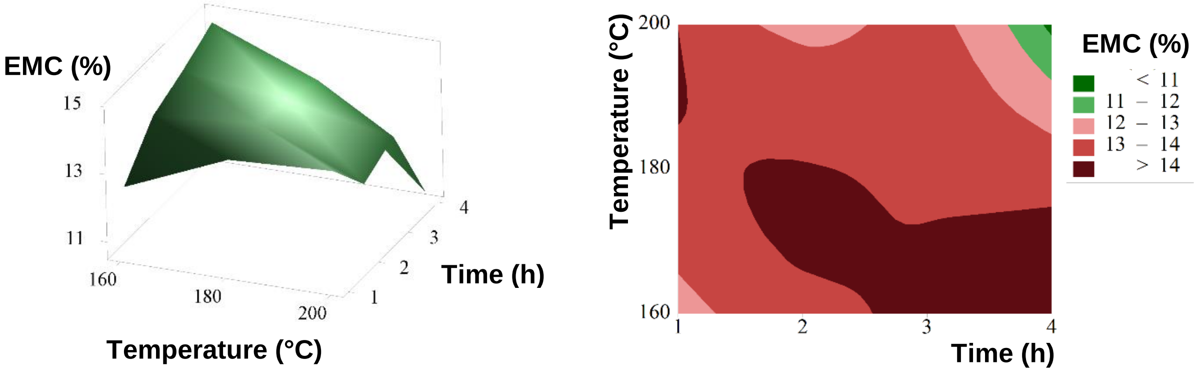

Fig. 9. Surface and contour plot EMC (%) *vs.* *T* (°C) and *t* (h)

There were no significant differences for the MOR results of untreated samples when compared to González *et al.* (2006) and Velásquez *et al.* (2005). There were no significant differences for the MOE results of untreated samples when compared to González *et al.* (2006) and Archila *et al.* (2014) and there was a difference of 24.5% when compared with Takeuchi (2014).

The MOR results obtained by Colla *et al.* (2011) for 180 ° C, 10 h in giant bamboo were lower than the results of the samples treated at 180 ° C and 1, 2, 3, and 4 h. This may be mainly due to the difference in the duration of the TT and multiple factors that influenced the results, such as the bamboo species, age, culm section, terrain, and the tensile strength test setup (especially the geometry of the fixation grip clamps).

CONCLUSIONS

1. The MOR and MOE initially increased and then decreased with treatment temperatures between 160 to 200 °C and treatment times between 1 to 4 h.
2. The MOE slightly increased with an increase in temperature and time, *i.e.* that the material became stiffer, while the MOR increased at treatment conditions of 160 °C and 2 h.
3. The results obtained for the MOR and MOE values after a 200 °C treatment for 4 h showed a high degree of variability.
4. In a closed steamed system, thermal treatment substantially decreased the EMC at temperatures above 180°C.
5. The EMC at 80% RH showed that there was an approximately 5% difference between the untreated samples and the 200 °C, 4 h treatment.

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