


Physical Properties of Thermally Modified Juvenile and Mature Wood of *Hevea brasiliensis* (Euphorbiaceae)

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Abstract

Exposing timber to temperatures approaching 200 °C causes thermal modification and changes its characteristics. This study evaluates the effect of various levels of thermal treatment on the physical properties of juvenile and mature wood from rubber tree (*Hevea brasiliensis*). Boards taken from 53-year-old rubber trees were thermally modified at up to 220 °C. Thermal treatment caused decreases on the oven-dried density, equilibrium moisture content, and swellings on juvenile and mature woods of *H. brasiliensis*. Influence of thermal modification at 180-200 °C in juvenile wood was lower than in mature wood, whereas the treatment at 220 °C caused a greater variation in properties of juvenile wood. The thermally modified wood is a suitable product for use in environments with high levels of relative humidity.

Keywords: thermal modification, rubber wood, maximum swellings, density of wood, equilibrium moisture content.

1. INTRODUCTION AND OBJECTIVES

Hevea brasiliensis (rubber tree) is a tree native to Brazil and is planted in many Asiatic countries for the production of latex (Severo et al., 2016). In Brazil, the commercial reforestation area of rubber trees is 229,059 ha (IBÁ, 2015). However, after 30 years, a decline in latex production makes further tapping of the trees uneconomical (Severo et al., 2016). Most plantations are from the State of São Paulo with federal government tax breaks.

In the past, felled rubber trees were either burned on the spot or used as fuel for steam engines, brick making or latex curing. Its favorable qualities and light color make a good substitute for many species (Ratnasingam & Ioras, 2012; Severo et al., 2016). Rubber wood is now one of the major resources for making furniture for export and for the production of panel products, such as particleboard, fiberboard (MDF), wood fiber cement-bonded particleboard, and plywood (Severo et al., 2016).

Variation in the properties of rubber wood occurs due to several factors, such as tree species, silviculture, and especially wood anatomy. Juvenile wood is also called pith wood or core wood and is the wood formed near the tree center, displaying a cylindrical shape with a diameter almost uniform from the base of the stem to the top (Bao et al., 2001; Calonego et al., 2005; Ferreira et al., 2011; Palermo et al., 2015). It differs from mature wood (outer wood) on account of several properties, including: chemical properties, fiber length, densities, and dimensional stability (Bao et al., 2001; Calonego et al., 2005; Calonego et al., 2014; Latorraca et al., 2011; Lobão et al., 2012; Severo et al., 2013; Severo et al., 2016; Palermo et al., 2015).

There are numerous hypotheses about the cause of juvenile wood. This type of wood is formed during the initial phase of the tree's life by cambium regions, which are influenced by the apical meristem activity (Bendtsen, 1978; Cown, 1992). According to Bendtsen (1978) and Cown (1992), juvenile wood is controlled by the production of auxin in the tree

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crown and results from close proximity to the foliage. Thus, the most accepted concept is that it is directly related to the age of the cambium that determines whether it will be formed juvenile, transition, or mature wood.

Fiber length in juvenile wood obtained from 50-year-old *H. brasiliensis* is 1.26 mm, whereas in mature wood, it is 1.51 mm. Anatomical characterization of this species showed the juvenile wood is confined between 40 and 55 mm from the pith (Ferreira et al., 2011).

Air-dried density of wood near the pith of 9-year-old *H. brasiliensis* RRIM 2020 clone ranges between 0.50 and 0.58 g cm⁻³, whereas near the bark, it lies between 0.54 and 0.61 g cm⁻³ (Naji et al., 2011). Basic apparent density, density at 12% moisture content, and the maximum volumetric shrinkage in the juvenile wood (cores of diameter 0.1 m with growth rings of approximately less than seven years old) of *H. brasiliensis* are 0.55 g cm⁻³, 0.614 g cm⁻³, and 8.2 %, respectively (Matan & Kyokong, 2003). The apparent oven-dried density in juvenile wood of 53-year-old *Hevea brasiliensis* (similar trees from this study) is 0.621 g cm⁻³, whereas in mature wood, it is 0.615 g cm⁻³. The volumetric, tangential, radial, and axial shrinkages in juvenile wood of this species are 7.44, 4.88, 2.22 and 0.41%, whereas in mature wood, they are 7.44, 4.88, 2.22, and 0.41%, respectively (Severo et al., 2013).

Thermal treatments exposing wood to temperatures approaching 200 °C for several hours can change its chemical composition. Heating wood at these temperatures, or thermal modification, causes degradation of the hemicelluloses and of the amorphous region of cellulose, contributing to the increase in the degree of crystallinity of this polymer (Arnold, 2010; Bächle et al., 2010; Brito et al. 2008; Calonego et al., 2016; Esteves & Pereira, 2009; Korošec et al., 2009; Mburu et al., 2008). In addition, a cross-linkage between the lignin and the polymers occurs, which causes the decrease in their hygroscopicity (Esteves et al., 2007; Esteves & Pereira, 2009; Calonego et al., 2012; Ratnasingam & Ioras, 2012).

Moreover, juvenile wood is characterized by high lignin content when compared with mature wood and consequently presents an adverse effect on thermal modification (Calonego et al., 2014; Calonego et al., 2016; Severo et al., 2012). *H. brasiliensis* presents opposite behavior (Severo et al., 2016) due to sugar content in the cell lumen of mature wood (Kadir & Sudin, 1989).

Thermal modification with steam (thermo hydrolysis) at 180 °C for 2 h in wood of *Hevea brasiliensis* from a 25–30-year-old plantation in Malaysia showed a decrease in the oven-dried density and the maximum tangential and radial swellings from 11.86%, 45.21%, and 11.11%, respectively (Ratnasingam & Ioras, 2012). However, neither the effects of thermal treatment on juvenile and mature wood nor the various temperatures of treatment on physical properties were studied by the authors.

As the rubber tree presents a high proportion of juvenile and mature woods (Ferreira et al., 2011) and the hygroscopicity and dimensional variation are important factors in the processing and use of wood, the aim of this study was to evaluate the effects of various levels of thermal treatment with heat irradiation on the physical properties of *Hevea brasiliensis* juvenile and mature woods.

2. MATERIALS AND METHODS

Wood specimens for this study were obtained from five 53-years-old *Hevea brasiliensis* (Willd. ex ADR. de Juss.) Muell. Arg. (Euphorbiaceae) trees, ungrafted from the Miraculous Water Farm, located in Tabapuã (20° 57' 50" S; 49° 1' 55" W), São Paulo, Brazil. The trees were felled at 0.30 m from the soil and sectioned into 3.0 m logs. The logs with an average diameter of 37 cm were cut into flat-sawn boards. Later, the boards were dried down to 10.00% moisture content in a dry kiln. Five boards containing the pith were cut into 34-mm thick pieces.

2.1. Thermal treatments of boards

One dried board taken from each tree was planed to 32-mm thickness and sawed into smaller pieces measuring 0.60 m in length. Regions with cracks and knots were discarded. One piece 32 by 180 by 600 mm in size from each board was kept in its original condition (untreated wood) and the other three pieces were used for thermal treatments (thermally modified wood).

A part of the pieces was placed in an electric oven with heat transfer by irradiation, 1-m³ net volume, air as inert atmosphere and a programmable controller, and thermally modified in the Laboratory of Wood Drying and Preservation from Unesp, Botucatu, SP, Brazil. Treatment started at an initial temperature of 100 °C over a period of 14 h and then the temperature was increased (1.34 °C/minutes) up to 180 °C and maintained over a period of 2.5 h (Severo & Calonego, 2009). The same procedure was performed with the thermal modification at final temperature of 200 °C and 220 °C.

After the end of the thermal treatment, the wood pieces were allowed to cool naturally until they reached 30 °C.

2.2. Specimens preparation

Standard specimens were removed from all the pieces (untreated and thermally modified) according to the methods in Associação Brasileira de Normas Técnicas² ABNT NBR 7190 (1997) for the physical characterization of juvenile and mature wood. The juvenile wood zone was defined as being located between 40 and 55 mm from the pith and identified by measurement of fiber length of the *H. brasiliensis* according to Ferreira et

al. (2011). Specimens of wood 20 by 30 by 50 mm in size were removed approximately 25 mm from the pith and 25 mm from the bark. Each specimen was cut to perfectly produce tangential, radial, and longitudinal directions and was then measured.

Although the *ABNT NBR 7190* (ABNT, 1997) standards state the necessary number of specimens to characterize the physical properties of wood is six, 15 specimens obtained from five boards were used to characterize each treatment (untreated wood and thermally modified woods at 180 °C, 200 °C, and 220 °C), aggregating 60 specimens for each type of wood.

2.3. Physical property test of the wood

The untreated and thermally modified wood specimens were placed in an oven at 103 ± 2 °C and were maintained in this condition until their mass stabilization (0% moisture content). Subsequently, the specimens were placed in a climatic chamber adjusted to 21 ± 2 °C and $65 \pm 5\%$ relative humidity (RH) until the specimens reached the equilibrium moisture content. The specimens were then weighed and their dimensions measured by using a 0.01-g accuracy balance and a 0.01-mm accuracy micrometer, respectively. Following these measurements, the specimens were submerged in water until the cell walls were completely saturated. Then the specimens were again measured and weighed. The evaluation of oven-dried density, equilibrium moisture content, and

maximum swelling were performed according to the *ABNT NBR 7190* (ABNT, 1997) standard.

2.4. Statistical analysis

To evaluate differences in oven-dried density, equilibrium moisture content, and maximum swellings, a Kolmogorov-Smirnov's normality test at 5% significance was performed. All variables had normal distribution. A parametric two-way test (Anova) at 5% significance was then performed considering the type of wood (two levels) and the thermal treatment (four levels), as well as Tukey's test at 5% significance for the comparison of the means.

3. RESULTS AND DISCUSSION

Oven-dried density for untreated *H. brasiliensis* was 0.640 g cm^{-3} for juvenile and 0.638 g cm^{-3} for mature wood (Table 1). The densities of untreated wood presented in this article are similar to those cited by Matan & Kyokong (2003), Naji et al. (2011), and Severo et al. (2013). The density of untreated mature wood was not different ($p = 0.965$) than that of juvenile wood. This behavior is similar with the one showed by Severo et al. (2013) and Severo et al. (2016), who reported non-influence of the type of wood on density can also be explained by the high levels of extractives content in the juvenile wood when compared with mature wood.

Table 1. Effect of thermal modification temperature on the density and equilibrium moisture content of juvenile and mature woods from *Hevea brasiliensis*.

Property	Temperature			
	Untreated	180 °C	200 °C	220 °C
Oven-dried Density (g cm^{-3})				
Juvenile Wood, CV	4.5	4.1	2.1	4.4
Juvenile Wood, Mean	0.640 a	0.622 ab	0.631 ab	0.612 b
Juvenile Wood, ↓ (%)	–	–2.81	–1.41	–4.38
Mature Wood, CV	4.9	6.4	4.5	5.0
Mature Wood, Mean	0.638 a	0.628 ab	0.626 ab	0.614 b
Mature Wood, ↓ (%)	–	–1.57	–1.88	–3.76
↓ or ↑ (%)	–0.31 ^{NS}	0.97 ^{NS}	–0.79 ^{NS}	0.33 ^{NS}
Equilibrium Moisture Content at 21 °C and 65% RH (%)				
Juvenile Wood, CV	1.8	4.0	3.2	7.6
Juvenile Wood, Mean	8.98 a	8.16 b	7.75 c	6.31 d
Juvenile Wood, ↓ (%)	–	–9.13	–13.70	–29.73
Mature Wood, CV	1.8	3.5	3.7	8.8
Mature Wood, Mean	9.23 a	8.30 b	7.81 c	6.80 d
Mature Wood, ↓ (%)	–	–10.08	–15.38	–26.33
↑ (%)	2.78 *	1.72 *	0.77 ^{NS}	7.77 *

Means followed by the same letters within rows denote significant difference by Tukey's test at 95% probability between treatments; * in same column denote significant difference by F test at 95% probability between type of wood; same letters within rows and ^{NS} in same column denote non-significant difference. CV: coefficient of variation; ↑: increase; ↓: reduction.

Thermal treatment promotes decreases ($p = 0.009$) of up to 4.38% and 3.76% in the oven-dried densities of respective juvenile and mature wood from *H. brasiliensis* when thermally modified at 220 °C.

This fact is explained by the influence of thermal treatment on the changes in the chemical composition by the degradation of extractives and cell wall compounds (Bächle et al., 2010; Brito et al. 2008; Esteves & Pereira, 2009; Korošec et al., 2009), mainly sugars from hemicelluloses (Bruto et al. 2008; Calonego et al., 2016; Severo et al., 2012; Severo et al., 2016) that, consequently, causes weight loss and decrease in apparent wood densities.

These results are consistent with those obtained by Esteves et al. (2007), Arnold (2010), Severo et al. (2012), and Calonego et al. (2014) who thermally modified the juvenile and mature wood from *Eucalyptus globulus*, *Eucalyptus grandis*, *Fagus sylvatica*, *Picea abies*, *Pinus elliottii* var. *elliottii*, and *Pinus pinaster*.

Respective equilibrium moisture contents (EMC) in the juvenile and mature wood of untreated *H. brasiliensis* were only 8.98% and 9.23% after acclimatized at 21 °C and 65% RH. According to Almeida & Hernández (2006), these lower values in the equilibrium moisture content can be attributed to the phenomenon known as *hysteresis*.

We found that the EMC of mature wood was significantly higher ($p < 0.001$) than that of juvenile wood. Thus, according to Calonego et al. (2005) and Severo et al. (2012), this result is explained as follows: mature wood has a higher number of hydroxyl groups available to adsorb moisture than juvenile wood.

This study also showed the thermal treatment from 180 °C to 220 °C promoted reductions ($p < 0.001$) of up to 29.73% and 26.33% in the EMC of juvenile and mature wood from rubber wood. Similar improvements were cited by Esteves et al. (2007), Brito et al. (2008), Severo et al. (2012), Calonego et al. (2012), Calonego et al. (2014), and Calonego et al. (2016) for thermally-modified wood of *Eucalyptus globulus*, *Eucalyptus grandis*, *Eucalyptus saligna*, *Pinus caribaea* var. *hondurensis*, *Pinus elliottii* var. *elliottii*, and *Pinus pinaster*. According to Esteves et al. (2007), Brito et al. (2008), Esteves & Pereira (2009), Korošec et al. (2009), and Ratnasingam & Ioras (2012), chemical changes lead to higher lignin reactivity with formation of crosslinks, responsible for less water absorption, which explain the decrease of equilibrium moisture content.

The volumetric, tangential, radial, and axial swelling in juvenile wood from untreated *H. brasiliensis* was 9.34, 5.56, 2.94, and 0.62%, respectively. In mature wood, the respective swellings were 9.55, 6.05, 2.80, and 0.48% (Table 2). The tangential and axial swellings of mature wood from untreated rubber wood are statistically different ($p = 0.001$) than that of juvenile wood, whereas the volumetric ($p = 0.324$) and radial ($p = 0.146$) swellings are not significantly different in both types of wood. We found the axial swelling of juvenile wood was greater (22.58%) than that of mature wood.

These results are consistent with those obtained by Matan & Kyokong (2003), Ratnasingam & Ioras (2012), and Severo et al. (2013), who studied the dimensional stability of untreated rubber wood. Several authors explain longitudinal swelling can be greater in juvenile wood because this type of wood has greater microfibril angles when compared with mature wood (Bao et al., 2001; Calonego et al., 2014; Severo et al., 2013).

Effect of thermal treatment on the dimensional instability of *H. brasiliensis* wood is shown in detail in Table 2. These results demonstrated that juvenile wood thermally modified at 220 °C had reductions ($p < 0.001$) of up to 28.59, 21.94, 33.33, and 56.45% in the volumetric, tangential, radial, and axial linear swellings when compared with the values found for untreated rubber wood. Mature wood when thermally modified under the same temperature presented reductions ($p < 0.001$) of up to 18.64, 19.01, 13.57, and 35.42% in these respective swellings. Improvement of dimensional stability in the thermally modified wood was explained by Korošec et al. (2009) and Bächle et al. (2010) as resulting from the increases in the degree of crystallinity and the width of cellulose crystallites; and by Esteves et al. (2007), Mburu et al. (2008), Esteves & Pereira (2009), Arnold (2010), and Severo et al. (2016) due to degradation in the hemicelluloses of the free hydroxyl groups in the amorphous region from cellulose and cross-linking of polymers of wood during thermal treatment.

Influence of thermal modifications presented in our study was smaller than those reported by Ratnasingam & Ioras (2012), who evaluated thermally modified *Hevea brasiliensis* treated at 180 °C between two and 10 h. The difference exists because in this study thermal treatment was performed with steam as an inert fluid and wood having high moisture content. Thus, this variation is consistent with the results of Mburu et al. (2008) and Arnold (2010), who explain that there is an increase in the thermo-degradation of the hemicelluloses by acid hydrolysis under high humidity.

Table 1 and 2 shows in general the influence of thermal treatment at 180 °C and 200 °C in juvenile wood was lower than in mature wood. Similar results were reported by Severo et al. (2012) and Calonego et al. (2014) for thermally modified *Pinus* and *Eucalyptus* wood. According to the authors, juvenile wood presents an adverse effect on the modification because of its high lignin content when compared with mature wood.

Improvement of dimensional stability in the rubber wood was lower for mature wood than for juvenile wood when thermally modified at 220 °C. These results corroborate those presented by Severo et al. (2016), who concluded the influence of this temperature from thermal treatment in the magnitude of chemical properties of mature wood from *H. brasiliensis* was lower than in juvenile wood.

Table 2. Effect of thermal modification temperature on the swellings of *Hevea brasiliensis* juvenile and mature woods.

Property	Temperature			
	Untreated	180 °C	200 °C	220 °C
Maximum Volumetric Swelling (%)				
Juvenile Wood, CV	6.0	10.1	9.0	13.1
Juvenile Wood, Mean	9.34 a	9.35 a	9.31 a	6.67 b
Juvenile Wood, ↓ or ↑ (%)	–	0.11	–0.32	–28.59
Mature Wood, CV	7.5	9.7	9.2	17.3
Mature Wood, Mean	9.55 a	9.12 a	8.88 a	7.77 b
Mature Wood, ↓ (%)	–	–4.50	–7.02	–18.64
↓ or ↑ (%)	2.25 ^{NS}	–2.46 ^{NS}	–4.62 ^{NS}	16.49 *
Maximum Tangential Swelling (%)				
Juvenile Wood, CV	9.0	10.8	9.5	19.2
Juvenile Wood, Mean	5.56 a	5.74 a	5.61 a	4.34 b
Juvenile Wood, ↓ or ↑ (%)	–	3.24	0.90	–21.94
Mature Wood, CV	6.6	9.9	8.2	18.1
Mature Wood, Mean	6.05 a	5.99 a	5.84 a	4.90 b
Mature Wood, ↓ (%)	–	–0.99	–3.47	–19.01
↑ (%)	8.81 *	4.36 *	4.10 *	12.90 *
Maximum Radial Swelling (%)				
Juvenile Wood, CV	23.7	23.6	22.3	11.9
Juvenile Wood, Mean	2.94 a	2.92 a	2.99 a	1.96 b
Juvenile Wood, ↓ or ↑ (%)	–	–0.68	1.70	–33.33
Mature Wood, CV	16.9	13.5	20.0	19.1
Mature Wood, Mean	2.80 a	2.52 a	2.51 a	2.42 a
Mature Wood, ↓ (%)	–	–10.00	–10.36	–13.57
↓ or ↑ (%)	–4.76 ^{NS}	–13.70 *	–16.05 *	23.45 *
Maximum Axial Swelling (%)				
Juvenile Wood, CV	25.0	15.2	10.0	40.5
Juvenile Wood, Mean	0.62 a	0.47 b	0.49 b	0.27 c
Juvenile Wood, ↓ (%)	–	–24.19	–20.97	–56.45
Mature Wood, CV	15.3	17.5	25.1	26.1
Mature Wood, Mean	0.48 a	0.42 ab	0.35 bc	0.31 c
Mature Wood, ↓ (%)	–	–12.50	–27.08	–35.42
↓ (%)	–22.58 *	–10.64 ^{NS}	–28.57 *	14.81 ^{NS}

Means followed by the same letters within rows denote significant difference by Tukey's test at 95% probability between treatments; * in same column denote significant difference by F test at 95% probability between type of wood; same letters within rows and ^{NS} in same column denote non-significant difference. CV: coefficient of variation; ↑: increase; ↓: reduction.

Moreover, interaction between type of wood and treatment is not significant for tangential swelling ($p = 0.663$) but is significant to volumetric ($p = 0.006$), radial ($p = 0.003$), and axial ($p < 0.001$) swellings. The significant interaction between type of wood and the treatment, mainly to volumetric, radial, and axial swellings showed thermal modification up to 200 °C caused less influence on juvenile wood than on mature wood and temperatures of 220 °C caused opposite behavior.

Previous studies about the chemical properties of untreated rubber wood can help explain this behavior in dimensional stability showed in our study. According to Kadir & Sudin (1989), this species contains high fructose, glucose, sucrose, maltose, and starch contents in cellular lumen. However, these compounds are relatively low at the central part of the stem (regions where the juvenile wood occurs) and are greater

in the periphery (regions where the mature wood occurs). Moreover, according to Shanks & Gunaratne (2011), heat treatments promote starch gelatinization, which results in lower heat capacity. Thus, these sugars and starches, which are present only in the cellular lumen of periphery of the *H. brasiliensis* stem, can delay the thermal degradation of wood cell wall and, therefore, maintain the mature wood closer to its original condition. Thus, kinetic events related to heat capacity should be examined in future studies with thermally modified wood that contains high starch content.

4. CONCLUSIONS

This study showed that thermal modification of *Hevea brasiliensis* wood decreases its oven-dried density, equilibrium

moisture content and maximum swellings. The influence of thermal modification at 180-200 °C in juvenile wood was lower than in mature wood, whereas the thermal modification in juvenile wood at 220 °C caused a greater variation in its physical properties, such as equilibrium moisture content, and volumetric, tangential and radial swellings. The thermally modified wood is a suitable product for use in environments with high levels of relative humidity.

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