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#### REFERÊNCIA

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# EFFECT OF THERMO-MECHANICAL TREATMENT ON PROPERTIES OF PARICA PLYWOODS (*Schizolobium amazonicum* Huber ex Ducke)<sup>1</sup>

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**ABSTRACT** – Thermo-mechanical treatment is a technique for wood modification in which samples are densified by means of heat and mechanical compression, applied perpendicularly to fibers, which under different combinations of time, temperature, and pressure increases wood density and thus improve some of its properties. This study aimed to treat thermo-mechanically parica plywood and observe the effects on its physical and mechanical properties. Specimens were submitted to two treatments, 120 and 150 °C, remaining under pressure for seven minutes and, subsequently, under zero pressure for 15 minutes. Results showed a significant increase in specific mass from 0.48 g cm<sup>-3</sup> to an average of 0.56 g cm<sup>-3</sup>, and a compression ratio of about 31.7% on average. Physical properties also varied significantly and results showed that treated samples swelled and absorbed more water than those untreated, leading to a greater thickness non-return rate. This indicates the proposed thermal treatments did not release the internal compressive stress generated during panel pressing, not improving its dimensional stability as a result. On the other hand, mechanical properties were positively affected, leading to an increase of 27.5% and 51.8% in modulus of rupture after treatments at 120 and 150 °C, respectively. Modulus of elasticity and glue-line shear strength did not vary statistically and Janka hardness was 29.7% higher after treatment at 150 °C.

**Keywords:** Thermo modification; Wood panels; Densification

## ***EFEITO DO TRATAMENTO TERMO-MECÂNICO SOBRE AS PROPRIEDADES DE COMPENSADOS DE PARICÁ (*Schizolobium amazonicum* Huber ex Ducke)***

**RESUMO** – O tratamento termomecânico é uma metodologia para modificação da madeira, onde as amostras são densificadas por meio do calor e da compressão mecânica aplicada perpendicularmente às fibras, que submetidas a diversas combinações de tempo, temperatura e pressão aumentam a densidade da madeira e assim melhoram algumas de suas propriedades. O presente trabalho teve como objetivo tratar termomecanicamente compensados de paricá e observar os efeitos nas suas propriedades físicas e mecânicas. Os corpos-de-prova foram submetidos a dois tratamentos: a 120°C e a 150°C, mantidos sob pressão por sete minutos e, posteriormente, sob pressão zero, por quinze minutos. Os resultados mostraram que houve aumento significativo da massa específica de 0,48g/cm<sup>3</sup> para, em média, 0,56 g/cm<sup>3</sup>, e a taxa de compressão foi de 31,7% em média. As propriedades físicas também variaram significativamente, e os resultados mostraram que as amostras tratadas incharam e absorveram mais água que as testemunhas, levando a uma maior TNRE (taxa de não-retorno em espessura). Isto indica que os tratamentos térmicos propostos não liberaram as tensões internas de compressão geradas durante a prensagem do painel, não melhorando sua estabilidade dimensional. As propriedades mecânicas, por sua vez, foram afetadas positivamente, levando a um aumento de 27,5% e 51,8% do MOR após os tratamentos a 120°C e a 150°C, respectivamente. O MOE e o cisalhamento na linha de cola não variaram estatisticamente e, a dureza Janka, ficou 29,7% maior após o tratamento a 150°C.

**Palavras-chave:** Modificação térmica; Painéis de madeira; Densificação.



## 1. INTRODUCTION

Thermo-mechanical treatment is a method for modifying wood, which is densified by means of heat and mechanical compression applied perpendicular to fibers, which, under different combinations of time, temperature, and pressure, increase wood density and thus improve some of its properties. Thermo-mechanical treatment is also a way to convert soft and porous woods into denser woods that can be used in situations where greater resistance is required. Likewise, this treatment can be used on wood laminates used for manufacturing plywood and LVL (Laminated Veneer Lumber). A previous densification of laminates can reduce the total pressing time of a panel and amount of adhesive used, in addition to improving mechanical properties (Kurowska et al., 2010; Arruda et al., 2011; Arruda, 2012; Fang et al., 2012).

Parica wood presents a medium density, which is a significant technical advantage in manufacturing plywood laminates for structural purposes, which requires greater mechanical resistance. Recent studies show that 30% of laminates produced with this species are used as a cover (plywood outer shell) and the remaining as a core, i.e. the inner part (Rossi et al., 2003).

Thermo-mechanical treatment can also be applied during or after panel consolidation, making it less hygroscopic and resistant to biological attack (Currier, 1962; Haygreen and Daniels, 1969; Heger et al., 2004; Unsal et al., 2010; Mendes et al., 2013). Regarding thermo-mechanical treatments in the post-production of plywood, the literature is still scarce.

This study aimed to determine and compare values of the main physico-mechanical properties of parica plywood densified by thermo-mechanical treatment in order to quantify its possible gains in resistance, rigidity, and dimensional stability in relation to an untreated plywood.

This study is justified by the fact that thermo-mechanical treatments can help improve final product quality, reducing dimensional instability of wood and products such as panels because they reduce moisture

content and liquid absorption, in addition to making them more mechanically resistant. Furthermore, the use of this treatment in parica plywood panels can encourage research with other tropical species less used, relieving the pressure on those most sought-after ones.

## 2. MATERIAL AND METHODS

Water-resistant plywood panels (WRP) with 20 mm thickness, bonded with phenolic resin, were purchased in Brasília - DF, Brazil. In order to determine the temperature, pressure, and time of treatments, a pre-test was performed (Costa and Del Menezzi, 2014). After analyzing the obtained results, two treatments were selected, as can be observed in Table 1.

The pressure in press gauge for the densification process was calculated according to Equation 1, using 50% of the perpendicular compression resistance of parica wood, which is equal to 5.88 MPa (IBAMA, 2001).

$$P_G = \frac{P_s - A_p}{551.55} \quad (\text{Eq. 1})$$

Where:

$P_G$  = gauge pressure, in  $\text{kgf cm}^{-2}$ ;

$P_s$  = specific pressure of parica, in  $\text{kgf cm}^{-2}$ ;

$A_p$  = area of panels, in  $\text{cm}^2$ .

After press closure, records of pressure corrections were taken frequently, which was made to keep it constant. These corrections occurred because the glass transition temperature has been reached, making wood malleable, and leading to a required pressure reduction to keep it compressed. When treatment temperature was reached, material was maintained under pressure during seven minutes and subsequently under zero pressure during 15 minutes.

This is a crucial stage in which the compressive stress relaxation occurs, which will reflect on dimensional stability of the material, thus characterizing the post-treatment. Subsequently, panels were removed from the press for cooling and then taken to climatization to proceed with the measurements.

**Table 1** – Thermo-mechanical treatments applied to parica plywood.

**Tabela 1** – Tratamentos termomecânicos aplicados no compensado de paricá.

Treatment	Temperature	Pressure	Time under pressure (min.)	Time after zeroed pressure (min.)
1	120 °C	50%	7	15
2	150 °C			

The mechanical properties were assessed according to the standard ASTM D1037 (1999), being static bending in the direction perpendicular to fibers, obtaining the modulus of elasticity ( $E_M$ ) and modulus of rupture ( $f_M$ ), and Janka hardness ( $f_H$ ). The glue-line shear strength ( $f_{gv,0}$ ) was assessed according to the European standard EN 314-1 (2004).

Static bending tests were performed with 10 samples from each treatment and controls, with dimensions of  $45 \times 260$  mm and thickness varying according to the treatment. The span used varied according to the final mean thickness of each treatment, characterizing mainly plywood hardness and resistance, also serving to assess whether the densification resulted in significant gains in these properties. From these samples, others were taken in order to perform Janka hardness. These tests were carried out in a universal testing machine (EMIC), with a maximum load capacity of 300 kN.

In order to perform Janka hardness test, specimens of  $45 \times 50$  mm were glued two by two to meet the standard minimum thickness requirement. Thus, 10 replications were used for each treatment.

The glue-line shear strength ( $f_{gv,0}$ ) was performed to assess the influence of treatment on plywood gluing quality using the same universal testing machine and 10 specimens of  $25 \times 90$  mm per treatment.

Water absorption and volumetric and thickness swelling tests, obtained according to the standard ASTM D 1037 (ASTM, 1999), as well as equilibrium moisture content (EMC), were performed to obtain the hygroscopic behavior of panels and observe the densification treatment contribution to the dimensional stability of the material. These tests were performed by using 10 samples of  $45 \times 45$  mm from each treatment, being submerged in ambient temperature water during a 24-hour period, within which, every 2 and 24 hours, mass and dimensions were measured with a precision balance and dial indicator.

Mass loss (ML, %) and compression ratio (CR, %) were also measured in the 10 treated samples of  $45 \times 45$  mm from each treatment. ML is the pre-treatment mass to post-treatment mass ratio and refers to the total sample mass loss, which includes water and extractives loss as well as wood polymers degradation. If ML is lower than the initial EMC, it means that there was no effective mass loss, i.e. ML was related only to water loss. CR represents the degree of material densification, relating the final to the initial thickness of a sample. The higher the CR is, the greater the degree of material densification. ML and CR were measured after climatization.

After swelling and absorption tests, specimens were dried in an oven until constant weight and subsequently the thickness non-return rate (TNRR) was measured. This measure represents the swelling caused by the release of compressive stress during plywood pressing. These data, together with thickness swelling data (2 and 24 h) and water absorption (2 and 24 h), were used to determine thermal treatment efficiency in improving dimensional stability. EMC was obtained from the same specimens after measuring TNRR, according to the standard ASTM D 4442 (ASTM, 2007).

### 3. RESULTS

Table 2 shows the specific mass (SM) and compression ratio of plywood. Specific mass varied significantly, with averages of 0.447 and 0.560 g cm<sup>-3</sup> for untreated and treated panels, respectively. A high compression ratio was observed resulting in increased density. CR also varied significantly, which means an average reduction in material thickness of 31.69%.

Table 3 shows the average of physical properties of treated and untreated panels. Treated panels presented lower values for all properties when compared to those untreated, except for the equilibrium moisture content. This is due to a greater water absorption and thickness swelling, which reflected in an increased TNRR.

**Table 2** – Specific mass (SM) and compression ratio (CR) of treated and untreated samples of parica plywood.

**Tabela 2** – Massa específica (ME) e taxa de compressão (TC) das testemunhas e das amostras tratadas de compensado de paricá.

Treatment	SM (g cm <sup>3</sup> )	CR (%)
Control	0.447	–
T1 (120 °C, 7', 15')	0.594	28.51
T2 (150 °C, 7', 30')	0.639	34.88
Average of treatments	0.560	31.69

**Table 3** – Dimensional stability properties of parica plywood panels.**Tabela 3** – Propriedades de estabilidade dimensional dos painéis compensados de paricá.

Treatment	Property (%)						
	TS2h	TS24h	WA2h	WA24h	EMC	ML	TNRR
Control	2.19 <sup>a</sup>	3.17 <sup>a</sup>	30.29 <sup>a</sup>	59.58 <sup>a</sup>	11.02 <sup>a</sup>	–	2.41 <sup>a</sup>
T1 (120 °C, 7', 15')	16.62 <sup>b</sup>	22.85 <sup>b</sup>	38.21 <sup>b</sup>	67.67 <sup>b</sup>	10.43 <sup>b</sup>	6.63 <sup>a</sup>	8.84 <sup>b</sup>
T2 (150 °C, 7', 15')	20.32 <sup>b</sup>	27.50 <sup>b</sup>	38.54 <sup>b</sup>	70.52 <sup>b</sup>	9.61 <sup>c</sup>	9.99 <sup>b</sup>	10.58 <sup>c</sup>
Average of treatments	18.47	25.17	38.37	69.10	10.02	8.31	9.71

Equal letters do not differ statistically from each other. TS2h – thickness swelling after 2-hour immersion; TS24h – thickness swelling after 24-hour immersion; WA2h – water absorption after 2-hour immersion; WA24h – water absorption after 24-hour immersion; EMC – equilibrium moisture content; ML – mass loss; TNRR – thickness non-return rate.

Equilibrium moisture content presented good responses to thermal treatments, as can be seen in Table 3. It differed statistically between treatments since it presented values from 11.02% to 10.43% after Treatment 1 and to 9.61% after Treatment 2. In its turn, mass loss, which is related to wood degradation due to temperature increase and duration of panel treatment, presented average values of 6.63% after Treatment 1 and 9.99% after Treatment 2.

Moreover, TNRR values of treated plywood were significantly higher than those untreated (Table 3), which presented a value of 2.41%. Although with a tendency to increase as temperature increases, the values of analyzed properties did not show statistical differences, except for TNRR, which presented a value 17.5% higher.

Table 4 shows the average of mechanical properties of treated and untreated panels. No one of the treated panels showed a reduction in mechanical properties when compared to those untreated ones.

Modulus of rupture ( $f_M$ ) presented values from 26.50 MPa (control) to 33.80 MPa (at 120 °C) and 40.23 MPa (at 150 °C), which represents an increase of 27.5 and 51.8%, respectively. On the other hand, modulus of elasticity ( $E_M$ ) was not influenced by treatments, remaining statistically equal to control. However, a clear tendency for this effect was observed, i.e., the

higher the temperature is, the greater the increment in material rigidity.

Thermo-mechanical treatment at 120 °C had no effect on plywood hardness, which reached 1954.1 N and remained statistically equal to control (1639.1 N). However, Tukey's test showed that the treatment at 150 °C was significantly higher in hardness than control, reaching a value of 2126.1 N, which is 29.7% higher.

As occurred for modulus of elasticity, the glue-line shear strength of plywood was not affected after treatment. In control,  $f_{gv,0}$  presented a value of 0.79 MPa and increased to 1.35 MPa at 120 °C and to 1.05 MPa at 150 °C.

#### 4. DISCUSSION

The average CR of 31.69% reached by using a pressure of 14.7 N mm<sup>-2</sup> was similar to that obtained by Bekhta and Marutzky (2007), who observed a CR of 33% by using a pressure of 15 N mm<sup>-2</sup> in beech laminates (*Fagus* sp.) before using them for plywood manufacturing. Arruda (2012) produced plywood with thermally treated laminates of amescla wood and obtained a CR ranging from 10.54% (at 140 °C) to 15.51% (at 180 °C).

Bekhta et al. (2012) observed a clear relationship between compression ratio and treatment parameters, such as temperature, pressure, and time. According

**Table 4** – Mechanical property values of parica plywood panels.**Tabela 4** – Valores das propriedades mecânicas dos painéis compensados de paricá.

Treatment	Property (MPa)			
	$f_M$	$E_M$	$f_H$	$f_{gv,0}$
Control	26.50 <sup>a</sup>	3161.4 <sup>a</sup>	1639.2 <sup>a</sup>	0.79 <sup>a</sup>
T1 (120 °C, 7', 15')	33.80 <sup>b</sup>	4443.4 <sup>a</sup>	1954.1 <sup>ab</sup>	1.35 <sup>a</sup>
T2 (150 °C, 7', 15')	40.23 <sup>b</sup>	5066.7 <sup>a</sup>	2126.1 <sup>b</sup>	1.05 <sup>a</sup>

Equal letters do not differ statistically from each other.  $f_M$  – modulus of rupture;  $E_M$  – modulus of elasticity;  $f_H$  – Janka hardness;  $f_{gv,0}$  – glue-line shear strength.

to these authors, the compression ratio is more sensitive to temperature increase than pressure or time. Inoue et al. (1993) cited the relationship between compression ratio and basic density and found an increase in density from 0.36 to 0.50 g cm<sup>-3</sup> with a compression degree of 30%. At a compression ratio of 60%, density increased to 0.9 g cm<sup>-3</sup>, which represents more than twice the initial density. In this study, which presented a CR slightly higher than 30%, density increased from 0.44 to 0.59 g cm<sup>-3</sup> after Treatment 1 and to 0.63 g cm<sup>-3</sup> after Treatment 2, representing an increase of 33 and 42%, respectively.

Kutnar and Sernek (2007) explained that an increase in density after a densification treatment will depend on several factors such as wood type, product thickness, how the wood is in the product (shape and particle size) and the applied treatments (pressure and/or heat). In general, an increase in density occurs at a rate of 25 to 500%, with a preferred rate of up to 200%.

The values obtained for physical properties (water absorption and thickness swelling after 2- and 24-hour immersion and TNRR) indicated that the proposed thermal treatments changed the relationships between water and wood, but in an unexpected way, since it is known that reducing wood's ability to absorb water by thermo-mechanical treatments, for example, an improvement in dimensional stability occurs. These values were higher in treated samples than in those untreated, which means the proposed thermal treatments did not release the internal compressive stresses generated during panel pressing. Similar results were also reported by Arruda et al. (2003), who treated thermally amescla laminates at 140 and 180 °C prior to plywood panel manufacturing; and by Arruda et al. (2011), who treated parica laminates at 150 °C and did not observe any tendency to reduce swelling with increasing treatment time. Del Menezzi (2004) also observed some negative results regarding swelling and TNRR by treating thermally OSB panels. An increase in temperature or treatment time could cause a greater reduction in water absorption. For an improvement in dimensional stability of panels, a significant reduction in thickness swelling and water absorption would be necessary.

Stresses are released according to the viscoelastic polymer nature composing the wood. Variations in its physical state occur depending on the temperature at which the polymer is. The temperature that divides

the states is known as viscoelastic transition temperature (T<sub>g</sub>), which varies with moisture. For lignin, the equilibrium moisture is reached at approximately 170 °C (HSU et al., 1989). Thus, when lignin is below this temperature, it behaves as a rigid solid (vitreous). However, when it is at a temperature above 170 °C, it behaves as a viscous polymer, losing its rigidity. Under this condition, which should have been provided by thermal treatment, the compressive stresses are released.

Unsal et al. (2011) observed a greater thickness swelling in samples of *Eucalyptus camaldulensis* treated at 130 and 150 °C and several pressures when compared to controls. The authors attributed this effect to springback and cited the study of Unsal et al. (2009), who studied pinewood and observed that the higher the pressure used in thermal treatment is, the higher the values of water absorption and swelling. In addition, these authors stated that the springback phenomenon is much more related to pressure level than to temperature degree, which is mostly related to permanent deformation of the material.

According to Del Menezzi (2004), EMC relates a number of water molecules adsorbed in sites of hydroxyl groups of the cell wall. Therefore, thermal treatments reduced these sites in such a magnitude implying in EMC reduction. Moreover, thermal treatment alters the structure of wood polymers, making them less hygroscopic or even transforming them chemically. Stamm et al. (1946) demonstrated that to reach a 40% efficiency in dimensional stability, the mass loss should be 8%, close to that reached by the treatments tested here. With increasing temperature and treatment duration, mass loss increases (Esteves et al., 2008). These authors observed for samples of *Pinus pinaster* a maximum reduction in EMC when mass loss reached 4%. Furthermore, at a temperature of 170 °C for 5 hours, mass loss is less than 1%; however, by increasing temperature to 200 °C and keeping the time constant, mass loss increases to 5%.

Frequently, effective mass loss (EML), which is the difference between ML and EMC values before treatment in percentage, is calculated to finding out the effectiveness of a treatment. If EML is positive, i.e. if ML is higher than EMC, the amount of heat applied was adequate to evaporate the water and degrade some other wood components. For any of the treatments, ML was higher than EMC before treatments (control), indicating that there was not enough heat to eliminate

the water from the samples. EML was calculated by Arruda et al. (2011), who treated thermally parica laminates at 150 °C for 5, 10, and 15 minutes and, in most of the samples, this value was negative. In samples which EML was positive, treatment was the longest, being applied for 15 minutes.

A material with high TNRR has greater swelling and expansion in thickness. Since TNRR represents the swelling caused by stress release, treated plywood accumulated the preexisting stress since panel manufacturing and those introduced with treatment application, leading to higher treated TNRE.

Moreover, in bonded materials, the release of compressive stresses causes loss of bonding quality. Thus, gluing quality is important to keep the panel bonded and limit stress release (Mohebbi et al., 2009).

Increases in modulus of elasticity and rupture have been widely reported in the literature, especially increasing material density (Kamke, 2006; Sundqvist et al., 2006; Gáborik et al., 2011). Hillis (1984) and Yildiz et al. (2006) observed that by using only thermal treatments, without compression influence, modulus of rupture is usually more affected than the modulus of elasticity. However, this was the effect reached in this study, even using pressure along with heat. Thus, Treatment 2 was advantageous for plywood static flexion since it made the material more resistant to rupture load, without reducing the elastic deformation resistance. Even though the decrease in  $E_M$  is common in thermal treatments due to thermal degradation of polymers and wood mass loss, this property was not significantly affected by treatment. The densification caused by mechanical compression, which was favored by temperature, contributed to increase plywood rigidity because empty spaces were reduced, increasing the proportion of mass in relation to volume.

Increasing hardness can be attributed to an increase in surface density of panels caused by heat treatment. Other authors have also obtained similar results, such as Arruda (2012), who observed hardness values from 17 N mm<sup>-2</sup>, for untreated amescla wood, to 45 N mm<sup>-2</sup>, for those treated at 200 °C. Dogu et al. (2010) treated pine samples at 120 and 150 °C for 60 minutes and observed an increase in Janka hardness and density. These authors stated that wood deformation is due to temperature increase rather than an increase in its compression.

Glue-line shear strength remained statistically equal to controls, indicating that thermal treatments did not compromise bonding quality, as observed by Larissa et al. (2011). Shear strength of plywood manufactured from thermally treated parica laminates decreased 16.70% in the treatment at 150 °C for 15 minutes when compared to control. Grzeskiewicz et al. (2009) observed a decrease of up to 84.21% for glue-line shear strength in the most severe treatment (220 °C for two hours).

## 5. CONCLUSION

The thermo-mechanical treatment made plywood denser and with lower equilibrium moisture content.

Due to the release of compressive stresses, thickness swelling, water absorption and thickness non-return rate presented higher values for treated plywood, which made them less dimensionally stable. However, thermo-mechanical treatment improved the modulus of rupture and hardness, not affecting negatively the other mechanical properties tested.

For further studies, it is recommended an investigation of thermo-mechanical treatments concomitantly to plywood pressing at manufacturing and consolidation. In addition, economic analyses should be performed to verify the viability of this treatment.

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