

INFLUENCE OF DRYING ON THE PHYSICAL AND MECHANICAL PROPERTIES OF WOOD FROM TREES GROWN IN AN AGROFORESTRY SYSTEM

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ABSTRACT – The cultivation of native and exotic species intercropped in an agroforestry system raises the interest for information on the properties of wood. Therefore, different methods are being tested to improve the technological properties of this material, including drying, which causes changes in the physical and mechanical properties of the wood. The present study investigated the influence of drying on the physical and mechanical properties of wood from tree species grown in an agroforestry system. *Parapiptadenia rigida* (Benth.) Brenan, *Peltophorum dubium* (Spreng.) Taub., *Eucalyptus grandis* W. Hill × *Eucalyptus urophylla* S.T. Blake (hybrid), and *Schizolobium parahyba* (Vell.) S.F.Blake were the species selected for the study. Three 9-year-old individuals of each of the species were obtained from an agroforestry system. Thirty wood samples (2.5 × 2.5 × 41 cm) were extracted from each species. The wood samples were divided between temperature treatments; 6 samples were used for each heat treatment (control, 120, 150, 180, and 210 °C), which were then dried for two hours in an oven (with forced air circulation). Following the heat treatment, the mechanical properties of wood samples were evaluated to determine the modulus of elasticity and rupture, the tension in the proportional limit, and maximum force according to the ASTM D-143-94 (2000) standard. Finally, the physical properties of the retractability of the wood samples were evaluated according to the NBR 7190 (ABNT, 1997) standard. Specimens used to analyze this variable came from sections of the wood (sample dimensions: 2.5 × 2.5 × 5 cm) not affected by the static bending test. Our findings indicate that, for all species investigated in this study, drying alters the physical and mechanical properties of the wood, with the most significant changes occurring at temperatures between 120 and 180 °C.

Keywords: Wood resistance; Dimensional stability; Heat treatment.

INFLUÊNCIA DA SECAGEM NAS PROPRIEDADES FÍSICAS E MECÂNICAS DA MADEIRA DE ESPÉCIES DE UM SISTEMA AGROFLORESTAL

RESUMO – O cultivo de espécies nativas e exóticas consorciadas em um sistema agroflorestal eleva o interesse de informações das propriedades da madeira. Portanto, diferentes métodos estão sendo testados com o objetivo de melhorar as propriedades tecnológicas desse material, incluindo a secagem, que provoca alterações nas propriedades físicas e mecânicas da madeira. O presente trabalho investigou a influência da secagem nas propriedades físicas e mecânicas da madeira de espécies arbóreas cultivadas em um sistema agroflorestal. *Parapiptadenia rigida* (Benth.) Brenan, *Peltophorum dubium* (Spreng.) Taub., *Eucalyptus grandis* W. Hill × *Eucalyptus urophylla* S.T. Blake (híbrido) e *Schizolobium parahyba* (Vell.) S.F.Blake foram as espécies selecionadas para o estudo. Três indivíduos de 9 anos de cada uma das espécies foram obtidos em um sistema agroflorestal. Trinta amostras de madeira (2,5 x 2,5 x 41 cm) foram extraídas de cada espécie. As amostras de madeira foram divididas entre tratamentos de temperatura. Para cada tratamento térmico foram utilizadas 6 amostras (controle, 120, 150, 180 e 210 °C), as quais foram secas por duas horas em estufa (com circulação forçada de ar). Após o tratamento térmico, as propriedades mecânicas das amostras de madeira foram avaliadas



através de testes para determinar; os módulos de elasticidade e ruptura, tensão no limite proporcional e força máxima de acordo com a norma ASTM D-143-94 (2000). Por fim, as propriedades físicas de retratibilidade das amostras de madeira foram avaliadas de acordo com a norma NBR 7190 (ABNT, 1997). Os corpos de prova utilizados para analisar essa variável foram provenientes de seções da madeira (dimensões da amostra: 2,5 × 2,5 × 5 cm) não afetadas pelo teste de flexão estática. Os resultados indicam que, para todas as espécies investigadas para o estudo, a secagem altera as propriedades físicas e mecânicas da madeira, com as alterações mais significativas ocorrendo a temperaturas entre 120 e 180 °C.

Palavras-Chave: Resistência da madeira; Estabilidade dimensional; Tratamento térmico.

1. INTRODUCTION

Wood, a product derived from the metabolism of trees, is considered a distinct raw material because of its unique properties; it is an organic material that is heterogeneous, porous, hygroscopic, and anisotropic (Almeida et al., 2016). These properties of wood make it an excellent source of quality material that can be utilized for the manufacture of wood products for industrial use (Gallio et al., 2018).

Owing to its unique characteristics, wood has been gaining popularity in different scenarios, among them, in civil construction and furniture manufacturing, leading to an increase in the number of planted forests over time (Fontoura et al., 2015). In this context, agroforestry systems (SAFs) are likely a promising alternative, with the plantation of a consortium of both native and exotic tree species for wood production, while also conserving natural resources (Lenci et al., 2018). Accordingly, SAFs are responsible for a number of benefits when used for wood production, including an improvement in the constituent characteristics of wood, as well as ecological benefits such as reduced soil degradation (Martins et al., 2019), thus reducing the impacts on the surrounding environment.

In order to expand the application of wood from SAFs, it is necessary to identify the characteristics and technological behavior of different types of wood (Motta et al., 2014). For this purpose, methods have been developed that aim to improve the physical and mechanical characteristics of the material, such as the process of drying (Freitas et al., 2016).

Drying is based on the application of heat; wood is exposed to different temperatures (which are lower than carbonization) for varying time periods (Batista et al., 2011; Cademartori et al., 2012; Conte et al., 2014; Sahin and Güler, 2018). The exposure to heat has been found to change the chemical, physical, and mechanical properties of the wood (Sahin and Güler, 2018). Thus,

an increase in temperature not only changes the color of the wood, but also results in a product with increased dimensional stability, less hygroscopicity, and greater resistance against wood pathogens (e. g., fungi) (Menezes et al., 2014; Zanuncio et al., 2014; Modes et al., 2017).

Among the technological characteristics that constitute the material, the physical and mechanical properties stand out, and the mechanics are determined by measuring the modulus of elasticity (MOE) and the modulus of rupture (MOR), which are usually obtained using static bending tests (Kol et al., 2017). These tests are very important because they identify the mechanical strength of wood with great precision and are consequently applied as classification criteria (based on classifications recommended in national and international standards) to determine the final use of the tested raw material (Gallio et al., 2016).

Among the physical properties, specific mass and shrinkage are emphasized, which are of significant importance when considering the quality of the final product. Wood does not shrink in a uniform manner due to its three-dimensional structure; the dimensions of wood can modify in varying ways depending on the equilibrium humidity of the environment to which it is exposed (when below the fiber saturation point) (Cezaro et al., 2016).

Due to the vast occurrence of native and exotic species with characteristics that are different from each other, the influence of methods that aim to improve the characteristics that constitute the material should be analyzed. Thus, the technological characterization of different species through physical and mechanical tests is of fundamental importance, since it is possible to obtain information that helps in determining the final use of the wood. Therefore, this study aims to investigate the influence of drying on the physical and mechanical properties of wood from species in an agroforestry system.

2. MATERIALS AND METHODS

2.1. Experiment location

The wood of four tree species; *Parapiptadenia rigida* (Benth.) Brenan, *Peltophorum dubium* (Spreng.) Taub., *Eucalyptus grandis* W. Hill × *Eucalyptus urophylla* S.T. Blake hybrid, and *Schizolobium parahyba* (Vell.) S.F. Blake, were obtained from an agroforestry system located at the Federal University of Santa Maria Frederico Westphalen campus (UFSM/FW), Rio Grande do Sul (27° 22" S; 53° 25" W), at an altitude of 480 m. According to the Köppen classification, the predominant climate in the region is characterized as sub-temperate sub-humid (Cfa), with an average annual temperature of 18.8 °C, the coldest month averaging 13.3 °C.

2.2. Sampling and evaluation

For each of the four species included in the study, three trees (approximately 9 years old) were sampled, and a log, 2 m in length, was removed from each individual in the region around the diameter at breast height (DBH). Central planks were subsequently made from the sapwood of the log samples in preparation for testing. Evaluations of wood samples were conducted at the UFSM/FW Wood Technology Laboratory.

For the assessment of static bending of wood, samples with dimensions of 2.5 × 2.5 × 41 cm were cut from the central planks; criteria such as anatomical orientation and dimensions of wood were taken into account when obtaining samples. Thirty samples per species were separated and identified, resulting in 120 samples in total.

Drying of wood samples was undertaken in an oven with forced air circulation at different temperatures (120, 150, 180, or 210 °C) for a period of 2 h, and one sample was retained untreated, to act as a control. Six replicates per species were exposed to each heat treatment. Following treatment, samples were subjected to static bending, which was carried out in a universal testing machine (model DL-2000), following the technical standard of the American Society for Testing and Materials (ASTM D-143-94, 2000). The values of modulus of elasticity and rupture, stress at the proportional limit, and maximum force, were obtained for wood samples tested. The retestability of wood was then tested using samples cut from the original samples measuring 2.5 × 2.5 × 5 cm, according to the NBR 7190 (ABNT, 1997) technical standard. These were weighed

on a scale (precision of 0.01 g), and their dimensions were measured with a digital caliper (precision of 0.01 mm) at points identified and marked on samples. Subsequently, wood samples were immersed in water until complete saturation of wood fibers occurred to obtain the weight and dimension values of the saturated samples. Swelling in the longitudinal, tangential, and radial planes was determined for each of the treatments.

The saturated samples were subsequently exposed to air-drying for 30 days, and then subjected to drying in an oven with forced air circulation at a temperature of 103 °C, until they reached constant weight. Weight and dimension values were collected again following drying to perform the calculations of shrinkage and swelling in the longitudinal, tangential, and radial planes. To obtain the anisotropy coefficient, only the tangential and radial planes were included in the measurements, and prior treatments were taken into account.

2.3. Experimental design and data analysis

A randomized design was used for the collection of data for analysis, characterized by a 4 × 5 factorial arrangement encompassing 4 wood species, 5 heat treatments, and 6 replications per treatment. The data were then analyzed using the Software "Statistical Analysis System" (SAS, 2003). Data were checked for normality using the Shapiro-Wilk test. Analysis of variance (ANOVA) and F-tests were used to determine variability between group means and the Bartlett test was used to check for homogeneity of variances. Average values were compared with the Tukey's means test at a 5% probability of error.

3. RESULTS

There was a significant difference in static bending, shrinkage, and swelling between the four wood species studied, and among the five heat treatments applied to the wood. Species × heat treatment interactions were also significant for all variables studied.

3.1. Static bending

E. grandis × *E. urophylla* recorded the highest values of the mechanical properties tested: MOR; 122.7 MPa (120 °C), MOE; 12713.3 MPa (120 °C), tension at the proportional limit (TPL); 77.7 MPa (180 °C), and maximum force (MF); 3498.0 MPa (120 °C). The results indicated that the values tended to increase until the treatments reached 150 °C and 180 °C, showing

a tendency to then decrease at 210 °C (Table 1). *S. parahyba* showed the lowest values among the studied species for all the mechanical properties and in all the heat treatments. For treatments measured at 210 °C, MOR, TPL, and MF recorded the lowest averages for the study (17.4, 16.5, and 507.8 MPa, respectively, Table 1).

3.2. Retratability: shrinkage and swelling

For longitudinal shrinkage, *E. grandis* × *E. urophylla* showed the lowest values of all the species

compared, recording 0.43% at 150 °C. However, at the highest temperature tested (210 °C), there was no notable difference between the species. The results for tangential and radial shrinkage showed optimal values for *S. parahyba*, recording 4.38% for tangential shrinkage, and 2.42% for radial shrinkage at 210 °C. Interestingly, the values did not differ for *P. dubium* in all the heat treatments tested (Table 2).

P. rigida showed the highest shrinkage values among all the species tested. The longitudinal shrinkage

Table 1 – Averages obtained by the static bending test for the mechanical properties of wood exposed to drying at different temperatures. **Tabela 1** – Médias obtidas pelo teste de flexão estática para as propriedades mecânicas de madeiras expostas à secagem em diferentes temperaturas.

Species	Treatment				
	Control	120 ° C	150 ° C	180 ° C	210 ° C
MOR (MPa)					
<i>P. rigida</i>	85.3 bA ± 3.8	115.8 aA ± 10.3	119.0 aA ± 16.3	117.9 aA ± 17.7	71.3 bA ± 8.9
<i>P. dubium</i>	65.0 bB ± 7.4	64.3 bB ± 13.4	89.8 aB ± 13.3	81.1 abB ± 11.3	43.2 cB ± 13.7
<i>E. grandis</i> x <i>E. urophylla</i>	89.3 bA ± 21.9	122.7 aA ± 7.9	114.7 aA ± 15.3	120.7 aA ± 28.0	65.9 cA ± 30.2
<i>S. paraiba</i>	30.9 abcC ± 6.6	40.2 abC ± 2.9	41.4 aC ± 11.2	23.7 bcC ± 11.7	17.4 cC ± 0.9
MOE (MPa)					
<i>P. rigida</i>	6113.2 bB ± 509.9	7054.6 abB ± 518.2	7036.9 abB ± 628.3	7515.7 abB ± 1263.2	8029.4 aB ± 1770.53
<i>P. dubium</i>	6948.5 aB ± 1658.6	6531.6 aB ± 1844.4	6991.6 aB ± 549.6	7442.0 aB ± 1500.8	6737.9 aB ± 419.3
<i>E. grandis</i> x <i>E. urophylla</i>	10304.1 bA ± 2463.46	12713.3 aA ± 1521.8	12560.2 aA ± 1585.8	12698.8 aA ± 1798.4	12030.8 aA ± 2451.0
<i>S. paraiba</i>	3095.0 aC ± 737.3	3341.3 aC ± 459.2	3437.2 aC ± 655.6	2754.8 aC ± 677.4	3147.1 aC ± 465.2
TPL (MPa)					
<i>P. rigida</i>	36.8 bB ± 5.1	44.7 abB ± 7.7	43.7 abB ± 5.3	50.0 aB ± 8.0	50.1 aAB ± 9.7
<i>P. dubium</i>	35.1 bB ± 3.6	31.7 bC ± 2.6	41.8 abB ± 4.9	47.5 aB ± 6.9	40.9 abB ± 1.1
<i>E. grandis</i> x <i>E. urophylla</i>	57.4 bA ± 9.8	74.3 aA ± 5.2	70.8 aA ± 7.6	77.7 aA ± 12.7	59.3 bA ± 19.1
<i>S. paraiba</i>	19.3 aC ± 4.5	23.2 aC ± 3.5	25.4 aC ± 5.8	19.1 aC ± 8.6	16.5 aC ± 1.3
MF(N)					
<i>P. rigida</i>	2430.6 bAB ± 3.3	3369.6 aA ± 5.2	3445.9 aA ± 6.1	3316.4 aA ± 7.1	1896.8 cA ± 2.7
<i>P. dubium</i>	2138.0 bB ± 3.1	2046.0 bB ± 4.5	2843.2 aB ± 4.6	2306.0 bB ± 1.9	1298.9 cB ± 5.0
<i>E. grandis</i> x <i>E. urophylla</i>	2711.3 bA ± 7.0	3498.0 aA ± 3.8	3264.3 aAB ± 5.2	3084.7 aA ± 5.4	1645.8 cAB ± 6.6
<i>S. paraiba</i>	952.0 abC ± 2.1	1220.7 aC ± 1.8	1134.6 aC ± 3.21	721.5 abC ± 4.2	507.8 bC ± 0.5

Where: MOE: module of elasticity; MOR: module of rupture; TPL: tension at the proportional limit; MF: maximum force. Lower case letters on the line compare temperature treatments and upper case letters on the columns compare species; values below the averages correspond to the standard deviation.

Onde: MOE: módulo de elasticidade; MOR: módulo de ruptura; TPL: tensão do limite proporcional; MF: força máxima. As letras minúsculas na linha comparam os tratamentos de temperatura e as letras maiúsculas nas colunas comparam as espécies; valores abaixo das médias correspondem ao desvio padrão.

was 1.03% in the 150 °C treatment, and the tangential and radial shrinkages were 9.96% and 5.14%, respectively, for both the control and treatment (Table 2).

For the anisotropic shrinkage coefficient, *S. parahyba* recorded the lowest value at 1.76, and *P. dubium* was the highest at 2.14. Both values were observed in the heat treatments at 150 °C (Table 2).

The results showed that the longitudinal swelling was lowest for *E. grandis* × *E. urophylla*, with a

value of 0.11% for the 210 °C treatment. The highest averages were obtained for *P. rigida* and *P. dubium*, with a longitudinal swelling of 0.59% at 120 °C for both species (Table 3). For the tangential and radial swelling, it was observed that the lowest values were recorded for *S. parahyba*, at 1.99% and 1.04%, respectively, at 210 °C. Conversely, the highest values were reported for *P. rigida* (8.38%) in tangential swelling, and *E. grandis* × *E. urophylla* (4.37%) in radial swelling (Table 3).

Table 2 – Average values of shrinkage obtained from the retractability of wood exposed to drying at different temperatures.

Tabela 2 – Valores médios de contração obtidos a partir da retratibilidade de madeiras expostas à secagem em diferentes temperaturas.

Espécie	Test.	Tratamento			
		120 ° C	150 ° C	180 ° C	210 ° C
		βLg (%)			
<i>P. rigida</i>	0.92 abBC ± 0.4	0.94 abB ± 0.3	1.03 bB ± 0.4	0.83 abB ± 0.3	0.71 aA ± 0.3
<i>P. dubium</i>	0.64 abAB ± 0.5	0.87 bB ± 0.4	0.55 aA ± 0.3	0.68 abAB ± 0.3	0.80 abA ± 0.5
<i>E. grandis</i> x <i>E. urophylla</i>	0.62 aA ± 0.4	0.45 aA ± 0.3	0.43 aA ± 0.3	0.47 aA ± 0.3	0.63 aA 0.4
<i>S. paraiba</i>	0.96 bC ± 0.4	0.63 aAB ± 0.5	0.95 bB ± 0.7	0.89 abB ± 0.5	0.70 abA ± 0.5
		βTg (%)			
<i>P. rigida</i>	9.96 cB ± 2.0	9.24 bcB ± 1.2	9.59 bcB ± 1.5	8.93 bB ± 1.3	7.38 aC ± 1.4
<i>P. dubium</i>	6.30 bA ± 1.1	7.61 cA ± 2.3	6.64 bcA ± 1.1	6.54 bA ± 0.8	4.45 aA ± 0.8
<i>E. grandis</i> x <i>E. urophylla</i>	9.33 bB ± 1.5	8.94 bB ± 1.0	9.30 bB ± 1.0	9.15 bB ± 0.7	5.63 aB ± 1.3
<i>S. paraiba</i>	5.86 bA ± 1.4	7.02 cA ± 2.0	5.87 bA ± 1.4	5.89 bA ± 3.1	4.38 aA ± 1.2
		βRd (%)			
<i>P. rigida</i>	5.14 cB ± 0.7	4.92 bcB ± 1.0	4.37 bB ± 0.8	4.41 bB ± 1.0	3.70 aB ± 0.7
<i>P. dubium</i>	3.06 abA ± 0.5	3.67 bA ± 0.8	3.15 bA ± 0.5	3.38 bA ± 0.8	2.46 aA ± 0.5
<i>E. grandis</i> x <i>E. urophylla</i>	4.81 bB ± 1.0	5.03 bB ± 1.0	4.90 bB ± 0.7	4.48 bB ± 0.4	3.04 aA ± 0.7
<i>S. paraiba</i>	3.11 bcA ± 0.6	3.60 cA ± 1.0	2.95 abA ± 0.6	3.72 cA ± 1.7	2.42 aA ± 0.7
		Caβ			
<i>P. rigida</i>	1.94 aA ± 0.5	1.94 aAB ± 0.5	2.18 bB ± 0.3	2.13 bA ± 0.4	2.05 abA ± 0.3
<i>P. dubium</i>	2.13 bB ± 0.4	2.08 abB ± 0.3	2.14 bB ± 0.3	2.01 abA ± 0.4	1.92 aA ± 0.4
<i>E. grandis</i> x <i>E. urophylla</i>	2.00 abAB ± 0.3	1.83 aA ± 0.3	1.93 abA ± 0.2	2.08 bA ± 0.2	1.95 abA ± 0.4
<i>S. paraiba</i>	1.96 bAB ± 0.4	1.98 bAB ± 0.4	1.76 aA ± 0.4	2.06 bA ± 0.4	1.96 bA ± 0.4

Where: βLg: Longitudinal shrinkage (%); βTg: Tangential shrinkage (%); βRd: Radial shrinkage (%); Caβ: Anisotropic shrinkage coefficient (%); Means followed by the same capital letter, per column, or the same lowercase letter, per line, do not differ by Tukey test ($p > 0.05$). Values below the averages correspond to the standard deviation.

Onde: βLg: Contração longitudinal (%); βTg: Contração tangencial (%); βRd: Contração radial (%); Caβ: Coeficiente de contração anisotrópica (%); Médias seguidas da mesma letra maiúscula, por coluna, ou da mesma letra minúscula, por linha, não diferem pelo teste de Tukey ($p > 0,05$); Valores abaixo das médias correspondem ao padrão desvio.

Table 3 – Average swelling values obtained from the retrainability of wood exposed to drying at different temperatures.
Tabela 3 – Valores médios de inchamento obtidos a partir da retrainabilidade de madeiras expostas à secagem em diferentes temperaturas.

Espécie	Test.	Tratamento			
		120 ° C	150 ° C	180 ° C	210 ° C
αLg (%)					
<i>P. rigida</i>	0.53 aA ± 0.3	0.59 aAB ± 0.3	0.56 aB ± 0.4	0.39 aA ± 0.2	0.36 aB ± 0.3
<i>P. dubium</i>	0.38 aA ± 0.4	0.59 aAB ± 0.5	0.58 aB ± 0.5	0.38 aA ± 0.2	0.38 aB ± 0.3
<i>E. grandis x E. urophylla</i>	0.58 cA ± 0.3	0.41 bcA ± 0.2	0.23 abA ± 0.1	0.26 abA ± 0.2	0.11 aA ± 0.1
<i>S. paraiba</i>	0.55 bA ± 0.4	0.72 bB ± 0.4	0.55 bB ± 0.5	0.50 bA ± 0.3	0.24 aAB ± 0.3
αTg (%)					
<i>P. rigida</i>	6.44 abB ± 1.8	7.52 bcB ± 1.3	8.38 cB ± 1.4	7.68 cB ± 1.5	5.54 aC ± 1.7
<i>P. dubium</i>	3.35 abA ± 0.9	5.33 cA ± 2.5	4.25 bcA ± 0.8	4.58 cA ± 0.9	2.77 aA ± 0.8
<i>E. grandis x E. urophylla</i>	8.83 cC ± 3.0	7.99 bcB ± 1.5	7.54 bB ± 1.1	7.14 bB ± 1.0	4.18 aB ± 1.1
<i>S. paraiba</i>	3.12 bA ± 1.2	4.39 cdA ± 1.1	4.65 dA ± 1.1	3.50 bcA ± 1.2	1.99 aA ± 1.2
αRd (%)					
<i>P. rigida</i>	3.10 aB ± 0.8	3.64 bB ± 0.6	3.92 bB ± 0.7	3.71 bB ± 0.8	2.84 aC ± 0.9
<i>P. dubium</i>	1.66 abA ± 0.4	2.60 cA ± 1.2	2.05 bA ± 0.4	2.18 bcA ± 0.5	1.36 aA ± 0.3
<i>E. grandis x E. urophylla</i>	4.37 cC ± 1.5	4.04 bcB ± 0.9	4.03 bcB ± 0.7	3.69 bB ± 0.6	2.10 aB ± 0.5
<i>S. paraiba</i>	1.50 abA ± 0.6	2.22 cA ± 0.6	2.23 cA ± 0.5	1.71 bcA ± 0.5	1.04 aA ± 0.6
Caa					
<i>P. rigida</i>	2.27 cB ± 0.2	2.10 bA ± 0.3	2.17 bcB ± 0.3	2.11 bcA ± 0.3	1.83 aA ± 0.3
<i>P. dubium</i>	2.13 aAB ± 0.5	2.08 aA ± 0.2	2.10 aB ± 0.3	2.16 aA ± 0.2	2.11 aBC ± 0.3
<i>E. grandis x E. urophylla</i>	2.10 bA ± 0.3	2.01 abA ± 0.2	1.92 aA ± 0.2	2.00 abA ± 0.3	2.04 aB ± 0.3
<i>S. paraiba</i>	2.20 abAB ± 0.5	2.09 aA ± 0.4	2.14 abB ± 0.4	2.11 abA ± 0.4	2.26 bC ± 0.4

Where: α Lg: Longitudinal swelling (%); α Tg: Tangential swelling (%); α Rd: Radial swelling (%); Caa: Anisotropic swelling coefficient (%); Means followed by the same capital letter, per column, or the same lowercase letter, per line, do not differ by Tukey test ($p > 0.05$). Values below the averages correspond to the standard deviation.

Onde: α Lg: Inchamento longitudinal (%); α Tg: Inchamento tangencial (%); α Rd: Inchamento radial (%); Caa: coeficiente de Inchamento anisotrópica (%); Médias seguidas da mesma letra maiúscula, por coluna, ou da mesma letra minúscula, por linha, não diferem pelo teste de Tukey ($p > 0,05$); Valores abaixo das médias correspondem ao desvio padrão.

The lowest and highest values for the anisotropic swelling coefficient were identified for *P. rigida*, with a value of 1.83 at 210 °C, and 2.27 for the control treatment (Table 3).

4. DISCUSSION

4.1. Static bending

The static bending analysis demonstrated that drying significantly influenced the mechanical properties

of the wood tested, with changes identified between the different heat treatments, as well as between species. *E. grandis* × *E. urophylla* individuals had the highest values for all static bending variables (Table 1). No information was found in the existing literature on the effects of drying on the four species analyzed.

In terms of the average values of MOR, in general, it was found that there was a growth variation between the heat treatments at 120 °C and 180 °C, with a subsequent decrease until a temperature of 210 °C was

reached (Table 1). These results do not corroborate those of Menezes et al. (2019), who studied the *Eucalyptus saligna* Sm. species. They reported an increase in MOR values up to 140 °C, with values varying from 123 MPa (control treatment) to 90 MPa (180 °C). This variation can be justified based on a study by Araújo et al. (2012), in which treatments at room temperature, 180 °C, 200 °C, and 220 °C were used. They found that an increase in temperature resulted in the wood becoming more friable, generating a decrease in hemicellulose content and lignin resolidification, the main cause of the loss of resistance.

The same authors, studying the species *E. grandis*, reported mean values of MOR, which ranged from 77.10 to 63.87 MPa, lower than those of this study for the species of *E. grandis* × *E. urophylla*. In contrast, Ferreira et al. (2019) studied the wood of *Hymenolobium petraeum* Ducke, which belongs to the same family as *P. rigida*; Fabaceae, and reported a value of 71.38 MPa, from the material treated at 200 °C, demonstrating the similarity to the value observed in our study for the wood of *P. rigida*, 71.3 MPa (Table 1).

In the present study, it was also found that the properties of wood had a greater influence on drying when compared to the MOE, likely due to the constituents of the cell wall having specific functions related to these properties (Esteves and Pereira, 2009).

Notably, we found that *E. grandis* × *E. urophylla* showed the highest values for all static bending variables tested (Table 1). Analysis of the MOE variable of *E. grandis* × *E. urophylla* showed similar results to those reported by Fontoura et al. (2015) for the species *Hovenia dulcis* Thunb., which recorded a value of 11811.1 MPa. Notably, the change in temperature from 150 °C to 180 °C resulted in an increase in the MOE values of *P. dubium* and *E. grandis* × *E. urophylla* for the present study. This can be explained by the increase in lignin cross-links, degradation, and modification of hemicellulose, as well as changes in the thermoplastic characteristics of heated wood (Gunduz et al., 2009).

The same variation was reported by Menezes et al. (2019), who observed that the increase occurred between the temperature ranges of 140 to 160 °C in the evaluation of the wood of two species (*E. saligna* and *Corymbia citriodora* K.D. Hill & L.A.S. Johnson). The results reported by Schneid et al. (2014), however, did not show variation in the MOE values when applied at

room temperature, 160 °C, 180 °C, and 200 °C for the species *Luehea divaricate* Mart..

An increase in TPL was observed in relation to the increase in temperature, with the species *E. grandis* × *E. urophylla* standing out in comparison with others. This behavior can be explained by Faria et al. (2015), who reported that an increase in temperature had a direct influence on TPL, and resulted in an increase.

We found that, for the most part, the average values of MF for *P. rigida* and *E. grandis* × *E. urophylla* were the highest at temperatures of 150 °C and 120 °C, respectively (both species were higher than the control). Similarly, Cademartori et al. (2012) studied the species *E. grandis* and found the highest averages in the control treatment and at 180 °C, with an exposure of 4 hours.

Other research studying flexion characteristics in the wood of the species *Attalea funifera* Mart., found a value of 1353.0 N, which is in accordance with *S. parahyba* heat-treated at 120 °C, which recorded 1220.7 N in the present study (Carvalho et al., 2019). Overall, it was found that, as the temperature increased, there was a reduction in the MF variable, demonstrating that MF is often affected by drying; its decrease is directly proportional to the temperature rise and exposure time of the treated wood (Korkut and Budakçi, 2009).

4.2. Retratibility: shrinkage and Swelling

In terms of the values of longitudinal shrinkage in the present study, we found that there was no tendency for growth or reduction between thermal treatments. With regard to tangential shrinkage, the same behavior was observed for *P. rigida* and *E. grandis* × *E. urophylla*, with a reduction in values between the range of 150 to 210 °C, whereas for *P. dubium* and *S. parahyba*, the results decreased from 120 to 210 °C.

Regarding radial shrinkage, our results indicated that *E. grandis* × *E. urophylla* was the most notable; *E. grandis* × *E. urophylla* showed a decrease in radial shrinkage with treatments applied after heat treatment at 120 °C. Another study investigating *E. grandis* × *E. urophylla* reported 4.5% shrinkage in the radial direction (Eleotério et al., 2015), which is in accordance with the results of this study. Further, Ferreira et al. (2019) investigated radial shrinkage in *H. petraeum* and found that wood treated at 180 °C for two hours recorded a radial alteration of 4.71%, in line with our results for *S. parahyba*, when heat treated at 210 °C.

Results for the anisotropic coefficient showed a reduction in values with increased temperature, which are according to the results from other research. This is expected to be caused by the degradation of accessible hydroxy groups, which are directly associated with the absorption of water in the cell walls of wood, thus resulting in a reduction in the anisotropic coefficient (Poubel et al., 2013).

We also found that the swelling variable in the longitudinal direction, for *E. grandis* × *E. urophylla*, showed a reduction behavior with increased temperature. Notably, the values found for the control samples of our study are in accordance with those found by Huller et al. (2017); *E. grandis* recorded a swelling of 0.54% under similar testing conditions.

Interestingly, the tangential and radial senses of the species *P. dubium*, when heat-treated at 120 °C, were found to be comparative to another woody species, *Tectona grandis* L.f., without the application of heat treatment, highlighting the similarity between the two species (Gil et al., 2018).

As observed for the anisotropic coefficient of shrinkage, there was a decrease in the results of anisotropic swelling coefficient with an increase in temperature. A study by Huller et al. (2017) evaluating *Eucalyptus cloeziana* F. Muell. found that wood samples not exposed to drying recorded a value of 1.66%, similar to our findings for *E. grandis* × *E. urophylla*, when treated at 150 °C.

This behavior can be explained by the high percentage of shrinkage and swelling in the tangential plane, compared to the radial plane of wood, which is defined by the orientations and dimensions of the wood being tested, thus allowing for contrasting dimensional variations of the anatomical planes (Oliveira et al., 2010).

In this sense, the smaller the difference between the tangential and radial planes, the more dimensionally stable the wood (Acosta et al., 2020). Therefore, as a general rule, anisotropic coefficients below 1.5 establish wood as 'optimal,' whereas values between 1.5 and 2.0 characterize wood as 'normal' (Logsdon et al., 2008). Accordingly, the higher the coefficient, the greater the probability of cracking and warping in the wood, thus making it more dimensionally unstable (Müller et al., 2014).

5. CONCLUSION

The temperatures that most affected the measured variables of species *Parapiptadenia rigida*, *Peltophorum dubium*, *Eucalyptus grandis* × *Eucalyptus urophylla*, and *Schizolobium parahyba*, ranged between 120 and 180 °C.

E. grandis × *E. urophylla* recorded the highest values for all static bending variables.

Additionally, we found that an increase in temperature directly influenced the values of shrinkage and swelling (retratibility of wood) in the different dimensional planes.

The anisotropic coefficient values of wood decreased with increasing temperature.

Drying alters the physical and mechanical properties of the four wood species studied.

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