PHYSICO-MECHANICAL PROPERTIES AND GROWTH CHARACTERISTICS OF PINE JUVENILE WOOD AS A FUNCTION OF AGE AND PLANTING SPACING

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ABSTRACT – *Pinus* forests have been implanted in the South of Brazil since the 1960s in different spacing and harvested in shorter terms to increase wood yield. Reducing the rotation period and changing the spacing of forest plantations can influence the wood's physical and mechanical properties, as they are younger trees that do not yet have a significant amount of mature wood in their composition. In this context, this research aimed to study the influence of three levels of planting spacing (3.0 × 2.0 m, 4.0 × 2.0 m, and 2.0 × 2.0 m) and two ages (13 and 15 years old) on growth characteristics and physical-mechanical properties of wood, as well as the relationship between them. Apparent density, latewood percentage, rings per inch, strength and stiffness in static bending as well as compression parallel to the grain, and shear strength were evaluated. The evaluated planting spacings did not cause statistically significant changes in the mechanical properties of juvenile *Pinus taeda* L. wood. The studied ages did not influence the wood's apparent density. However, changing the cutting age from 13 to 15 years significantly increased the strength and stiffness of the wood. There was a statistically significant correlation between tree growth characteristics and strength, and stiffness in bending and parallel compression, around 0.500 R^2, which suggests that this parameter can be used to assist in estimating those properties. The wood of *Pinus taeda* L used in this study can be classified as structural wood, class C20 for 13 years-old trees and classes C25 and C30 for 15 years-old trees, according to NBR 7190/97 requirements.

Keywords: Strength; Stiffness; Growth characteristics.

PROPRIEDADES FÍSICO-MECÂNICAS E CARACTERÍSTICAS DE CRESCIMENTO DA MADEIRA JUVENIL DE PINUS EM FUNÇÃO DA IDADE E DO ESPAÇAMENTO DE PLANTIO

RESUMO – As florestas de pinus vêm sendo implantadas no sul do Brasil desde a década de 1960 em diferentes espaçamentos e colhidas em prazos mais curtos para aumentar a produção de madeira. A redução do período de rotação e a alteração do espaçamento das plantações florestais podem influenciar nas propriedades físicas e mecânicas da madeira, por tratar-se de árvores mais jovens que ainda não possuem uma quantidade significativa de madeira adulta em sua composição. Nesse contexto, o objetivo desta pesquisa foi estudar a influência de três espaçamentos de plantio (3,0 × 2,0 m, 4,0 × 2,0 m e 2,0 × 2,0 m) e duas idades (13 e 15 anos) nas características de crescimento e nas propriedades físico-mecânicas da madeira, bem como a relação entre elas. Foi avaliada a densidade aparente, a porcentagem de lenho tardio, o número de anéis por polegada, a resistência e a rigidez em flexão estática e em compressão paralela, e a resistência ao cisalhamento. Os espaçamentos de plantio avaliados não causaram alterações estatisticamente significativas nas propriedades mecânicas da madeira juvenil de ***Pinus taeda*** *L. As idades estudadas não influenciaram na densidade aparente*

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*da madeira, mas o aumento da idade de corte de 13 para 15 anos aumentou significativamente a resistência e a rigidez da madeira. Houve correlação significativa entre as características de crescimento das árvores e a resistência e rigidez, em flexão estática e em compressão paralela, com R^2 próximo de 0,500, o que sugere que as características de crescimento podem ser utilizadas para auxiliar na estimativa destas propriedades. A madeira de **Pinus taeda** L. utilizada neste estudo pode ser classificada como madeira estrutural, classe C20 para 13 anos de idade e classes C25 e C30 para 15 anos de idade, de acordo com a norma NBR 7190/97.*

Palavras-Chave: Resistência; Rigidez; Características de crescimento.

1. INTRODUCTION

Brazil has 1.6 million hectares occupied by *Pinus* sp. plantations located mainly in the country's southern region. Exports reached US$ 11.4 billion in 2018, highlighting the main destinations, such as sawn wood and pulp. The Paraná state stands out with the largest area of planted forests, about 42% (IBÁ 2019), with the main cultivated species being *Pinus taeda* L. and *Pinus elliottii* Engelm (Wrege et al. 2016; Tavares et al. 2020).

Brazilian pine plantations began in the 1960s, with tax incentives for forestry and few management studies. At the time, they were generally deployed with a 2 x 2 meter spacing and expected rotations between 20 and 30 years. These parameters were studied and improved, predominating the increase in initial spacing and the decrease in rotations (Shimizu, 2008; IBÁ, 2019).

Currently, pine forests are planted with reduced spacing and shorter forest rotation periods due to the increased demand for raw material. For instance, plantations handled with two thinning and final cutting between 18 and 20 years of age (Remasa, 2016), or without thinning and final cut at 17 years of age (WestRock, 2017). Some companies have used 15-year rotations and no thinning. At these ages, Pine species such as *Pinus elliottii* and *Pinus taeda* do not have a significant amount of adult wood, which can influence their physical and mechanical properties (Palermo et al., 2013).

Thus, although extensively studied in previous occasions, with the changes in the forest management plans currently used, the effect of age and initial spacing in *Pinus* sp. plantations is once again the focus of studies to adapt its characteristics to commercial interests. Furthermore, it should be considered that *Pinus taeda* is a species subjected to intense genetic improvement programs, which can change the characteristics of its populations and influence the wood's properties (Coutinho et al. 2017; Essien et al., 2018).

Variables related to growth can change wood characteristics and influence its properties (Vidaurre et al., 2013). The characteristics of the growth rings of pine species can express their physical-mechanical performance, which can be a reference for quality control. The wider the growth rings of initial woods, the lower their mechanical performance. The inverse occurs for latewood proportion, with a positive correlation between its amount with density and wood mechanical properties (SPIB, 2014).

Forest planting spacing can be used to improve wood mechanical properties. The literature reports that several species are more sensitive to this variation. In studies with *Pinus patula*, tree spacing significantly influenced the mechanical properties of wood (Erasmus et al. 2018; Erasmus et al., 2020). 11-year-old *Pinus radiata* forests, planted with high planting densities (2500 stems ha^{-1}) had positive effects on wood stiffness in relation to the planting of 833 stems ha^{-1}.

Changes in wood characteristics can cause a significant decrease in its stiffness, such as high microfibril angle, large ring width, short fiber length, lower incidence of latewood, and thinner cell wall (Lasserre et al. 2005). On the other hand, a study carried out with *Pinus taeda* in the south of the United States, suggests that forest managers have flexibility in managing the spacing of plantation of this pine species without altering wood properties (Blazier et al., 2021).

Forest cutting age can be determined as a function of the tree's dimensions required for certain commercial products, however, it is one of the conditioning factors for the produced wood quality since the cutting age will determine the proportion of juvenile and adult wood in the logs. Tree age can influence anatomical characteristics and the physical, chemical, and mechanical properties of the wood (Latorraca et al. 2000).

Dobner Jr. et al. (2018) verified that harvest age was a determinant factor for obtaining *Pinus taeda* wood of higher density and the thinning intensity influenced the beginning of mature wood production. According to the authors, the production of mature wood started at the age of 13 years in stands without any thinning, with moderate and heavy thinning, and at the age of 17 years with extreme thinning. The same mean wood density produced at the age of 30 years could be obtained at the age of 20 years in all intensity of thinning studied, but not in cycles of less than 20 years.

The proportion of wood meeting the visually graded quality (air-dry density, microfibril angle – MFA, and modulus of elasticity - MOE) in *Pinus taeda* plantation-grown trees aged 13 and 22 years were investigated. Zones of high density, low MFA, and high MOE wood increased markedly in size in maps of the older trees, demonstrating the impact of age on end-product quality (Schimleck et al., 2018a).

Therefore, for *Pinus taeda*, changing the harvesting age cause change in the characteristics of the wood as a product, but it is important to know if this is valid when considering that the tree has only produced juvenile wood, at younger ages and with a few years of difference. For other species of reforestation, such as *Toona ciliata*, *Acacia mearnsii*, and *Schizolobium amazonicum*, it is known that young trees harvested at different ages present variations in wood properties (Braz et al. 2013, Delucis et al. 2016, Vidaurre et al., 2018).

Palermo et al. (2013) found that *Pinus elliottii* presented a variation in wood density in the log radial direction that allowed the demarcation of juvenile and mature wood, and that this variation was similar to that found by other researchers for *Pinus taeda*. According to the authors, it was verified that juvenile wood occurs up to the 5th growth ring and mature wood occurs after the 14th ring in relation to the pith. As a result, 13-year-old *Pinus taeda* trees do not yet have mature wood, but only juvenile and transitional wood, and 15-year-old trees have just started their production of mature wood.

Thus, spacing and harvesting age are alternatives that can be used to increase the volume of the produced wood; however, few studies have been dedicated to evaluating the influence of these variables on the mechanical properties of wood from juvenile trees.

In this context, this study aims to evaluate the influence of initial planting spacing and age on the growth characteristics, and physical and mechanical properties of *Pinus taeda* juvenile wood, harvested from forest stands without thinning aged 13 and 15 years.

2. MATERIAL AND METHODS

2.1 Biological material

The data for this study were collected from a *Pinus taeda* forest planted in May 2003, altitude of 836 meters, latitude: 25° 28' 3" South, longitude: 50° 39' 4" West, State of Paraná, Brazil. Data were collected in two approaches: 13 and 15 years, analyzing three levels of plantation spacing in each age of the plantation: (2 × 2 m); (3 × 2 m), and (4 × 2 m).

Sampling was performed with temporary plots installed in each level of studied spacing. Based on the information provided by the forest inventory, trees were selected and harvested at different spacing and at the two evaluated ages, in a sample of three trees per condition (age x spacing). Two logs from each tree were collected with a length of 1 m each and stored for posterior processing in a mobile sawmill. Logs were identified and submitted to natural drying until they reached the moisture content of approximately 18%, which was verified by using an electrical moisture meter.

2.2 Physical and mechanical properties

Specimens were cut after drying for static bending, compression parallel to the grain, and shear parallel to the grain, avoiding the presence of knots, defects and pith. To avoid the effects of the radial sampling position on the log, specimens were taken from the middle portions of the boards. Five specimens were made for each of the 18 trees utilized, a total of 90 specimens for each test performed. The specimens were conditioned at a temperature of 20°C ± 3 and relative humidity of 65% ± 1 until reaching the equilibrium moisture content of the acclimatized chamber.

ASTM D 143-14 (2016) standard was followed for making, conditioning and testing the specimens (Table 1), with adaptation in the specimens of the static bending tests that were produced with dimensions of 5 × 2.5 × 41 cm (width x thickness x length). This adaptation in the standard was carried out to obtain a more accurate measurement of the growth rings size of the static bending specimens, which were made with the radial direction in their width, however, maintaining the L/h (span/width) ratio of the specimens. Mechanical tests were performed in the Universal Mechanical Testing Machine EMIC – DL 30.000.

Wood apparent density was determined by the ratio between their mass and their volume at equilibrium moisture content. Specimens remain conditioned in a climate-controlled chamber until constant moisture content. Then, they were weighed on an analytical scale, a precision of 0.1g. Volume was obtained by measuring the specimen's length, width, and height using a caliper and a ruler.

After being tested, the specimens were dried in an oven and weighed until constant weight, to determine the moisture content at the time of the test. Subsequently, the results were corrected for a moisture content of 12% using Equations 1 and 2, for strength and modulus of elasticity estimations, respectively (ABNT, 1997).

Table 1 – Mechanical properties and specimens dimensions used for each test.
Tabela 1 – *Propriedades mecânicas e dimensões dos corpos de prova utilizados para cada teste.*

Mechanical tests	Mechanical properties	Dimension (cm)*
Static bending	MOR and MOE	5.0 x 2.5 x 41.0
Compression Parallel to Grain	f_{c0} and E_{c0}	5.0 x 5.0 x 20.0
Shear Parallel to Grain	f_{v0}	5.0 x 5.0 x 6.3

Where: MOR: Modulus of rupture; MOE: Modulus of elasticity; f_{c0}: Compressive strength; E_{c0}: Modulus of elasticity in compression; f_{v0}: Shear strength.
*Width; Thickness; Length.
Onde: MOR: Módulo de ruptura; MOE: Módulo de elasticidade; f_{c0}: Resistência à compressão paralela; E_{c0}: Módulo de elasticidade em compressão; f_{v0}: Resistência ao cisalhamento.
**Largura; Espessura; Comprimento.*

$$f_{12} = f_M\%\left[1 + \frac{3(M\% - 12)}{100}\right] \quad \text{Eq.1}$$

Where: f_{12}: Strength at 12% of moisture content (MPa): f_M%: Specimen strength at M% (MPa); M%: specimen moisture content.

$$E_{12} = E_M\%[1 + \frac{2(M\% - 12)}{100}] \quad \text{Eq.2}$$

Where: E_{12}: modulus of elasticity at 12% of moisture content (MPa), E_M (%): Specimen stiffness at M% (MPa). M%: specimen moisture content.

Finally, the characteristic values of compression strength were calculated for each condition of wood production (age x spacing), according to equation 3 of the NBR 7190/97 standard (ABNT, 1997). For the calculation, the 15 values of wood lot each (every condition with 3 trees x 5 specimens per tree) were used. The results were classified in increasing order $f_1 \leq f_2 \leq ... \leq f_n$, disregarding the highest value because the number of specimens was odd, and fc0k was not taken for a value lower than f1 or 0.70 of the average value.

$$f_{c0k} = [2 + \frac{f_1 + f_2 + \cdots + f_{\frac{n}{2}-1})}{\frac{n}{2} - 1} - f_{\frac{n}{2}}]\; x\; 1.1 \quad \text{Eq.3}$$

Where: f_{c0k}: characteristic values of parallel compression strength (MPa).

2.3 Wood Growth Characteristics

Measurements of the growth ring size and the latewood percentage from each specimen used in the determination of mechanical properties were obtained. The specimens had their faces sanded and the measurement was performed on both sides to obtain the average. With these measurements, the latewood percentage (LWP) was calculated by the ratio between the sum of the latewood widths of each growth ring and the total width of the specimen perpendicular to the rings, and the number of rings per inch (RPI) was calculated as the ratio between 2.54 cm and the average width of the rings.

2.4 Experimental design and statistical analysis

Apparent density, latewood percentage, rings per inch, MOR, MOE, f_{c0}, E_{c0}, f_{v0} (variables of interest) were submitted to the Bartlett test (α = 1%) to verify the homogeneity of the data variances. A 3 × 2 factorial analysis was performed for all variables,

Table 2 – Average physical and mechanical properties for *Pinus taeda* L. wood at different ages and planting spacing levels.
Tabela 2 *– Médias das propriedades físicas e mecânicas para madeira de* ***Pinus taeda*** *nos diferentes níveis de idade e espaçamento de plantio.*

Factor	Level	ρap(g.cm^{-3})	LWP(%)	RPI	MOR(MPa)	MOE(MPa)	f_{c0}(MPa)	E_{c0}(MPa)	f_{v0}(MPa)
Age	13 years old	0.46^a	23.37^b	1.78^b	41.45^b	4183^b	28.88^b	6310^a	9.11^b
		(0.05)	(6.64)	(0.55)	(14.08)	(1624)	(6.49)	(2132)	(2.29)
	15 years old	0.47^a	26.16^a	2.28^a	58.78^a	5383^a	36.72^a	6855^a	10.02^a
		(0.08)	(8.37)	(0.86)	(14.33)	(1574)	(7.60)	(3213)	(1.58)
Spacing	2,0 x 2,0 m	0.46^b	25.75^a	2.27^a	52.39^a	5048^a	31.87^a	7982^a	9.96^a
		(0.05)	(6.75)	(0.73)	(17.09)	(1593)	(8.25)	(3533)	(2.41)
	3,0 x 2,0 m	0.49^a	25.34^a	1.94^b	50.52^a	4696^a	35.26^a	5607^b	9.48^a
		(0.07)	(8.56)	(0.86)	(17.03)	(1596)	(7.64)	(1235)	(1.76)
	4,0 x 2,0 m	0.45^b	23.21^a	1.88^b	47.41^a	4605^a	31.26^a	6159^b	9.27^a
		(0.07)	(7.42)	(0.63)	(15.83)	(1918)	(7.95)	(2366)	(1.78)
Interac.	F1 x F2	10.109*	1.968^{ns}	0.592^{ns}	2.573^{ns}	1.089^{ns}	0.343^{ns}	3.612*	9.384*
CV (%)		13.63	30.16	34.73	27.86	33.53	21.26	37.69	18.80

Where: ρ_{ap}: Apparent density; LWP: latewood percentage; RPI: rings per inch; MOR: Modulus of rupture; MOE: Modulus of elasticity; f_{c0}: Compressive strength; E_{c0}: Modulus of elasticity in compression; f_{v0}: Shear strength; Interac.: Interaction; CV (%): Coefficient of Variation; ^{ns} = not significant, *significant at $p \leq 0.05$; Means followed by the same letter do not differ statistically according to "F" or Tukey's test (5%). Values in brackets refer to the standard deviation.
*Onde: p_{ap}: Densidade aparente; LWP: porcentagem de lenho tardio; RPI: número de anéis por polegada; MOR: Módulo de ruptura; MOE: Módulo de elasticidade; f_{c0}: Resistência à compressão paralela; E_{c0}: Módulo de elasticidade em compressão; f_{v0}: Resistência ao cisalhamento; Interac: Interação; CV (%): Coeficiente de variação; ^{ns}=não significativo; *significativo à $p < 0,05$; Médias seguidas de mesma letra não diferem estatisticamente pelo teste "F" ou teste de Tukey (5%); Valores entre parenteses referem-se ao desvio padrão.*

with two factors evaluated: planting spacing at three levels (2 × 2 m, 3 × 2 m, and 4 × 2 m) and ages at two levels (13 and 15 years old), with 3 repetitions of trees and 5 specimens per tree.

Analysis of variance was performed to verify the effect of each factor and the interaction between them (spacing × age). In cases where ANOVA detected differences between the levels of each factor (α = 1 %), the means were compared by the Tukey test (α = 1 %) and in cases where the interaction was significant, the Tukey test between each condition of wood was performed.

3. RESULTS

Pinus taeda's wood apparent density presented statistically equivalent means between the two ages studied, although, for the growth characteristics and mechanical properties at 15 years old, the wood presented higher values, except for the modulus of elasticity in compression parallel to the grain. On the other hand, planting spacing did not show a statistically difference in the studied properties, except for apparent density, rings per inch, and modulus of elasticity in compression parallel (Table 2).

The interaction between age and spacing factors for apparent density, compression modulus, and shear strength was statistically significant. Apparent density showed a significant difference for the factor spacing, 3.0 x 2.0 m, increasing the values with increasing age from 13 to 15 years old. The modulus of elasticity in compression also showed a significant difference for the 2.0 x 2.0 m spacing with age increasing. For shear strength, except for the 3.0 x 2.0 m spacing, the others

Table 3 – Mean values of apparent density, modulus of elasticity in compression, shear strength and characteristics values of compression strength for each evaluated treatment.
Tabela 3 *– Valores médios de densidade aparente, módulo de elasticidade em compressão paralela; resistência ao cisalhamento e valores característicos de resistência à compressão para cada tratamento avaliado.*

Spacing (m)	Age (years)	ρ_{ap} (g.cm^{-3})	E_{c0} (MPa)	f_{v0} (MPa)	f_{c0k} (MPa)
2 x 2	13	0.45^b	6717^{ab}	8.67^b	21.75
	15	0.46^b	9247^a	11.25^a	25.92
3 x 2	13	0.46^b	5885^b	10.14^{ab}	21.18
	15	0.51^a	5329^b	8.81^b	34.91
4 x 2	13	0.46^b	6328^b	8.53^b	20.01
	15	0.44^b	5991^b	10.01^{ab}	31.14

Where: ρ_{ap}: Apparent density; E_{c0}: Modulus of elasticity in compression; f_{v0}: Shear strength; f_{c0K}: Characteristics values of compression strength. Means followed by the same letter do not differ statistically from each other according to the Tukey test (5%).
pap: Densidade aparente; E_{c0}: Módulo de elasticidade em compressão; f_{v0}: resistência ao cisalhamento; Médias seguidas de mesma letra não diferem estatisticamente de acordo com o teste de Tukey (5%).

Table 4 – Pearson correlation matrix for apparent density, growth characteristics, and mechanical properties.
Tabela 4 *– Matriz de correlação de Pearson para densidade aparente, características de crescimento e propriedades mecânicas.*

	ρ_{ap}	LWP	RPI	MOR	MOE	f_{c0}	E_{c0}	f_{v0}
P_{ap}	1	0.506*	0.392*	0.698*	0.532*	0.476*	0.308*	0.119
LWP		1	0.682*	0.453*	0.352*	0.532*	0.218*	0.182
RPI			1	0.494*	0.534*	0.338*	0.454*	0.075

Where: ρ_{ap}: Apparent density; LWP: latewood percentage; RPI: rings per inch; MOR: Modulus of rupture; MOE: Modulus of elasticity; f_{c0}: Compressive strength; E_{c0}: Modulus of elasticity in compression; fv0: Shear strength; * significant at $p \leq 0.05$.
*p_{ap}: Densidade aparente; LWP: porcentagem de lenho tardio; RPI: número de anéis por polegada; MOR: Módulo de ruptura; MOE: Módulo de elasticidade; f_{c0}: Resistência à compressão paralela; E_{c0}: Módulo de elasticidade em compressão; f_{v0}: Resistência ao cisalhamento; *significativo à p < 0,05.*

showed greater strength at the age of 15 years (Table 3). Also, in Table 3, parallel compression strength characteristic values for each wood production condition were presented.

There was a statistically significant correlation between growth characteristics, apparent density, and mechanical properties, except for shear strength (Table 4). The coefficient of determination ranged from 0.218 to 0.698, with a mean of around 0.500 which demonstrates a tenuous correlation between these properties.

4. DISCUSSION

Increasing age positively influenced the wood's mechanical properties. MOR showed an increase of 41% and MOE of 28%, comparing harvest wood aged 13 and 15 years old, respectively. In this study, different ages did not cause statistical differences in apparent density and modulus of elasticity in compression. There was no difference in MOR, MOE, compression strength, and shear strength in the different spacing levels analyzed.

Woods aged 13 and 15 years old were considered juvenile or transitory. Thus, the effect of competition between individuals which would supposedly be caused by the reduction in planting spacing was not observed. This fact may be related to the site where the forest is located. Also, it is observed that the numerical values were smaller in the larger levels of spacing, which suggests that larger sample size could capture these differences.

Woods from trees cut at more advanced ages have greater parallel compression strength, an increase of 27% was observed comparing the ages of 13 and 15 years. Compression modulus was not statistically different from each other in the ages studied.

Apparent density values observed in this study corroborate with the data found in the literature (Ballarin and Palma 2003, Melo et al. 2013). The density variation in the tree and between trees is a known characteristic of the *Pinus* genus, which is due to environmental, genetic, silvicultural, and juvenile wood, among others (Ballarin and Palma 2003).

MOE and MOR corroborate the data observed in the literature (Santini et al. 2000, Trianosky 2014). Trianosky et al. (2014) found mean values of 64 for MOR and 8234 for MOE of 18-year-old *Pinus taeda* wood, the limit of transition from juvenile to adult wood. Oliveira et al. (2006) observed an increase in static bending strength with increasing age from 9 to 20 years old. According to Mustefaga et al. (2019), for *Pinus taeda* and *Pinus patula*, the influence of age may be more pronounced on strength compared to wood stiffness.

Lassere et al. (2009) in a study with *Pinus radiata*, cultivated in initial levels of spacing of 2500 trees/ha (proportional to the spacing of 2 x 2 m) and 833 trees/ha (proportional to the spacing of 4 x 3 m), observed a 35% increase in the MOE of wood planted in the spacing of 2 x 2 m. Larson et al. (2001) highlight a correlation between MOE and MOR and wood density.

The woods of *Pinus sylvestris*, *Pinus radiata*, and *Pinus taeda* showed the highest mean of MOR and MOE at the sites with the highest forest stand density (Šilinskas et al., 2020; Schimleck et al., 2018b). It should be noted that the studies evaluated the properties of 35, 17, and 21-year-old trees, which may have accounted for the difference in MOR, that were not found in this study with *Pinus taeda* of 13 and 15 years old.

Ballarin and Palma (2003) in a study with 37-year-old *Pinus taeda*, demonstrated the influence of juvenile and mature wood characteristics on MOR, MOE, and its apparent density. Results showed that MOR, MOE and apparent density of juvenile wood were always smaller and presented more variability when compared to mature wood. Also, results showed that the juvenile wood zone occurs approximately up to the 18th growth ring, demonstrating that the wood used in this study is juvenile wood or of transition. Therefore, the average values found by the authors for 37-year-old *Pinus taeda* wood were: 13,812 MPa, 107.02, and 0.605 for MOE, MOR, and apparent density.

The results of compression parallel to the grain test (f_{c0} and E_{c0}) corroborate the data found in the literature (Santini et al. 2000, Oliveira et al. 2006, Trianoski et al. 2014). Lassere et al. (2005) observed an increase in the modulus of elasticity with a decrease in planting spacing. Trianoski et al. (2014) found a mean of 37 MPa for parallel compression strength (f_{c0}) and 12,432 MPa for parallel compression modulus (E_{c0}) in 18-year-old *Pinus taeda* wood, an indication that stiffness was more affected than strength by increasing age.

On the other hand, Oliveira et al. (2006), in a study with 9, 13, and 20-year-old *Pinus taeda* wood (mostly juvenile wood), found an increase in bending and compressive strength with increasing age, the same trend found in this study which evaluated ages much closer. This indicates that the strength properties of juvenile/adult wood change over time in a mild and not abrupt way, however, which can be seen in a small age difference such as the two-year difference in this study.

Spacing can influence the growth rate of trees, however, it may not directly affect wood properties. According to Lasserre et al. (2009) and Blazier et al (2021), different spacing levels do not significantly affect wood density, however juvenile wood proportion declined with spacing decrease due to greater diameter growth and earlier transition from juvenile wood to mature wood.

Growth characteristics presented values between 23% and 26% for latewood percentage and between 1.78 and 2.28 for rings per inch. These characteristics are related to the quality of wood and growth of the forest which is favored by the climate in Brazil. *Pinus taeda* is one of the most important species cultivated in the South of the United States, where it also has fast growth, but less than that verified in the South of Brazil (França et al., 2018; Irby et al., 2020).

For instance, samples for bending properties of No. 2 grade southern pine lumber aged between 16 and 22 years presented averaged 4.6 rings per inch and 43.8% latewood proportion (França et al., 2018). Comparing the means with those of this study, it is verified that they are close to half, despite the younger ages. Thus, for wood from younger pine trees cultivated in Brazil it is important to define specific parameters that can be used to express the wood quality.

In the analysis of the interaction, it is important to the unexpected superiority of the 13-year-old shear strength mean values in the planting spacing of 3 x 2m (Table 3). Trianoski et al. (2014) verified for *Pinus taeda* wood harvested at the age of 18 years an average value of 10.52 for shear strength, which was similar to the average values verified for wood from other tropical pine species.

The apparent density was correlated with all other properties, except shear strength, corroborating the studies found in the literature (Chrzazvez et al. 2014; Trianoski et al., 2014). However, Trianoski et al. (2014) found a positive correlation between shear strength and apparent density, which indicates that other factors that were not possible to determine may have caused the variation of this property in this study.

The results of the study with *P. taeda* wood suggest that density is a better predictor than rings per inch (RPI) for parallel compression strength (Irby et al., 2020). In this study, RPI was better correlated with MOR, MOE, and modulus of elasticity in compression. The best correlations of latewood percentage were density, MOR, and compressive strength. Even so, the correlations found were of magnitude close to 0.500, which demonstrates that these parameters explain only part of the variation observed in wood strength and stiffness.

Biblis et al. (2004) thus concluded that the most important wood characteristics in predicting strength were density (45%), followed by the latewood percentage (30%), and the width of the growth rings (25%). Mustefaga et al. (2019) fitted a model for *P. taeda* and *P. patula* wood species at 12 years old to estimate the static bending modulus as a function of apparent density, finding a determination coefficient (R^2) of 0.70 and standard error (Syx) of 10.54%.

Haselein et al. (2000) fitted equations for the properties of MOR and MOE as a function of the rings per inch and the latewood percentage for 30-year-old *P. elliottii*, finding R^2 of 0.71 and 0.79, respectively. The younger age of the trees used in this study contributed to minimizing the variation in the growth characteristics and wood density, which was reflected in the lower correlation coefficient of these variables with the wood's physical and mechanical properties.

Finally, according to NBR 7190/97, *Pinus taeda* in this study, aged 13 and 15 years old, can be classified as structural wood in class C20 (13-year-old wood; spacing 2 x 2, 3 x 2, and 4 x 2 m), C25 (15-year-old wood; spacing 2 x 2 m) and C30 (15-year-old wood; spacing levels 3 x 2 and 4 x 2 m) based on the characteristic values of compression strength (ASTM, 1997). Mustefaga et al. (2019) found classification for 12 years-old *Pinus taeda* L as structural wood in class C20. This demonstrates that the juvenile wood of *Pinus taeda* can reach strength values that qualify it as structural wood of superior classes, as long as it comes from comes from trees with ages closer to the beginning of the period of mature wood formation, in this case, 15 years old.

5. CONCLUSIONS

Based on the results presented, it can be concluded that:

Harvesting age significantly influenced the mechanical properties and growth characteristics of *Pinus taeda* L. juvenile wood. Increasing the age from 13 to 15 years significantly increased the wood strength and stiffness, rings per inch, and latewood percentage. The studied ages did not influence the wood's apparent density.

The wood mechanical properties (strength and stiffness, in-parallel compression and static bending, and shear strength) were equivalent between the spacing studied, a fact attributed to juvenile wood coming from young trees, local characteristics of the site, and the number of trees sampled that may not have been sufficient to detect differences.

There was a significant correlation between apparent density, growth characteristics, and mechanical properties studied with R^2 around 0.500, except for shear strength, which suggests that those parameters can be used to assist in estimating strength and stiffness in static bending and compression parallel to the grain.

Pinus taeda L. wood used in this study can be classified as structural wood, according to NBR 719/97 standard, based on parallel compression strength, class C20 for 13 years old and classes C25 and C30 for 15 years old. However, the properties of mean values were lower and the variation between specimens is greater than those reported in other papers that studied trees between 18 and 37 years old, which contain mature wood.

AUTHOR CONTRIBUTIONS

Érica Machado Garbachevski: Conceptualization, Methodology, Data analysis, Statistical analysis, Visualization, Writing and Editing. Éverton Hillig: Conceptualization, Methodology, Writing-Reviewing, Editing, Supervision and Project management. Raul De Abreu Neto: Visualization and Writing-Reviewing. Fabiane Aparecida de Souza Retslaff: Conceptualization, Methodology, Writing-Reviewing, Supervision. Henrique Soares Koehler: Methodology, Statistical analysis, and Writing-Reviewing.

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