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STATIC BENDING STRENGTH AND STIFFNESS IN JUVENILE AND ADULT WOOD OF FAST-GROWING *Pinus taeda* L.

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Resumo

Resistência e rigidez à flexão estática nos lenhos juvenil e adultos da madeira de Pinus taeda L. *de rápido crescimento.* Em razão das altas taxas de crescimento das florestas plantadas no Brasil e das variações das propriedades mecânicas dentro de uma árvore, neste estudo foi avaliada a resistência (MOR) e a rigidez (MOE) na flexão estática em função dos lenhos juvenil e adulto, e da inclinação dos anéis de crescimento na área transversal de corpos de prova livre de defeitos da madeira de *Pinus taeda*. Posteriormente, os lenhos foram classificados nas classes para uso estrutural. Toras de *Pinus taeda* com 30 anos tiveram os anéis de crescimento delimitados cada seis anos de idade na área transversal. Os lenhos juvenis foram representados pelas zonas de 0-6 anéis cambiais (marcada com vermelho) e 6,1-12 anéis (azul). A zona de 12,1-18 anéis (laranja) foi considerada como lenho de transição e a de 18,1-24 (verde) e 24-30 anéis (amarelo), lenho adulto. Após o desdobro, 25 tábuas foram selecionadas para o corte dos corpos de prova (n=104) para o teste de flexão estática. A inclinação dos anéis de crescimento foi mensurada em função da direção da força aplicada no teste de flexão. Com o MOR e MOE à flexão estática foram executados testes estatísticos em esquema fatorial. Houve independência dos fatores (propriedades mecânicas e a inclinação dos anéis de crescimento). O lenho juvenil de 0-6 anéis não foi indicado para uso estrutural. Os lenhos entre 12-30 anos apresentaram resultados mínimos compatíveis para serem classificados para o uso estrutural. A inclinação não apresentou influência no MOE ou MOR.

Palavras-Chave: Classe estrutural. Coníferas. Madeira Serrada. Tipos de lenhos. Desvio da grã.

Abstract

Due to the high growth rates of the forests planted in Brazil and the variations of the mechanical properties within a tree, this study aimed to evaluate the strength (MOR) and stiffness (MOE) in static bending according to the juvenile and adult wood, and the grown-rings inclination at the transversal area of clean specimens of *Pinus taeda*. Subsequently, the woods were classified in its structural gradings. *Pinus taeda* logs with 30 years old had the growth rings delimited at every six years on the transversal area. The juvenile wood was represented by the zone of 0 to 6 years of growth (marked with red), and 6.1-12 years (blue). The zone of 12.1-18 (orange) was considered as transition wood and from 18.1-24 (green) and 24.1-30 years (yellow), adult wood. After the sawing, 25 boards were selected to the sawing of the specimens (n = 104) for the static bending test. Growth-ring inclination was measured as a function of the direction of the load applied at the bending test. Statistical tests were performed in a factorial scheme with the MOR and MOE to static bending. Factors were independent (mechanical properties and growth-rings inclination). The 0-6-year-old wood was not indicated for structural use. Woods between 12-30 years old showed a minimum compatible result to be classified for structural use. The inclination did not influence at the modulus of elasticity and strength at bending.

Keywords: Structural grading. Softwoods. Lumber. Types of wood. Grain deviation.

INTRODUTION

Advances in the quality of timber products and the increasing consumption of these materials in construction have stimulated the worldwide demand for wood. For that reason, the planted forests industries prioritized increasing the growth rates of forest species to meet the needs of the market, maximizing the volume of wood in a short period. As a consequence, the increasing growth rates result in greater juvenile wood (JW) proportion, because the trees usually reach the diameter for harvesting in a short time, characterizing a short rotation (MOORE; COWN, 2017; SCHIMLECK *et al*., 2018). This high growth leads to a negative effect on the wood quality, due to higher JW proportion. This can be particularly problematic and a critical factor in the quality of solid wood products for timber industries such as structural use (MOORE *et al*., 2012; RAIS *et al*., 2014).

The JW is located close to the pith along the entire stem. Because of its formation in the first years of tree growth, its presence is more expressive in fast-growing softwoods. On the other hand, the formation of adult wood (AW) only begins in older trees, whose rotation is longer. While the AW forms, the JW proportion in the radial direction decreases concerning to the total area of the log (ZOBEL; SPRAGUE, 1998). JW can be defined as the wood formed in the first years of tree growth, whose growth is under the influence of the apical meristem and the cambium (LARSON *et al*., 2001). It exhibits different characteristics from AW, such as a shorter tracheid, a lower percentage of latewood, larger microfibril angles, and occasionally, disproportional amounts of compressed wood, and spiral grain (ZOBEL; SPRAGUE, 1998; LARSON *et al*., 2001; TREVISAN *et al*., 2014).

Due to the possibility of JW showing spiral grain, it should be considered that the grain irregularity can considerably affect the deformations in woods subject to bending. This irregularity causes the wood to respond in an unstable and unexpected way when mechanically stressed, as well as impacting bent elements. The grain inclination, represented by the angle between the central axis of the trunk and the direction of the fibers, when above six degrees, can directly impact the wood properties (ABNT, 1997; ISO, 2018), such as strength (MOR) and stiffness (MOE) at bending.

In a study with tropical woods, the authors concluded that the grain influences the properties of MOR and MOE on the bending test (RAVENSHORTST *et al*., 2020). In another study, the authors found a reduction of up to 60% in MOR, with an increase of the angled slope by 15° (MANIA *et al*., 2020). These different results show that there may be a variation in the mechanical properties due to the inclination grain. However, at the present, no study is known to evaluate whether there is any influence between grain inclination along with JW and AW in fast-growing *Pinus taeda* wood.

Although there are studies about the JW and its impact on wood properties, age of transition between JW and AW and anatomical characteristics (BENDSTEN; SENFT, 1986; BALLARIN; PALMA, 2003; PALERMO *et al*., 2013; MOORE *et al*., 2017), it is still costly and time-consuming to establish exactly where the JW ends. Since its characteristics gradually change in a more pronounced way, in the zone called transition wood (TW), until they become less similar to those of the JW and become AW (LARSON *et al*., 2001). Nevertheless, the scientific community agrees that there are variations in the age at which the wood transition occurs, either due to the species or the growth site. Furthermore, this variation usually comprises an average of 1 to 2 growth rings (ZOBEL; SPRAGUE, 1998). It was also stated that although the JW is usually delimited based on anatomical characteristics or density, other properties can be used to determine it, such as MOE, and MOR.

When analyzing the *Pinus taeda* wood to demarcate JW, AW, and TW (BENDSTEN; SENFT, 1986) the authors concluded that JW was formed until the 12th growth ring when density, MOE and MOR were used. Ballarin *et al*. (2003), also studying *Pinus taeda* concluded that the JW was formed until the 14th growth ring and the AW began to be formed after the 18th growth ring.

Furthermore, part of the wood supplied to the timber industry comes from thinning. Normally, the first thinning occurs between the 6th to 8th year of age and the second around the 12th year of growth, with harvesting occurring from the 20th year of growth (DAVID *et al*., 2017). Thus, it is necessary to know the properties of wood at these different ages since there may be logs of various ages and origins in a sawmill.

The *Pinus taeda* considered a fast-growing specie, has an annual increment of around 30 m^{-3}. ha^{-1}.$year^{-1}$ (IBÁ, 2019), it is the second most planted specie and marketed genus in Brazil. Reports indicate that the planted area of Pinus in the year 2019 was approximately 1,979.6 thousand hectares and about 28.9% of the production was destined for the lumber industry and its derived products (IBGE, 2019).

Considering the time spent segregating the wood by anatomical properties, it is necessary to understand the changes in strength and stiffness properties at several ages and positions within the log. Hence, with the knowledge of these characteristics, it is possible to assist in decision-making for the best use of this wood, either for structural or furniture use. In addition, as these industries need to meet minimum requirements for material strength, it is necessary to know the age that the wood begins to present the minimum required characteristics.

As the *Pinus taeda* planted forests in southern Brazil have high growth rates, consequently, the mechanical properties within the same tree can be variable. Therefore, this study evaluated: (a) the MOE and MOR at static bending as a function of wood with different ages of growth in *Pinus taeda* wood in clear specimens; (b) whether there is an influence of the inclination of the growth rings in the cross-sectional area of the specimens for static bending; (c) and complementarily, the wood was classified into classes for structural use by EN 338 (EN, 2016).

MATERIAL AND METHODS

The wood used in this study originated from a plantation located in Campo Belo do Sul, Santa Catarina state, Brazil (latitude 27°53’55” S and longitude 50°45’26” W) and it was provided by a sawmill located in Capão

Alto, Santa Catarina. The climate in the planting region is Cfb according to the Köppen classification, with average annual precipitation of 1,406 mm.

Five logs of *Pinus taeda* were randomly selected in the sawmill yard, with diameters varying from 350 to 450 mm, length of 3,060 mm, and age of 30 years. The average diameter of the logs was obtained as a function of the average circumferences determined by the measurements of the base and top of each log.

Considering the studies on the demarcation of the JW by the length of the tracheids, the average of the years when thinning occurs, the use of multiples of 1 inch for thinning in sawmills (DOBNER JR *et al*., 2012), as well as the age of the trees in this study, six growth rings were chosen to represent each wood. In such a way that the log was divided into five distinct radial positions. The growth rings were counted on each log in the pith-bark direction and the areas demarcated with spray paint to facilitate visualization after sawing. During the ring counting, no false growth rings were identified.

The selection of the six-year interval between the wood was adopted to facilitate the evaluation since the interval between colored rings is wider than when compared to an interval with fewer growth rings. In practice, the distance of six growth rings facilitated the removal of specimens for destructive evaluations, resulting in a sufficient area for the removal of material according to each type of wood.

The total area corresponding to the first six growth rings, including the pith, was colored red and named Position 1 (P1). The same process was accomplished for the following growth rings, always with an interval of six rings (years). Between 6.1-12 years it was colored blue and named Position 2 (P2); the orange color for the Position 3 (P3), was placed in the interval of 12.1-18 years; between 18.1-24 years the green color for the Position 4 (P4), and in the remaining rings between 24.1 and 30 years, painted with yellow for the Position 5 (P5). The mean wood thicknesses were obtained with the radius from the pith to the periphery of the stem and are illustrated in Figure 1a.

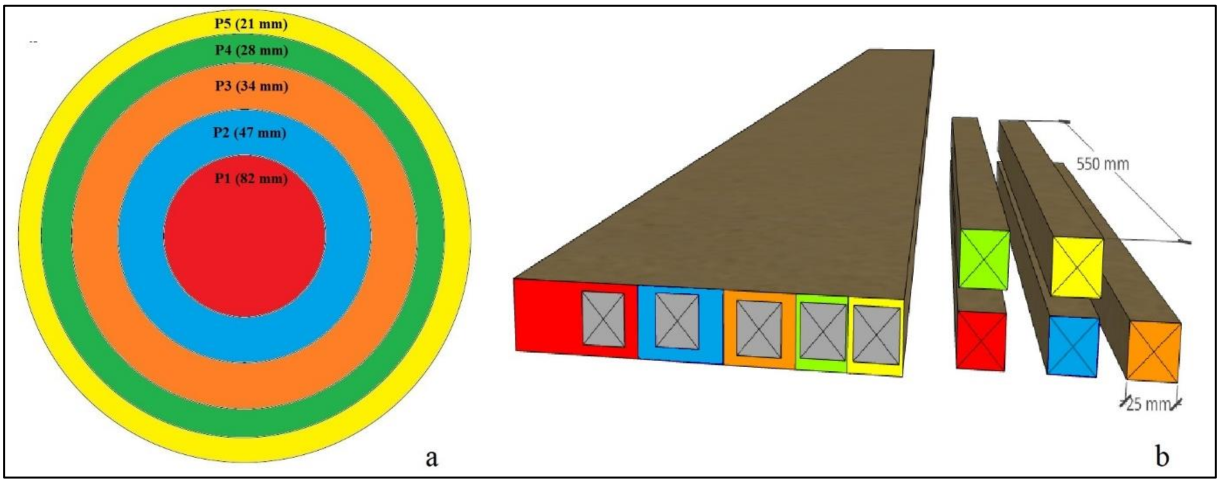

Figure 1: Sampling and cutting scheme for making the specimens for the bending test, in different radial positions within a board.

Figura 1. Esquema de corte e amostragem para confecção dos corpos de prova para o teste à flexão, em diferentes posições radiais dentro da tábua.

The sawing system was carried out according to the commercial measures practiced by the sawmill, whose dimensions were 25 x 150 x 3,060 mm and 25 x 100 x 3,060 mm (thickness, width, and length). Due to the sawing model, most of the boards had a radial distribution.

The logs were numbered before they entered the sawing line. After the sawing, each board was identified according to its original log. Afterwards, the boards were placed in a drying kiln, with a total program of 70 hours, aiming for a final moisture content of 10%. The drying program used was also established by the sawmill itself. After drying, the wood was transported to the Materials Laboratory at the Santa Catarina State University, in the Agro-Veterinarian Science Center, located in Lages, SC.

The procedures for making the specimens followed the specifications of the European Standard EN 408 (EN, 2012). The cross sections of the specimens were 30 mm wide x 25 mm thick and 605 mm long. To avoid the presence of different positions within the same specimen, the growth rings were marked with their respective colors along the entire longitudinal length of the boards, and finally, the specimens were cut (Figure 1b).

In all, 114 specimens were prepared for the static bending test. Ten specimens were used for calibration of the test speed. The number of specimens for each wood was: P1 with 14 specimens, P2 with 23; P3 and P4 with 27 and P5 with 13 specimens.

A testing machine EMIC (DL 300kN) was used for the destructive four-point static bending test, according to the recommendations of the European Standard EN 408 (EN, 2012). The span between supports was 525 mm, and the distance of load application between supports was 150 mm (these values are determined by the standard, i.e., the length should be 18h+3h, where h is the thickness of the specimen). The standard defines that the loading should be set, in a way that the failure of the specimen is within the total test time between 180 - 420 s. For this purpose, ten specimens with different types of wood were randomly selected and previously tested. In the end, a load application speed of 4.5 mm/min was obtained.

Immediately after the end of the test, as recommended by the European Standard EN 384 (EN, 2004), the moisture content was measured in the specimens with a Digisystem needle hygrometer, model DL 2000. The needles were inserted as close as possible to the rupture zones. The average moisture content of the specimens was 12.6 ±1.1%. Additionally, the ruptures of the specimens were evaluated by the standard ASTM D143 (ASTM, 1994) to determine the type of rupture, and the results were presented in percentage values.

Subsequently, the MOE and MOR values were calculated and then corrected to 12% humidity based on dry mass. Then, statistical analysis was performed using the spurious values test (Grubbs) and normality test (Kolmogorov-Smirnov) at a 5% significance level.

The inclination of the rings to the load application, in the destructive bending test at four points, was measured in the cross-sectional area of each of the 104 specimens, according to the methodology of Carrasco e Mantilla (2016). These were 0°, 15°, 30°, 45°, 60°, 75°, and 90° to the load application (Figure 2).

A Grubbs test for spurious values was performed at a 5% significance level. No values of the MOE were found to be spurious within the groups of Position. For MOR, one specimen from each group of Position P2, P3, P4, and P5, was considered spurious and therefore excluded from the data analysis. After exclusion, a normality test was run. In cases where the variable did not present a normal distribution, the transformation of the data by BoxCox was performed, whose transformation is performed by the power of a lambda estimated by the software.

Then, a factorial test (5 positions x 7 inclination) was run to verify if there was independence or dependence among the factors with a significance level of 5%. In the results that identified the independence of the factors, a test of means (Tukey) was applied, with a significance level of 5%.

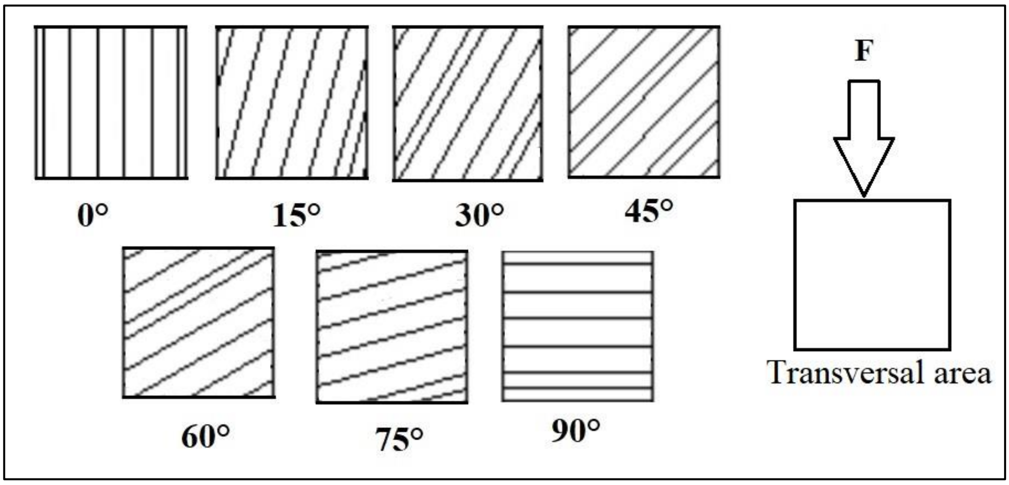

Figure 2: Inclination of the growth rings on the cross-sectional area of the specimens.
Figura 2. Inclinação dos anéis de crescimento na seção transversal dos corpos de prova.

RESULTS

The MOE values showed normal distribution (p-value 0.3044). However, the MOR did not show normality (p-value 0.0139) and was transformed by Box-Cox (p-value 0.2487). The Table 1 presents the results of Tukey's test of means for the five different radial positions for the mechanical properties of MOE and MOR.

Table 1. Mean values of modulus of elasticity and flexural strength in different radial positions of *Pinus taeda* at 30 years of age.
Tabela 1. Valores médios do módulo de elasticidade e resistência à flexão em diferentes posições radiais no *Pinus taeda* de 30 anos de idade.

Position		P1	P2	P3	P4	P5
MOE[1] ($N{\cdot}mm^{-2}$)	Average	5.277,00 c	7.315,20 b	7.932,50 b	8.259,90 b	9.617,00 a
	C.V. (%)[3]	19,61	21,48	21,21	14,77	13,74
	n[4]	14	23	27	27	13
MOR[2] ($N{\cdot}mm^{-2}$)	Average	52,69 c	68,11 b	79,62 a	78,54 a	84,88 a
	C.V. (%)	18,47	16,00	11,83	13,02	11,08
	n	14	22	26	26	12
	MOR_k[5]	38,81	51,32	61,39	59,03	58,31
Grade by EN 338 (2016)		Nonstructural	C14	C14	C16	C20

[1] Modulus of elasticity values corrected for moisture content at 12%; [2] Values of flexural strength corrected for moisture content at 12%; [3] Coefficient of variation in percentage; [4] Number of repetitions; [5] Characteristic flexural strength. Lowercase letters differ in the row by the Tukey test at a 5% significance level.

The MOE increased significantly from 5,277 to 9,617 $N{\cdot}mm^{-2}$, from the central region to the periphery of the stem. It is also observed that the radial positions P2 (6.1-12 years), P3 (12.1 to 18), and P4 (18.1 to 24) had MOE averages statistically equal and above 7,000 $N{\cdot}mm^{-2}$.

The ANOVA for the interaction between the factor position and inclination indicated factor independence at the 5% significance level for MOE and MOR (p-value 0.6872 and 0.2574, respectively). The position factor (p-value 0.0000 and 0.0000) and the inclination factor (0.0395 and 0.0051) were significant on both MOE and MOR properties, respectively. Due to the independence of the factors, the test of means was performed to verify possible differences for MOE and MOR in specimens with different inclinations to the applied force. Tukey's test indicated significant differences between the means for the 0 and 75° angles (Table 2).

Table 2. Mean values of MOE e MOR at the growth ring inclination.
Tabela 2. Valores médios do MOE e MOR na inclinação dos anéis de crescimento.

Inclination (°)	0	15	30	45	60	75	90
MOE ($N{\cdot}mm^{-2}$)	6538,14b	6679,51ab	7944,84ab	7163,55ab	7936,09ab	8827,10a	7910,56ab
C.V. (%)	29,81	21,62	33,31	28,98	17,30	19,53	18,96
MOR ($N{\cdot}mm^{-2}$)	59,96b	63,50ab	70,16ab	68,21ab	71,23ab	80,01a	73,61ab
C.V. (%)	27,29	20,31	27,01	23,05	29,81	14,17	17,76

Lowercase letters differ in the row by Tukey's test at 5% significance.

When checking the types of ruptures of the specimens by ASTM D143 (ASTM, 1994), no abrupt or shear ruptures were found. The P1 specimens presented approximately 77% of rupture characterized as rupture cross-grain. A decrease in this type of rupture was observed as the distance from the pith to the stem periphery increased. Compression rupture was observed in only one specimen (P4; 60° inclination). P5 had more than half of the specimens without apparent rupture. For inclination, less than 30° more than half of the specimens showed cross-grain rupture.

Table 3. Rupture types in percent for different radial positions and inclinations of the growth rings according to ASTM D143 (ASTM, 1994).
Tabela 3. Tipos de ruptura em percentual para diferentes posições radiais e inclinações dos anéis de crescimento de acordo com a ASTM 31.

Rupture occurrence (%)		**a**	**b**	**c**	**d**	**e**
Position	P1	23	77	-	-	-
	P2	39	35	13	-	13
	P3	59	26	4	4	7
	P4	48	24	16	-	12
	P5	34	8	-	-	58
Inclination (°)	0	33	67	-	-	-
	15	44	56	-	-	-
	30	33	67	-	-	-
	45	43	29	9	-	19
	60	67	17	-	8	8
	75	36	21	29	-	14
	90	39	30	7	-	24

a: simple tension; b: cross-grain tension; c: splintering tension; d: compression; e: no apparent rupture.

DISCUSSION

In Table 2, a significant increase in the properties of MOE and MOR was observed as the wood ceases to be composed of JW and TW and becomes to be forming by AW. P1, under the conditions studied, was not indicated to be present in quantity in *Pinus taeda* wood boards for uses that require mechanical properties, such as structural wood or for some panels. Since the standards for the use of this wood for Glued Laminated Timber and Cross-Laminated Timber usually indicate that the MOE is above 7000 N·mm^{-2} (EN, 2016). As well as for products such as Edge Glued Panel, which standard (EN 2008) indicates a minimum MOE of 6000 N·mm^{-2} for multilayer EGP.

It would be indicated using boards with the presence exclusively of P5 wood; however, since most plantations have short rotations, boards with the presence of only that wood becomes difficult to obtain in quantity. In that way, an increase in the rotation time could benefit the formation of a larger area of AW, thus having sufficient area to perform the sawing and to obtain boards with greater mechanical properties (MOORE *et al*., 2012; MOORE; COWN, 2017; SCHIMLECK *et al*., 2018). Since this solution depends on the forest base industry, there is a need to use boards mixing the wood from P5, P4, and P3. To this end, one could use sawing methods that promote tangential boards to the rings, obtaining a greater number of boards with only AW.

As the P3 (12.1 to 18) and P4 (18.1 to 24) logs had MOE averages above 7,000 N·mm^{-2}, which value is higher than that required by the standards, these positions could be within the boards intended for structural use (EN, 2016). Consequently, that would facilitate the decision process of log harvesting, since there would be more wood area with desirable characteristics for this end, and the average sum of the thicknesses of these three positions totaling 830 mm in radius.

When considering both average values and characteristic values, it is observed that the woods with P2, P3, P4 and P5 lumber are classified for structural use. The P2 and P3 wood were classified in the minimum grade C14, whose MOE value is 7,000 N·mm^{-2} and MOR is 14 N·mm^{-2}. However, due to their high variety, in the case of the individual board classifications, there is a possibility that a large part of the lumber from P3 will be classified as C16. The wood from P4 was classified as C16 and the wood from P5, as C20, however, the possibility of a large part of the wood being classified as C22 (EN, 2016).

Regarding inclination, the results of this study were contrary to the results of Carrasco *et al*. (2017) and Mania *et al*. (2020), who observed a decrease in MOR and MOE with increasing grain inclination. In this study, with *Pinus taeda*, a trend of increase or decrease of MOE and/or MOR was not observed as the inclination increased.

The main factor that influences the strength and stiffness of bending is the fiber inclination in tropical woods, mainly by considering the deviation of the fibers in the longitudinal direction (REVENSHORST *et al*., 2020). However, as in this study, the total length of the specimens was 550 mm, this trend was not observed in the statistical results. Possibly because the dimensions of the specimens do not allow large variations of the inclinations, for this, specimens with structural dimensions should be considered in the next studies.

Additionally, it was observed that due to the proximity of the pith and the arrangement of the growth rings, angles greater than 60° did not have P1 wood (zone with a greater proportion of JW). Moreover, the angles below 30° did not have P4 and P5 (considered AW), because they are in the peripheral zone of the stem. This helps explain the average MOE and MOR properties for the inclination since some angles did not have all positions present in the sampling. Considering that there are significant differences among positions within the stem for both mechanical properties considered in this study, the presence or absence of a particular position in the evaluation of the inclination may have been an influential factor for the higher or lower properties.

When verifying the specimens by the type of rupture (ASTM, 1994) in the longitudinal direction, it was found that the specimens from P1 presented mostly ruptures of cross-grain tension. Moreover, the presence of this type of rupture decreased with the distance from the pith and the proximity of the stem's periphery. As this rupture is characteristic of grain deviations, this corroborates with the fact that JW normally presents grain deviations (LARSON *et al*., 2001). This indicates that the more central the wood, the greater the chances of grain deviations.

Additionally, due to the sawing being predominantly radial, there was difficulty in obtaining specimens with inclinations from 0 to 30° of the peripheral positions (P4 and P5). It can be observed that in this case, the smaller inclinations result in higher cross-grain and lower mechanical properties, than angles above 30°. It was also found that due to the longitudinal growth of the tree, the first positions of the wood have greater distances between the growth rings, and this was reflected in the longitudinal variation of the growth ring inclination, with greater amounts of ruptures by cross-grain tension. In the specimens with narrower rings, the cross-grain tension rupture was less than 25%.

Since the inclination does not statistically affect the properties of strength and stiffness at bending in *Pinus taeda*, this characteristic might not impact the quality of the wood for structural use. Woods with different inclinations of the growth rings can be used since the factor that most impacts higher value products is the grade of wood by stiffness and strength. However, this study alone cannot state whether, for solid wood products, there is a chance that the inclination of the growth rings has an impact on their performance.

It is reinforced that one of the factors that influenced the properties of stiffness and strength was the age of the trees and consequently the presence of JW and AW. As indicated in this study, the JW as in P1, is not indicated for structural use, and its presence should be limited in this type of wood after a classification. However, woods with a high proportion of JW can be used for applications that do not require minimum characteristics of stiffness or strength. On the other hand, 6- to 12-year-old wood (P2) can be used in structural products, provided that it is classified since it presents a high variation in MOR and MOE properties. The TW and AW, (P3, P4 and P5) were indicated for structural use, but they depend directly on long rotations to be formed. However, when classified they can have higher sales values than the others, but this depends on a reformulation in the current market.

CONCLUSIONS

By studying the variability in the pith-bark direction within the same tree and specie, different wood types and inclinations of the growth rings were evaluated in the cross-sectional area of *Pinus taeda* wood, concluding that:

- The inclination and position of the wood act independently on the variation of the mechanical properties of MOE and MOR.
- The inclination of the growth rings showed no negative or positive tendencies with the mechanical properties evaluated.
- There are differences among the woods, with woods up to 6 years old not indicated to be present in quantities for products requiring mechanical properties greater than 7,000 $N.mm^{-2}$.
- Woods older than 12 years were all classified as structural. The highest structural classes were obtained in adult wood older than 18 years.
- This study provides practical information on the classification of *Pinus taeda* wood for structural use, which may contribute to the market analysis of classified wood. Furthermore, it provides preliminary information on the best forms of sawing and utilization of the wood in future studies.

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