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Relationship between strength and density in juvenile and mature *Eucalyptus sp.* wood

Relação entre resistência e densidade em madeira juvenil e adulta de *Eucalyptus sp.*

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ABSTRACT
In the future, the trend is that the main type of wood supplied to the market will be juvenile wood, and to understand its properties is highly relevant to the adequate use of this material. Timber specimens from 25-years-old trees (sampled in the heartwood closest to the bark) and 6-years-old from many *Eucalyptus* sp. species were tested under compression load parallel to grain and had their specific mass measured. Literature data from native wood from the same genus were used for proper comparisons. Adult wood was similar in density and strength in relation to native wood, and juvenile wood had lower properties, although strength had a higher decrease in relation to adult wood than density, resulting in a lower specific strength. The juvenile wood features affected specific strength, but not the proportion of resistance that is influenced by density.

Keywords: specific strength, compression parallel to grain, planted forest.

RESUMO
No futuro, a tendência é de que o principal tipo de madeira ofertada seja juvenil, e entender suas características é extremamente relevante para um uso adequado deste material. Amostras de madeira de árvores de 25 anos (amostradas na porção mais distal do cerne) e de 6 anos, de diversas espécies de *Eucalyptus* sp. foram ensaiadas na compressão paralela às fibras e tiveram sua densidade aferida. Dados de madeira nativa do mesmo gênero provindos da literatura foram utilizados para devida comparação. A madeira adulta se mostrou similar em densidade e resistência em relação à madeira nativa, já a madeira juvenil foi inferior em ambas as propriedades, ainda que a resistência tenha apresentado uma queda maior do que a densidade, resultando em uma resistência específica menor. As características da madeira juvenil afetam a resistência específica, mas não a proporção em que a resistência é influenciada pela densidade.

Palavras-chave: resistência específica, compressão paralela, floresta plantada.

1 INTRODUCTION

Juvenile wood is a plant tissue formed by the immature cambial meristem (Zobel & Sprague, 1998), and although it has been vastly studied in the temperate region, tropical species have not received the appropriate attention (Vidaurre et al., 2011).In comparison to adult wood, juvenile wood has smaller cells, shorter fibers, thinner cell walls (Trevisan et al., 2017) and higher cellulose microfibrillar angle (Vaněrek et al., 2017), what makes it have a lower density, strength and, stiffness (Missanjo& Matsumura, 2016).

Even though its characteristics limit its application, to understand the properties of juvenile wood is extremely important, as all wood from planted fast-growing forests is juvenile (Senft & Bendtsen, 1984). *Eucalyptus* sp. plantations are an important source of raw material for reconstituted wood products, such as paper, medium density fiberboards, among others, but due to the considerable planted area, they can also be a source of timber. In 2018 there were 5.67 10^6 hectares of planted *Eucalyptus* sp. forests in Brazil, with average productivity of 36 m^3 ha^{-1} $year^{-1}$ (IBA, 2019), but reaching values above 80 m^3 ha^{-1} $year^{-1}$(Gava & Gonçalves, 2008) on certain conditions.

With very high increment rates, big planted areas and proximity to the consumer market, it is undeniable the role young eucalypts forests can play on the Brazilian timber industry. Derikv and et al. (2017) indicate the glued laminated timber as the best destination to wood from young *Eucalyptus* sp. plantations. They consider it a simple objective but highlight the need for a better understanding of the behavior of this wood source to reach the minimum requirements of safety and economic viability.

With that, our objective in the present study is to assess the relationship of compressive strength with the density of juvenile wood in comparison to adult wood from planted and native forests of the genus *Eucalyptus*.

2 MATERIAL AND METHODS

We collected trees from 15 species (*E. citriodora, E. cloeziana, E. saligna, E. maculata, E. microcorys, E. paniculata, E. pellita, E. pilularis, E. phaeotricha, E. propínqua, E. pyrocarpa, E. resinífera, E. tereticornis, E. torelliana*e *E. urophylla*) at the age of 25 years old, as well as six-years-old *Eucalyptus* sp. trees managed for pulp and paper from several clones. The mentioned plantations, named *mature* and *juvenile* wood, respectively, were from the Itatinga Experimental Forest Science Station from the University of São Paulo, Brazil.

Between 3 and 10 trees per species or clone were sampled and from 5 to 10 samples per tree were collected from the first log (2.5 m length), depending on the material availability. Mature wood samples were collected always on the outer edge of the heartwood, to avoid the presence of juvenile material.

The mechanical tests, compression parallel to grain, were conducted following the Brazilian standard NBR7190 (ABNT, 1997). Prior to the mechanical tests, the specimens were used to assess wood density. After achieving the hygroscopic equilibrium in an acclimation room at the temperature of 25°C and air relative humidity of 65% to reach 12% moisture content (MC), the samples were weighed and measured. The dimensions were taken with a digital caliper (0.01 mm precision) and the mass assessed in a semi-analytical scale (0.01 g precision). The samples were then tested in parallel-to-grain compression in a universal testing machine with load capacity of 300kN.

Data from 61 *Eucalyptus* sp. species from native forests in Australia (Bolza&Kloot,1963) configure the treatment named *native* wood. We calculated the specific strength by the ratio of compression strength by wood density at 12% MC.

The normal distribution of the data was evaluated by the comparison of the observed and the theoretical quantiles. As the data violated the theoretical premises of the parametric statistics even after mathematical transformations, we compared the treatments with a non-parametric test, the Kruskal-Wallis test ($\alpha = 0.05$).

We proposed four linear models associating compression strength to the wood density at 12% MC (Figure 1). The model I has no differentiation between the three sources of wood evaluated (juvenile, mature planted, mature native); on models II, III, and, IV there is a differentiation between the wood sources. Model II has the same linear coefficient (β_0) and different angular coefficients (β_1), model III has different β_0 and the same β_1, and model IV has different β_0 and different β_1.
All the statistical analysis and graphics were done with the *R* software (R Development Core Team, 2019).

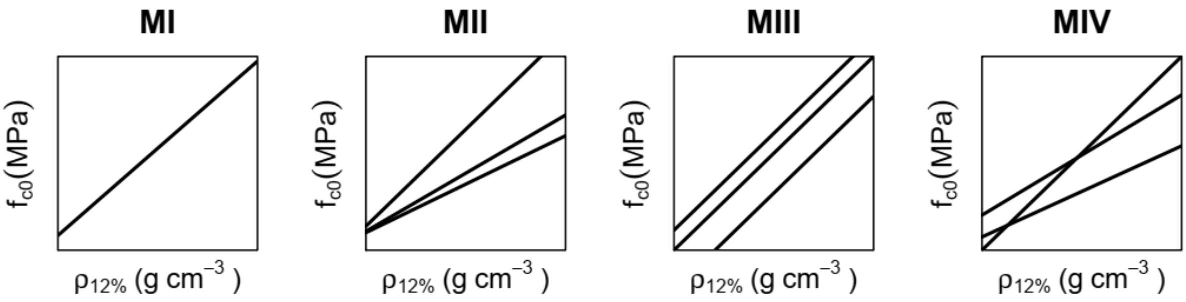

Figure 1. Linear models proposed

3 RESULTS

The density and compressive strength (Figure 2) on mature wood were not different from native wood ($p = 0.1246$ e $p = 0.0645$, respectively). Juvenile wood, on the other hand, was different from both mature and native wood ($p = 0.0000$ for all four comparisons).

The parameters of the four models are displayed in Table 1, and in Figure 3, the models I and III. Specific strength followed the same trend of density and compressive strength (Figure 4): mature and native wood had no difference ($p = 0.3625$), but they both were different from juvenile wood ($p = 0.0000$ in both cases).

Table 2 displays the average values of the analyzed data, as well as their respective standard deviations, characteristic value, and the class of resistance. Juvenile wood was fit in the lowest class for hardwoods, C20, although the characteristic value (f_{c0k}) was very close to the upper class, C30. Mature wood had f_{c0k} higher than 50, but it was fit on the class C40, because the next class is C60.

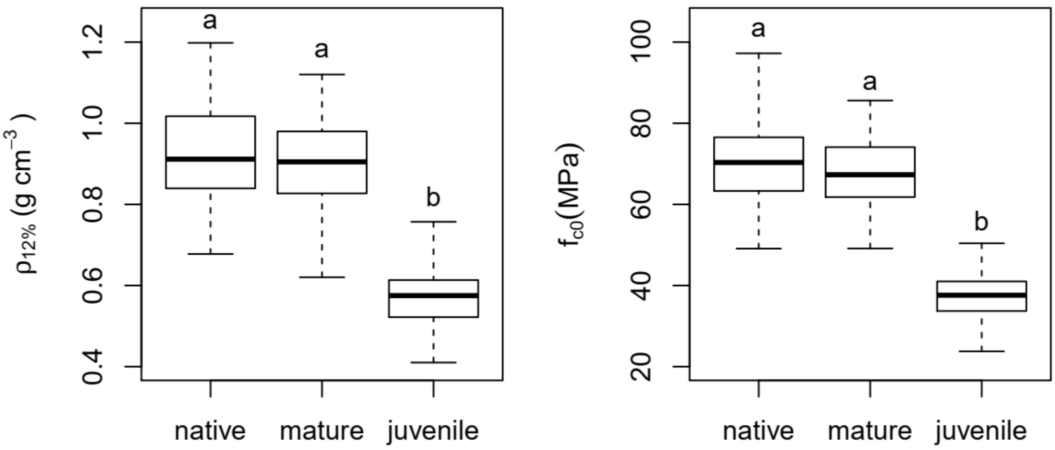

Figure 2. Wood density at 12% MC (left) and compressive strength parallel to the grain (right) by the distinct wood source evaluated. Different letters represent significant difference on the Kruskal-Wallis test ($\alpha = 0.05$).

Table 1. Linear (β_0), angular (β_1) and determination (R^2) coefficients of the curves from models I, II, III and IV associating compressive parallel strength to wood density at 12% MC

model	curve	β_0	β_1	R^2
I	general	-7.927	83.167	0.8586
	native		62.087	
II	mature	13.144	60.929	0.8942
	juvenile		42.181	
	native	18.086		
III	mature	16.824	56.886	0.8963
	juvenile	4.569		
	native	19.095	55.799	
IV	mature	16.527	57.217	0.8957
	juvenile	4.220	57.495	

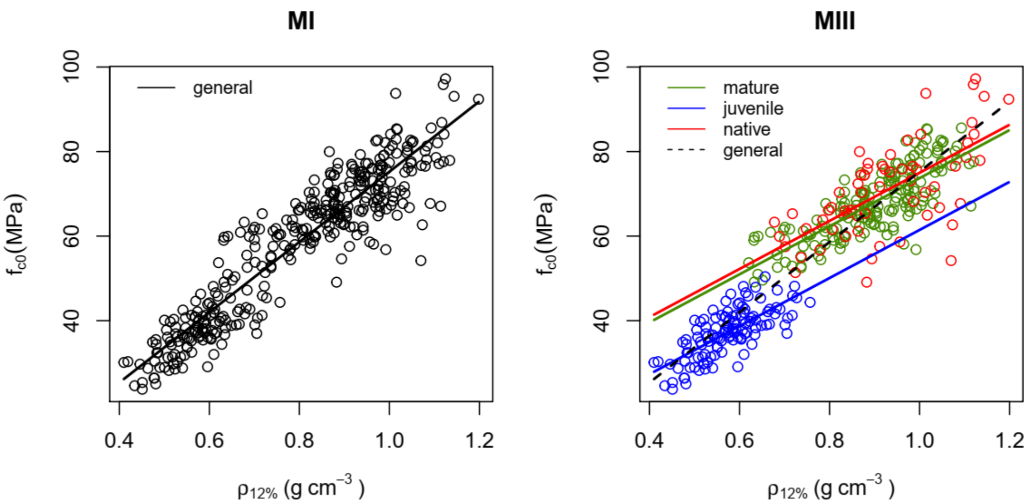

Figure 3. Model I (left), where all three wood sources have the same linear and angular coefficients, and model III (right), where each wood source has a different linear coefficient but distinct angular coefficients

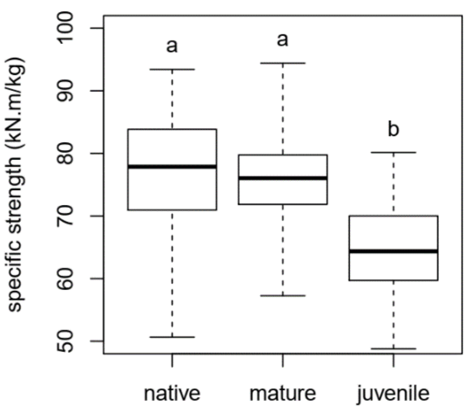

Figure 4. Specific strength on compression parallel to the grain by wood source. Different letters represent significant difference on the Kruskal-Wallis test (α = 0.05)

Table 2. Average of the variables analysed followed by the standard deviation between parenthesis, their characteristic value and resistance class

source	n	$\rho_{12\%}$ (gcm^{-3})	f_{c0} (MPa)	$f_{c0}/\rho_{12\%}$ (kNm kg^{-1})	f_{c0k} (MPa)	resistance class
native	61	0.928 (0.131)	70.89 (11.21)	76.81 (9.40)	-	-
mature	178	0.897 (0.113)	67.86 (8.12)	75.97 (6.13)	54.31	C40
juvenile	119	0.574 (0.072)	37.21 (5.73)	64.94 (7.06)	28.03	C20

4 DISCUSSION

The variances of the three wood sources were similar but higher for native wood, which was expected due to the heterogeneity of the site where these trees had developed, when comparing to plantations.

There is a pattern in common on density and compressive strength values: native and mature woods are similar, with superior values than juvenile wood. This pattern is an indication that the lower strength observed on juvenile wood is a consequence of its lower density. This relationship is vastly discussed in the literature for wood in general (Missanjo & Matsumura, 2016; Zhang, 1997), as well as for other lignocellulosic materials (Berndsen et al., 2013; Balboni et al., 2019).

The high value of the coefficient of determination from the model I ($R^2 = 0.8586$) strengthens the hypothesis that juvenile wood is weaker because of the lower density values. However, model III was the one with the highest coefficient of determination ($R^2 = 0.8963$), a model in which all three curves have the same angular coefficient (β_1). Although the model IV had an R^2 very similar, the lower number of parameters (5) on model III makes it favorable (Brunham& Anderson, 2001) in relation to the former, with 7 parameters.

Model I is usually the model adopted in the literature, in which there is no differentiation between juvenile and mature woods, probably due to the difficulty of identifying and segregating both types of wood. On Figure 3, we can see the adoption of the model I overestimates the influence of density on compressive strength, as it has a higher β_1. Juvenile wood with higher density would have its strength overestimated, and mature wood with lower density would have its strength underestimated.

When interpreting the linear coefficients (β_0) from the curves in model III, we note that mature and native woods do not have differences in compressive strength, supporting the exposed in Figure 1. The identical angular coefficients (β_1) show that, although juvenile wood has lower strength than mature and native woods, they three share the same relationship between strength and density. The immature features of juvenile wood reduce its strength, as also reported by Knapic et al. (2018), but do not affect the proportion of strength gain due to the increase of density.

It does not mean we should discard juvenile wood from applications where mechanical stresses are required. In the last years, there have been reports about the use of juvenile *Eucalyptus* sp. wood for structural purposes. Liao et al. (2017) used wood from eucalypts trees with diameters ranging from 60 to 120 mm on the manufacture of cross-laminated timber panels and found properties similar to the products already available on the market. Crafford & Wessels (2016) suggested the use of eight-years-old *E. grandis* for the composition of structural roof elements, a product which now already being commercialized in South Africa.

When adopting the criteria established in the Brazilian Standard NBR7190 (ABNT, 1997), juvenile wood fits the resistance class C20, and the mature wood C40, both of them with characteristic values (f_{c0k}) very close to the next class, C30 and C60 respectively (Table 2). A genetic selection focused on the increase of wood density and strength certainly would bring them to these higher resistance classes, as both wood properties have high heritability in *E. grandis* (Lima et al., 2019). Nevertheless, the resistance classes were developed to eliminate the need for a complete wood characterization before its application, and the relationships between properties in juvenile wood are not fully understood. One of the next steps for understanding the behavior of this material is to check if the relationships between mechanical properties follow the same pattern observed in mature wood. Additionally, the portions of the trees containing juvenile wood usually come together with other undesirable features, such as grain deviation, knots, and reaction wood (Derikvand et al., 2017). These wood defects are also essential to be studied before a broad application of juvenile wood is possible.

5 CONCLUSIONS

Eucalyptus sp. juvenile wood had lower density and strength than mature wood from plantations, and the latter was similar to native wood. However, the difference of strength was higher than the difference of density, resulting in a lower specific strength on juvenile wood.

The juvenile wood features affect the specific strength but not the proportion strength is influenced by density.

Studies about the relationships between physical and mechanical properties in juvenile wood, as well as about the wood defects, should be carried out to stimulate the broad use of eucalypts juvenile wood for non-reconstituted products.

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