

# RELATIONSHIP BETWEEN WOOD DENSITY AND ANATOMY WITH DRILLING RESISTANCE BY NON-DESTRUCTIVE EVALUATION METHOD

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## Resumo

*Relação entre densidade e anatomia da madeira com resistência à perfuração por método de avaliação não destrutivo.* O resistógrafo tem se destacado como método de avaliação não-destrutiva por permitir uma avaliação rápida da resistência mecânica, densidade e outras propriedades da madeira. O objetivo do trabalho foi avaliar a influência da densidade e anatomia da madeira na resistência a penetração da haste do resistógrafo. De vinte árvores de *Eucalyptus grandis* x *Eucalyptus grandis urophylla*, com 6 anos, foram retirados discos na altura do peito (DAP) de onde foram confeccionadas baguetas diamétrais que foram perfuradas. Após análise visual do resistograma, foram selecionados os locais críticos na posição radial das baguetas que apresentavam picos de amplitude de onde foram retiradas amostras para mensuração da estrutura anatômica e determinação da densidade em diferentes condições de umidade. A resistência a perfuração aumentou em função do aumento da densidade da madeira. A correlação de Pearson entre amplitude de perfuração do Resistógrafo e densidade básica foi de 0,67 e com a densidade no teor de equilíbrio higroscópico (TEH) 0,65. Observou-se correlação moderada entre a amplitude e a espessura de parede da fibra (0,65). A espessura da parede, o comprimento e diâmetro de lume de fibra, são as principais características anatômicas que contribuem para os maiores valores de resistência à perfuração.

*Palavras-chaves:* métodos não-destrutivos, resistografia, qualidade da madeira, eucalipto

## Abstract

The Resistograph has emerged as efficient non-destructive evaluation method, because it allows the fast assessment of mechanical resistance, density and other wood properties. The aim of the present study is to assess the influence of wood density and anatomy on resistance to resistograph drilling. Twenty trees of *Eucalyptus grandis* x *Eucalyptus urophylla* hybrids, at the age group of 6 years, whose chest height discs (CHD) were removed and subjected to diametrical strip drilling, were herein assessed. The critical locations of amplitude radius were selected after the visual analysis of the resistogram; it was done to remove samples for the anatomical analysis and density carried out to determine several moisture contents. Resistance to drill increased due to increased wood density. Person's correlation between resistance to drill and basic density reached 0.67; density in hygroscopic moisture was 0.65. There was moderate correlation between fiber wall amplitude and thickness ( $r=0.65$ ). Cell wall thickness, fiber length and lumen diameter were the main anatomical features contributing to higher resistance to resistograph drilling.

*Keywords:* non-destructive methods, resistography, timber quality, eucalyptus

## INTRODUCTION

Density is one of the most important wood properties; it is closely related to the performance of forest operations and industrial processes. Its value is expressed by the association between wood mass and volume, besides being closely related to wood anatomical structure: vascular dimensions and frequency, fiber width, cell wall thickness, parenchyma relations, among others. Chemical composition, mainly the extractive content, can also play important part in this process; thus, even species presenting similar densities can differ from each other in fiber properties and cell size (DIAS *et al.*, 2017; CARRILLO *et al.*, 2017).

New tools were developed to indirectly estimate wood density and other properties, since these parameters are quite relevant for the wood industry. Accordingly, timber non-destructive evaluation has emerged as powerful tool to determine technological features and variability knowledge between individuals and materials' featuring in the field; it has been more often used by several forest and industrial sectors (GOUVÊA *et al.*, 2011). The main advantages of this assay type lies on its fastness in data collection, low costs and on the possibility of assessing a larger number of samples, a fact that leads to individuals' best selection and analysis in the field, in comparison to traditional methods.

The resistograph is one of these equipment; it allows the indirect measuring of wood features. Moreover, it can be applied through several ways, to the same trees and wood parts, stakes and structures. This technique concerns

a semi-destructive mechanical drill that measures drilling torque over the material, when the rotary drill heads the timber at constant speed. A graphic is plotted to show resistance profile based on crossed trajectories. This method can show changes in the relative-density drill path, as well as be used to diagnose any inner condition and to detect defects in parts of structural wood and in standing trees.

Rinn *et al.* (1996) described resistograph as a device capable of measuring wood resistance to high-quality stain steel rotary drill (3mm in diameter). The drill rotates when it is introduced in the wood at constant rotary speed, whereas resistance to drill value, also known as drilling, is measured as the rate of energy consumed by the engine. The drill finds different resistance intensities when it crosses the wood, and it reflects variations inside the stem as early and late wood, based on the growth rings, as well as structural conditions and cell wall variability.

Studies have shown resistograph's efficiency and reliability to assess wood density in living trees. Carrillo *et al.* (2017) observed good correlation between the density and amplitude of *Eucalyptus globulus* (0.84) and *Eucalyptus nitens* (0.85) recorded in resistograph. Equally similar results were also observed for *Cedrela fissilis* (Silva *et al.*, 2017), *Pinus radiata* (Barría *et al.*, 2017), *Eucalyptus* sp. (Gouvêa *et al.*, 2011), *Eucalyptus grandis* x *Eucalyptus urophylla* (Oliveira, Wang & Vidaurre, 2017). However, there are only few studies correlating resistance to drill to timber anatomical parameters.

The aim of this study was to evaluate the influence of wood density and anatomy on the resistance to puncture of the resistograph in *Eucalyptus* clones.

## MATERIAL AND METHODS

The herein used timber came from 20 trees of 6-year old *Eucalyptus grandis* x *Eucalyptus urophylla* hybrids. It was collected from a clone test located in Aracruz City, Espírito Santo State, Brazil, at geographic coordinates 19°49'11" S, latitude; and 40°16 '27" W, longitude. Discs were removed at CHD position, after their felling; they provided diametrical samples for the study – the marrow had to be concentrated over the discs.

Initially, samples were weighed and stored in cool place to air dry. Samples' initial moisture content was recorded and variations in it were follow-up until hygroscopic balance content was reached.

Tree barks were removed after the diametrical samples were acclimated in order to reach the desired moisture condition; the distance between periphery and marrow was measured to set the drilling distance in the resistograph. Subsequently, samples were fixed on wood support coupled to the resistograph in order to keep stability during the process; drilling was made at radial direction, from the periphery to the marrow.

RINNTECH Resistograph® model Rinn-R650-SC was used in the current study. Data on resistance to drill amplitude recorded in the equipment's inner memory were downloaded to a computer, in DECOM™ software, and exported to Excell spreadsheet. Regions in the graphic presenting peaks with larger, intermediate and smaller amplitude were located after the visual analysis of each tree's resistogram. Three points over the radius located 10mm away from each other were selected.

Smaller samples were removed from the selected points after each diametrical drilling (1.0x3.0x4.0cm in dimension) at the radial, tangential and longitudinal direction, respectively, for density determination purpose. Basic density, dry or anhydrous density, and hygroscopic balance content density were recorded. Procedures adopted to determine basic density followed the Brazilian Regulatory Standard 11941 by the Brazilian Association of Technical Standards, also known as ABNT (2003). Thus, densities were set based on the liquid displacement method, according to which, samples' mass is measured at semi-analytical scale (0.01g) and their volume is found through the mercury displacement method.

Quantitative analysis focused on measuring the vessels (tangential lumen diameter and frequency per mm<sup>2</sup>) and fibers' elements (length, fiber diameter, lumen diameter and cell wall thickness) was carried out for anatomical analysis purpose.

Samples were collected and properly softened in boiling water, at histological sections ranging from 18 µm to 20 µm, in a cross-sectional plane microtome, for the vessel analysis. Histological slide preparation followed routine procedures adopted at the Wood Sciences Laboratory of DCFM/UFES.

Sample parts were reduced to thin sticks and immersed in 25ml of solution with acetic acid and hydrogen peroxide at 1:1 ratio to measure the fibers right after the histological cuts were made. The flasks were placed in stove, at 60 °C, for 48 hours, after they were sealed. Suspended cells were washed in distilled water, inked with safranin, after the solution had decanted; the histological slides were prepared with glycerin and distilled water, at 1:1 ratio.

Anatomical element measuring was carried out in image acquisition system comprising a camera coupled to a polarized light microscope, added with the AxioVision software, for images' analysis purpose.

The study followed the completely randomized design. Data were subjected to normality test after their tabulation in order to find out the dataset distribution.

Analysis of variance (ANOVA) was applied when variables were significant; Scott-Knott was adopted to compare the means at 5% significant level.

Person's correlations at 5% significance level was carried out to assess the existing associations between resistograph amplitude of wood, and its density and anatomical parameters. Statistical analyses were carried out in R software, version 3.5.2.

## RESULTS

The herein assessed wood recorded mean basic-density value ranging from 0.402g/cm<sup>3</sup> in points presenting the smallest amplitude, to 0.499 g/cm<sup>3</sup> in those accounting for the largest amplitude (Table 1). These results meet the expected ones for genus *Eucalyptus* and corroborate those found by Gonzalez *et al.* (2014), who recorded basic-density values ranging from 0.427 g.cm<sup>-3</sup> to 0.623 g.cm<sup>-3</sup> in the same hybrids, at the age of 8 years.

Table 1. Mean amplitude and resistance to drill values at critical positions of the radius in *E. grandis* x *E. urophylla* trees at the age of 6 years.

Tabela 1. Valores médios amplitude e densidades nas posições críticas do raio em árvores de *E. grandis* x *E. urophylla* aos 6 anos de idade.

Position	Amplitude (%)	Basic density (g/cm <sup>-3</sup> )	Anhydrous Density (g/cm <sup>-3</sup> )	Density 12% (g/cm <sup>-3</sup> )
1	48.85c (20.42)	0.402b (8.33)	0.448b (9.40)	0.501b (9.35)
2	84.04b (49.54)	0.429b (5.85)	0.481b (6.33)	0.535b (6.37)
3	133.72a (35.36)	0.499a (12.37)	0.580a (14.42)	0.633a (13.80)

(1) (1) Smallest amplitude; (2) intermediate amplitude; (3) largest amplitude. Values in parenthesis refer to the coefficient of variation. Mean values followed by the same letter in the column did not differ from each other in the Scott-Knott test ( $p < 0.05$ ).

Results recorded for the anatomical analysis applied to dimensioned fibers and vessels are shown in Table 2. With respect to fibers' anatomical parameters, it was possible observing that the radial position with the largest resistance to drill amplitude (133.72%) evidenced the longest length (1,126.7  $\mu\text{m}$ ) and the thickest wall (5.4  $\mu\text{m}$ ), as well as the widest width (21.7  $\mu\text{m}$ ) and intermediate heat diameter (10.9  $\mu\text{m}$ ) in comparison to the other positions.

Table 2. Mean values recorded for fibers and vessels' dimension values observed at critical positions in the radius of *E. grandis* x *E. urophylla* trees at the age of 6 years.

Tabela 2. Valores médios de dimensões de fibras e vasos observados nas posições críticas do raio em árvores de *E. grandis* x *E. urophylla* aos 6 anos de idade.

Position	Fiber length ( $\mu\text{m}$ )	Fiber width ( $\mu\text{m}$ )	Lumen Diameter ( $\mu\text{m}$ )	Cell wall thickness ( $\mu\text{m}$ )	Vessel Frequency (n <sup>o</sup> .mm <sup>-2</sup> )	Vessel diameter ( $\mu\text{m}$ )
1	956.53b (8.30)	20.20b (7.88)	11.39a (15.11)	4.60b (7.47)	12.37a (26.47)	85.11b (14.61)
2	977.43b (12.35)	20.58b (7.33)	10.87b (17.57)	4.83b (12.68)	11.62a (17.69)	87.28b (12.39)
3	1126.74a (10.79)	21.74a (8.62)	10.54b (20.90)	5.44a (11.21)	9.63b (18.39)	94.85a (13.86)

(1) Smallest amplitude; (2) intermediate amplitude; (3) largest amplitude. Values in parenthesis refer to the coefficient of variation. Mean values followed by the same letter in the column did not differ from each other in the Scott-Knott test ( $p < 0.05$ ).

Associations between resistance to drill amplitude, and the density and anatomical parameters of the herein assessed wood are shown in Figure 1. There was moderate correlation (0.67) between amplitude and basic density. This result was higher than that recorded by Silva *et al.* (2017), who assessed these same variables in *Cedrela fissilis* wood, at the age of 14 years – its correlation reached 0.55. Carrillo *et al.* (2017) reported high correlation between basic density values and resistance to drill amplitude in *Eucalyptus globulus* (0.84) and *Eucalyptus nitens* (0.85), at the age of 6 years.

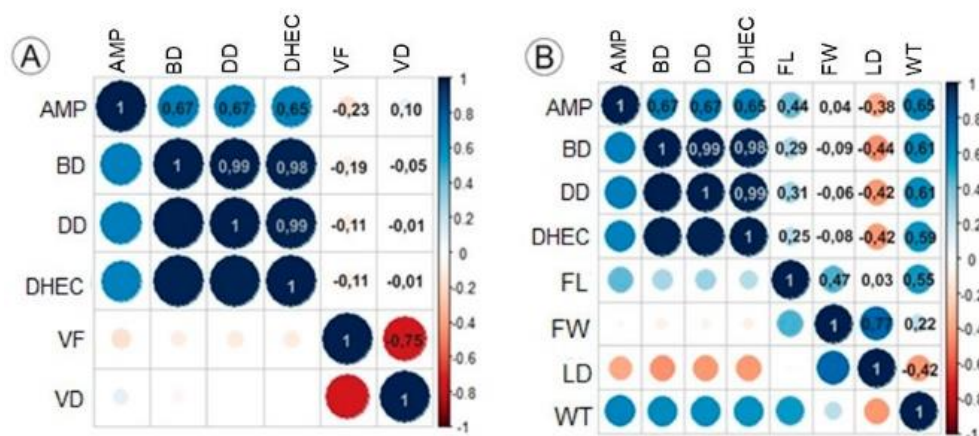


Figure 1. Values and intensities recorded through Pearson's correlation ( $p < 0.05$ ) between amplitude and resistance to drill, and the density and anatomical variables of *E. grandis* x *E. urophylla* wood, at the age of 6 years.

Figura 1. Valores e intensidades de correlação de Pearson ( $p < 0,05$ ) entre amplitude, densidades e variáveis anatômicas de vasos da madeira de *E. grandis* x *E. urophylla* aos 6 anos de idade.

A = Drilling Amplitude (AMP); Basic Density (BD); Dry density (DD); Density at hygroscopic equilibrium content (DHEC); Vessel Frequency (VF); Vessel diameter (VD);

B = Fiber Length (FL); Fiber width (FW); lumen diameter (LD); Cell Wall thickness (WT).

## DISCUSSIONS

There was upward trend of resistance to drill (amplitude) due to increased basic density and anhydrous, and to increased hygroscopic balance. This behavior corresponds to the expected, as described by Rinn *et al.* (1996), Couto and colleagues (2013), and Oliveira *et al.* (2017). It is so, because the higher the density, the bigger the fraction of the fiber wall; therefore, it provides more resistance to drill, which is likely linked to a larger ratio of late wood with thicker and more resistant walls (BARRÍA *et al.*, 2017).

Based on the present results recorded for drill amplitudes, there was high coefficient of variation, and it points out timber heterogeneity due to the morphological variability of its cells, which differed between early and late wood (CARILLHO, *et al.* 2017). Similar heterogeneity was also detected in fiber length and vessel diameter results. This high variation reflects on the resistogram, given the resistograph's ability to collect a large amount of data within a small distance – it records 100 measurements per drilled millimeter.

According to SETTE JR *et al.* (2012), thicker fiber walls increase wood basic density that, in its turn, increases the mechanical properties (ABRUZZI *et al.*, 2012) and makes the wood more resistant to puncture in the resistograph. Results recorded for the anatomical analysis applied to *Eucalyptus grandis* x *Eucalyptus urophylla* fibers (at the age of 6 years) showed approximate values for fiber length (1.1 mm) and fiber width (20  $\mu\text{m}$ ), as well as lower values for lumen diameter (7.8  $\mu\text{m}$ ) and higher values for wall thickness (6.1  $\mu\text{m}$ ).

With respect to vessels' anatomical analysis, there was no significant correlation between these cells' dimensions and drill amplitude in the resistograph (Figure 1). However, it was possible finding that, overall, the position presenting the largest mean amplitude was the same of that presenting the widest mean tangential diameter of the lumen (94.85  $\mu\text{m}$ ) and the lowest vascular frequency (9.63  $\text{v}\cdot\text{mm}^{-2}$ ), as observed in Table 2.

Zanuncio *et al.* (2016) assessed the wood anatomy of *Eucalyptus grandis* x *Eucalyptus urophylla* clones and found mean vessel diameters ranging from 77.5  $\mu\text{m}$  to 129.4  $\mu\text{m}$ , whereas vessels' frequency ranged from 7.7 to 14.3  $\text{v}\cdot\text{mm}^{-2}$ . These results corroborate the herein observed ones.



Positions accounting for the smallest mean amplitude (position I: 48.85%) and intermediate amplitude (position II: 84.04%) did not statistically differ in fibers and vessels' anatomy parameters, not even in density. This behavior points out that even very small differences between cell structures in wood have significant effect on resistance to resistographic drilling, due to its ability to record variation in every 0.01-mm penetration; this finding can represent structural variability even inside cell walls.

Several studies have shown resistograph's efficiency and reliability to assess wood density in living trees (SILVA *et al.*, 2017; GOUVÊA *et al.*, 2011; OLIVEIRA, WANG and VIDAURRE, 2017; BARRÍA *et al.*, 2017). However, other factors must be considered, such as wood moisture and drill depth, must be considered to increase equipment effectiveness in predicting this wood property, by increasing correlations between the two herein assessed parameters, since they influence equipment accuracy (IÇEL and GULLER, 2016).

Based on results recorded for fiber anatomy correlation coefficients shown in Figure 1-B, it is possible observing positive and moderate correlation between drill amplitude and fiber wall thickness (0.65). Therefore, lumen diameter recorded negative correlation ( $r = -0.38$ ); in other words, points presenting higher resistance to drill have fibers with thicker walls and smaller lumen diameter. Correlation was also positive and significant for fiber length ( $r = 0.44$ ), but intensity was moderate.

These results may point out that cell wall thickness, fiber length (at smaller degree) and lumen fiber diameter are the main features contributing to the highest values of resistance to resistograph drilling and, consequently, to wood density, since these two properties are associated with each other (CARRILLO *et al.* 2017).

Oliveira and cols. (2017) have stated that density increase can be the outcome of increased fiber cell thickness or of increased fiber ratio, such as the case of increased vessel ratio. On the other hand, increase in the vessels' ratio, with or without cell wall thickness reduction, leads to density reduction.

## CONCLUSIONS

Given the aforementioned findings, it is possible concluding that:

- The drilling amplitude generated by the resistograph showed a positive and significant correlation with the basic, anhydrous density and hygroscopic equilibrium content, proving to be an efficient method to predict these parameters.
- Cell wall thickness, fiber length and the smallest degree of resistance amplitude values are the main anatomical features contributing to higher resistance amplitude values of the drilling rod resistograph.

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