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Nota Técnica

Physical-mechanical properties of Cajueiro wood estimated by non-destructive methods based on apparent density and natural vibration frequency

Propriedades físico-mecânicas da madeira de cajueiro estimadas por métodos não destrutivos com base na densidade aparente e frequência natural de vibração

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ABSTRACT

Wood has several properties that make it attractive when compared to other materials, however, for its use, it is necessary to know the values of resistance and stiffness. In this sense, the use of non-destructive techniques adds to the process. Among the non-destructive techniques of mechanical evaluation, we highlight those that use the natural frequencies of vibration whose results can be repeated and compared over time. This research aimed to relate the physical and mechanical properties of cajueiro wood [Anacardium sp], with the apparent density and with the natural frequency of the transversal vibration test, through regression models. Twenty-four transverse vibration tests and 204 experimental determinations were performed. Linear regression models were then generated as a function of apparent density and transverse vibration frequency, as well as quadratic multivariable regression models, to estimate wood properties. From the linear regression models, weak correlations were noted between density and natural frequency with the physico-mechanical properties evaluated, resulting in low precision estimates. Regarding the multivariable regression models, quadratic adjusted coefficients of determination (R^2aj) higher than 80% were verified for 03 models of the 16 evaluated.

Keywords: *Anacardium*; Wood characterization; Regression models; Coefficient of determination

RESUMO

A madeira possui diversas propriedades que a torna atraente frente a outros materiais, entretanto, para sua utilização, com segurança, é necessário o conhecimento dos valores de resistência e elasticidade. Nesse sentido, a utilização de técnicas não destrutivas vem a agregar no processo de avaliação. Entre as técnicas não destrutivas de avaliação mecânica, destacam-se aquelas que utilizam as frequências naturais de vibração cujos resultados podem ser repetidos e comparados ao longo do tempo. Esta pesquisa objetivou relacionar as propriedades físicas e mecânicas da madeira de cajueiro [*Anacardium sp*], com a densidade aparente e com a frequência natural do ensaio de vibração transversal, por meio de modelos de regressão. Foram realizados 24 ensaios de vibração transversal e mais 204 determinações experimentais. Na sequência, foram gerados modelos de regressão lineares em função da densidade aparente e da frequência de vibração transversal, bem como modelos de regressão multivariáveis quadráticos, de forma a estimar as propriedades das madeiras. Dos modelos de regressão lineares, foram notadas fracas correlações entre a densidade e a frequência natural com as propriedades físico-mecânicas avaliadas, resultando em estimativas de baixa precisão. Em relação aos modelos de regressão multivariáveis, quadráticos foram verificados coeficientes de determinação ajustado (R^2aj) superiores a 80 % para 03 modelos dos 16 avaliados.

Palavras-chave: *Anacardium;* Caracterização da madeira; Modelos de regressão; Coeficiente de determinação

1 INTRODUCTION

Wood is a material that comes from natural or planted forests and has great potential for use in construction (Ter Steege; Vaessen; Cárdenas-López; Sabatier; Antonelli; Oliveira; Pitman; Jørgensen; Salomão, 2016; Tuisima-Coral; Odicio-Guevara; Weber; Lluncor-Mendoza; Lojka, 2017). Among the materials commonly used in structures, wood is the only one that is renewable and its extraction and processing consume less energy than other materials, as well as having a good strength-to-density ratio.

Brazil has the second largest forest cover on the planet and the largest continuous area of tropical forest in the world, with approximately 498 million hectares, made up of 98% natural forests and 2% planted forests (Boletim SNIF, 2020). In 2021, the total area of trees planted in the country amounted to 9.93 million hectares, with 75.8% of the area made up of eucalyptus, 7.53 million hectares, and 19.4% of pine, with approximately 1.93 million hectares. In addition to this cultivation, there are around 475 thousand hectares planted with other species, including rubber trees, acacia, teak and paricá (IBA, 2022). The Brazilian forestry sector has the highest productivity, considering the volume of wood produced per area per year, and one of the shortest rotations, considering the time between planting and harvesting trees in the world. As a result, the country is an important player in the forestry economy, ranking among the largest producers and exporters of forestry products worldwide.

The construction sector is mainly responsible for the use of wood products, whether they are used as temporary structures during the initial stages or permanently, incorporated into structural parts and in the finishing stages. For rational use and as a structural element, wood should be classified according to its physical and mechanical properties (Trevisan; Tieppo; Carvalho; Lelis, 2007; Lin; Fu, 2008). Therefore, carrying out tests is essential for characterizing the species, and the execution is relatively quick, however, the preparation of the test specimens is a laborious stage, in addition to being necessary to use instruments and equipment capable of measuring the mechanical properties, the which present high costs for acquisition and maintenance.

In this sense, the use of non-destructive methods to characterize the physical and mechanical properties of wood is of fundamental importance due to the speed with which they can be verified and, above all, because they eliminate the need to extract specimens from the piece being tested. In addition, Wang, Chen, Tsai, Lin and Yang (2008) stated that non-destructive evaluation can be used industrially to improve the quality control process due to the greater uniformity of raw materials and their by-products.

Various studies using non-destructive testing methods have been carried out to obtain and correlate wood properties, such as Ribeiro, Gonçalez, Souza and Paula (2016), Faydi, Brancheriau, Pot and Collet (2017) and Segundinho, Cossolino, Pereira and Junior (2018). The results obtained by these authors indicate that dynamic methods are suitable for determining some intrinsic characteristics of wood, in particular the modulus of elasticity.

Another important property for characterization is density, which can be assessed using different methodologies. It's considered by many authors to be the main qualitative characteristic of wood (Louzada; Gaspar; Bento, 2005; Goulart; Mori; Ribeiro; Coutto; Arantes; Mendes, 2012), as well as making it possible to estimate the mechanical properties of the species, to create alternatives to carrying out tests in laboratories, according to studies by Simsek and Baysal (2015), Christoforo, Almeida, Almeida, Santos, Panzera and Lahr (2016) and Almeida, Almeida, Araujo, Silva, Christoforo and Lahr (2017).

The available literature presents few results on the physical-mechanical properties of the species studied in this research, Cajueiro [Anacardium sp]. In this context, it can be seen that the very characterization of wood is a contribution to the technical environment.

The Cajueiro tree is a predominant species in the tropical region of South America. In Brazil, it occurs naturally in the following states: Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, and Roraima (Klein, 2020). Cajueiro wood is light, low-density, and has low mechanical properties, with an average resistance to compression parallel to the fibers and an apparent density of around 31.8 MPa and 0.48 g/cm^3, respectively, at 15% humidity. It is used in light internal applications, such as finishes, trims, ceilings, and moldings (IPT, 2020).

This research aimed to evaluate the indication for the use of Cajueiro tree wood in civil construction and establish the relationships between the physical-mechanical properties as a function of apparent density tests and the natural frequency of transverse vibration through regression models.

2 MATERIALS AND METHODS

Twelve Cajueiro wood beams from a homogeneous batch, with original dimensions of 6×12×400 cm, with a moisture content close to 12% (11, 22%) and properly stored, were evaluated in static bending in a non-destructive way [maximum displacement limited to the length of the span between supports (L) divided by 200

(L/200) - ABNT NBR 7190 (1997)] and also using the transverse vibration method to obtain the modulus of elasticity. It should be noted that for transportation reasons, these beams were sawn in half (6 cm × 12 cm × 200 cm), resulting in 24 pieces.

After these tests, the beams were processed to generate test specimens to obtain physical (3 properties) and mechanical (14 properties) properties, whose shapes, dimensions, procedures, and test methods followed the prescriptions of the standard Brazilian ABNT NBR 7190 (1997) "Design of wooden structures".

A specimen was taken from each of the beams to obtain each of the properties of interest, Table 1, resulting in 204 experimental determinations plus 24 others (modulus of elasticity) from the beams themselves.

Table 1 – Physical and mechanical properties evaluated

Property	Abbreviation
Apparent density	ρ_{12}
Full radial retraction	RRt
Full tangential retraction	RTt
Compressive strength parallel to the fibers	f_{c0}
Compressive strength normal to the fibers	f_{c90}
Tensile strength parallel to the fibers	f_{t0}
Tensile strength perpendicular to the fibers	f_{t90}
Shear strength in the direction parallel to the fibers	f_{v0}
Resistance to splitting parallel to the fibers	f_{s0}
Conventional strength in the static bending test	FM
Hardness parallel to the fibers	f_{h0}
Hardness perpendicular to the fibers	f_{h90}
Tenacity	W
Modulus of elasticity in compression parallel to the fibers	E_{c0}
Modulus of elasticity in compression perpendicular to the fibers	E_{c90}
Modulus of elasticity in tension parallel to the fibers	E_{t0}
Conventional modulus of elasticity in the static bending test	E_{M0}

Source: Authors (2023)

The analysis of parts with structural dimensions using the transverse vibration method was carried out using the equipment *Transverse Vibration* E-Computer, model 340 from Metriguard. This equipment consists of an electronic interface unit, two sets of tripods, a calibration weight, a software module on disk, a load cell, and the necessary connection cables. For the results to be accurate, the device was calibrated using a material with a known modulus of elasticity (aluminum bar). As input data, the program requests the base measurements, height, and length of the part to be evaluated, as well as the external measurement of the supports. It should be noted that the location of the part under analysis must correspond precisely to the external measurement between the supports provided. The weight of the element is obtained automatically by the existing load cell. The test begins by applying an external force to the middle of the span, using a hammer, which causes the element to vibrate. The load cell on one of the tripods picks up the vibration frequency and sends the data to the computer. Finally, the computer program performs the relevant calculations and stores the finished data and results in a text file, including the peak frequency (natural frequency) to be used in the regression models to estimate the properties. The calculation of the dynamic modulus of elasticity by transverse vibration (E_{din}) is given by Equation (1).

$$E_{din} = \frac{f_r^2 \cdot P \cdot L^3}{2.46 \cdot I \cdot g} \quad (1)$$

Where: f_r is the vibration frequency (Hz); P is the weight of the beam (N); L is the distance between the supports (m); I is the moment of inertia of the cross-section (m4); g is the acceleration due to gravity (9.80665 m/s²).

According to ABNT NBR 7190 (1997), the resistance and elasticity properties were corrected using Equations (2) and (3) for the standard moisture content (12%), and specifically for the resistance properties, the characteristic values Equation (4) were determined, it is worth noting that the characteristic value of the compressive strength in the direction parallel to the fibers is responsible for classifying the species into one of the four resistance classes (C 20, C 30, C 40, C 60) of the group of hardwoods established by the aforementioned standard.

$$f_{12} = f_{U\%} \cdot \left[1 + \frac{3 \cdot (U\% - 12)}{100}\right]; \quad 10 \leq \text{U}\% \leq 20\% \tag{2}$$

$$E_{12} = E_{U\%} \cdot \left[1 + \frac{2 \cdot (U\% - 12)}{100}\right]; \quad 10 \leq \text{U}\% \leq 20\% \tag{3}$$

$$f_{wk} = Máx \begin{cases} f_1 \\ 0{,}7 \cdot \dfrac{\sum_{i=1}^{n} f_i}{n} \\ 1{,}1 \cdot \left[2 \cdot \left(\dfrac{f_1 + f_2 + f_3 + \ldots + f_{(n/2)-1}}{(n/2) - 1}\right) - f_{n/2}\right] \end{cases} \tag{4}$$

Where: In equations (2) and (3), $f_{U\%}$ and $E_{U\%}$ are the strength and elasticity values obtained considering the moisture content (*U*%) of the pieces (11.22%), respectively, and f_{12} and E_{12} are the strength and elasticity values corrected for the standard moisture content. From Equation (3), f_{wk} is the characteristic value obtained for this resistance property, f_i is the resistance sample value and *n* is the number of property determinations (in this study, n = 12).

The apparent density (ρ12) was correlated with the sixteen other properties (physical and mechanical), while the natural frequency (*fr*) of the transverse vibration test was correlated only with the mechanical properties (fourteen properties). Correlations were measured by Pearson's r coefficient (-1 ≤ r ≤ 1), and the significance of these coefficients was measured by analysis of variance (ANOVA) at a 5% significance level. According to the wording of the test, a p-value (probability p) equal to or greater than the significance level adopted implies that the linear correlation tested is not significant, and significant (p-value < 0.05) otherwise.

Linear regression models were generated from the significant correlations and also evaluated by analysis of variance at the 5% significance level, with the quality of the fits being measured by the adjusted coefficient of determination (R2 aj). From ANOVA, p-value ≥ 0.05 implies non-significance of the model, and non-significance otherwise (p-value < 0.05).

In an attempt to generate better precision adjustments, multiple regression models (Equation (5)) dependent on apparent density and natural frequency of vibration were generated to estimate the sixteen other properties (physical and mechanical). By ANOVA of the regression models, a p-value lower than the significance level adopted ($\alpha = 0.05$) implies that the model and the terms of the model are considered significant, and not significant otherwise.

$$Y = \beta_0 + \beta_1 \cdot \rho_{12} + \beta_2 \cdot fr + \beta_3 \cdot \rho_{12}^2 + \beta_4 \cdot fr^2 + \beta_5 \cdot \rho_{12} \cdot fr + \varepsilon \tag{5}$$

Where: Y denotes the dependent variables considered (sixteen); β_i consists of the coefficients adjusted by the least squares method; ε is the random error, with the quality of the adjustments also being assessed by the adjusted coefficient of determination.

In addition, also using ANOVA (5% significance level), the equivalence between the modulus of elasticity obtained from the samples (small and defect-free - EM), the structurally dimensioned beams (EEst) tested in static bending in a non-destructive way and also via the transverse vibration test (Edin) was evaluated, as well as the analysis of the equivalence between the densities of the samples and the structurally dimensioned beams.

The Anderson-Darling normality test, at a 5% significance level, was used to validate the ANOVA as well as the confidence intervals of the mean (95% reliability) obtained for the physical and mechanical properties evaluated. According to the wording of the test, a p-value greater than or equal to the significance level implies normality in the distribution of values (real or residual in the case of regression models), and non-normality otherwise (p-value < 0.05).

3 RESULTS AND DISCUSSIONS

Table 2 shows the average values ($\bar{x}$), the coefficients of variation (CV), the lowest (Min.) and highest (Max.) values, as well as the confidence intervals (CI) of the mean (95% reliability) for the physical and mechanical properties obtained from the defect-free samples of Cajueiro wood.

Table 2 – Physical and mechanical properties evaluated

Properties	$\bar{x}$	CV (%)	Min	Max	IC (95%)	FWK
ρ_{12} (g/cm^3)	0,55	9,40	0,50	0,68	(0,51; 0,58)	---
RRt (%)	4,39	22,56	2,99	6,17	(3,76; 5,02)	---
RTt (%)	6,39	32,23	2,99	10,71	(5,08; 7,69)	---
fc0 (MPa)	39,71	10,69	28,87	44,65	(37,01; 42,40)	35,20
fc90 (MPa)	8,12	12,73	6,88	10,47	(7,46; 8,77)	7,48
ft0 (MPa)	83,69	33,46	34,10	126,65	(65,90; 101,49)	58,62
ft90 (MPa)	2,81	18,61	1,86	3,90	(2,48; 3,14)	2,00
fv0 (MPa)	10,32	16,88	6,82	12,61	(9,21; 11,42)	7,92
fs0 (MPa)	0,57	23,40	0,40	0,84	(0,48; 0,65)	0,46
fM (MPa)	72,29	9,88	55,40	81,53	(67,75; 76,83)	65,34
fh0 (MPa)	50,33	10,83	39,90	59,30	(46,87; 53,80)	44,90
fh90 (MPa)	27,95	12,46	20,00	33,40	(25,74; 30,16)	23,12
W (daN·m)	0,44	25,65	0,32	0,75	(0,37; 0,51)	---
Ec0 (MPa)	11300	20,86	6970	14500	(9783; 12773)	---
Ec90 (MPa)	896	14,23	664	1070	(814,8; 976,7)	---
Et0 (MPa)	12500	25,57	7520	19600	(10475; 14539)	---
EM0 (MPa)	12000	10,96	9630	13900	(11205; 12882)	---

Source: Authors (2023)

In where: *ρ12 – Apparent density; RRt – Total radial retraction; RTt – Total tangential retraction; fc0 – Resist. to compression parallel to the fibers; fc90 – Resist. to compression normal to the fibers; ft0 – Resist. to traction parallel to the fibers; ft90 – Resist. to traction perpendicular to the fibers; fv0 – Resist. to shear in the direction parallel to the fibers; fs0 – Resist. to splitting parallel to the fibers; fM – Resist. conventional in the static bending test; fh0 – Hardness parallel to the fibers; fh90 – Hardness perpendicular to the fibers; W – Tenacity; Ec0 – Modulus of elasticity in compression parallel to the fibers; Ec90 – Modulus of elasticity in compression perpendicular to the fibers; Et0 – Modulus of elasticity in traction parallel to the fibers; EM0 – Conventional modulus of elasticity in the static bending test.

Table 2 shows that, as the p-values of the Anderson-Darling test were greater than 5% for all the properties evaluated, the distribution of all the variables was normal, validating the results obtained from the confidence intervals of the mean.

About the coefficients of variation (CV) for the values of compressive and shear resistance, both in the direction parallel to the fibers, it was observed that they are lower than that established by the Brazilian standard ABNT NBR 7190 (1997) which recommends the percentages of 18% and 28% for normal and tangential loads, respectively, considering hardwoods with moisture close to 12%, for structural calculation purposes.

The characteristic resistance to compression parallel to the fibers (f_{wk}) was 35.20 MPa, classifying the batch of Cajueiro wood studied as C30, of the dicotyledonous (hardwood) class, according to ABNT NBR 7190 (1997), which defines minimum values of resistance to compression parallel to the fibers of 30 MPa, average modulus of elasticity to compression parallel to the fibers of 14500 MPa and apparent density of 0.8 g/cm^3 at 12% humidity. In this context, unlike the applications suggested by the IPT (2020), the species can be used as structural elements in civil construction.

With an average apparent density of 0.55 g/cm^3, the species is considered medium-density wood using the criteria presented in the studies by Coradin, Camargos, Pastore and Christo (2010) and Silveira, Rezende and Vale (2013), which classify low-density woods as those with values below 0.50 g/cm^3, medium density as those with wood density between 0.51 and 0.72 g/cm^3, and heavy or high-density woods as those with values above 0.73 g/cm^3.

Table 3 presents the relationships between the characteristic values of resistance and elasticity properties established by the Brazilian standard ABNT NBR 7190 (1997) when it is impossible to carry out all tests to characterize some species of wood, compared to the relationships obtained in this study.

Table 3 – Comparison between the relationships established by ABNT NBR 7190 (1997) and the results of the properties of the species studied

Relation	**NBR 7190 (1997)**	**Present research**
Relation 1	fc0,k = 0,77•ft0,k	fc0,k = 0,60•ft0,k
Relation 2	fv0,k = 0,12•fc0,k	fv0,k = 0,225•fc0,k
Relation 3	Ec0,m = Et0,m	Ec0,m = 0,90•Et0,m
Relation 4	Ec0,m = 0,90•Et0,m	EM0,m = 1,06•Ec0,m

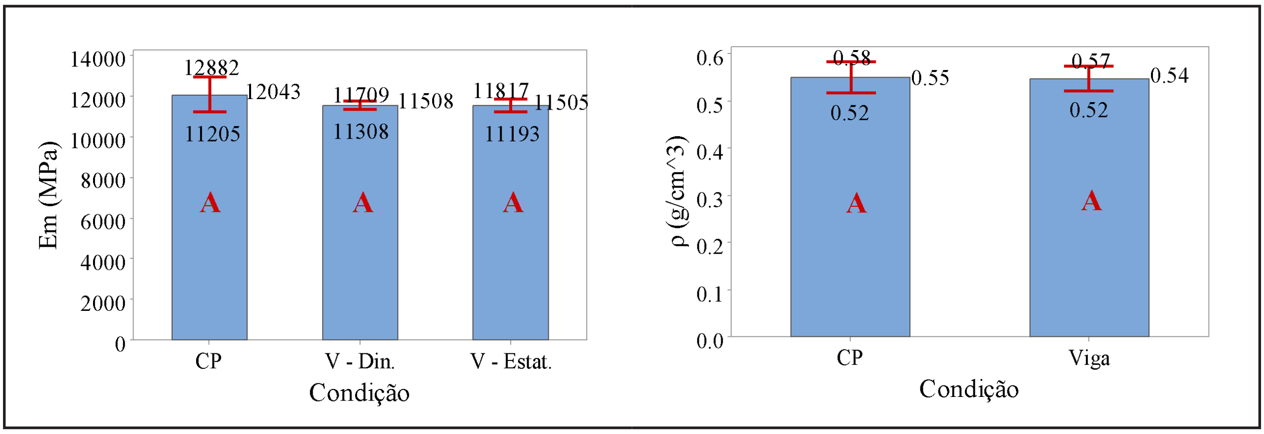
Source: The Authors (2023)

As can be seen in Table 3, the compressive strength parallel to the fibers was around 60% of the tensile strength parallel to the fibers, 22.08% less than the value proposed by ABNT NBR 7190 (1997). The resistance to shear parallel to the fibers was in the order of 22.5% of the resistance to compression parallel to the fibers, 87.50% higher than the value proposed by the aforementioned Brazilian standard. The discrepancies between the standard and the study's ratios can be explained, in part, by the intrinsic variability of the material and the number of specimens tested to determine the experimental results, as well as the fact that the ratios presented by ABNT NRB 7190 (1997) consider native and reforested woods in the same set. Regarding elasticity properties, the ratios were close to those established by the standard.

The comparison between the moduli of elasticity obtained from the tensile (Et0) and compression (Ec0) tests in the direction parallel to the fibers by ANOVA (5% significance) showed equivalence between the two (p-value = 0.295), a result in line with that presented by the Brazilian standard ABNT NBR 7190 (1997), and it should be noted that the p-value of the Anderson-Darling normality test was greater than 5%, which validates the results obtained from the analysis of variance.

Figure 1 shows the results of Tukey's test to compare the average values of modulus of elasticity and densities obtained from the specimens and beams (structural dimension pieces).

Figure 1 – Tukey test results referring to elasticity values - a) density with a moisture content of 12%; b) obtained from samples and pieces of structural dimensions



Source: Authors (2023)

In where: * CP: specimen of small dimensions and free of defects; V - Din: beams tested using the transverse vibration method; V - Est.: beams tested in static bending in a non-destructive manner.

The p-values greater than 0.05 (5%) of the Anderson-Darling test indicate normality in the distributions of the properties shown in Figure 1, thus validating the results of the Tukey test.

From the analysis of Figure 1, it can be seen that the modulus of elasticity was evaluated as equivalent, as were the densities. The statistical equivalence is justified by the fact that the species tested comes from native forests, as well as the absence of defects in the pieces and the longer cutting time compared to reforested wood. ABNT NBR 7190 (1997) allows the characterization of wood for structural use based on the results obtained through tests with small-sized test specimens.

About the equivalence of the modulus of elasticity, comparing them with the correlated literature, the results obtained corroborate the studies by Segundinho, Cossolino, Pereira and Junior (2012), in which structural pieces of reforested wood (Pinus oocarpa and Eucalyptus sp.) showed very close elastic property values, with a significant correlation at 1% probability, when assessed using non-destructive testing methods based on the natural vibration frequencies (resonances) of the longitudinal and transverse modes and relating them to the results obtained in static bending. In the same way, Carreira, Dias and Segundinho (2017) verified the effectiveness of the transverse vibration method, compared to the static bending test, for determining the modulus of elasticity of trunks of the Corymbia citriodora species, with a correlation of around 0.92, indicating that the free transverse vibration method provides reliable data on the modulus of elasticity to bending of trunks of the species.

Table 4 presents the results of correlation tests involving apparent density and other physical and mechanical variables and between the frequency (fr) obtained from the transverse vibration test and the mechanical properties, it is worth highlighting that the average, the coefficient of variation and the confidence interval of the average (95% and reliability) of the frequency values obtained for the twelve wooden pieces of structural dimensions were equal to 62.58 Hz; 3.71% and IC = (61.11; 64.06 Hz), respectively. The p-value of the normality test for frequency was 0.952, and since it was greater than 0.05, the distribution was normal, validating the results obtained from the confidence interval for the mean.

Table 4 – Results of correlation analyses

Properties	ρ_{12} (g/cm3)		f_r (Hz)	
	r Pearson	p-value ANOVA	r Pearson	p-value ANOVA
RRt (%)	-0,050	0,876	---	---
RTt (%)	0,768	0,004	---	---
fc0 (MPa)	-0,685	0,014	0,234	0,463
fc90 (MPa)	0,448	0,144	0,049	0,880
ft0 (MPa)	-0,415	0,180	0,265	0,404
ft90 (MPa)	0,068	0,833	0,286	0,367
fv0 (MPa)	0,125	0,698	0,481	0,114
fs0 (MPa)	0,540	0,070	0,348	0,268
fM (MPa)	-0,440	0,152	0,654	0,021
fh0 (MPa)	0,588	0,044	-0,041	0,900
fh90 (MPa)	-0,202	0,530	-0,232	0,468
W (daN·m)	0,284	0,371	0,413	0,182
Ec0 (MPa)	-0,225	0,482	-0,134	0,677
Ec90 (MPa)	-0,496	0,101	0,627	0,029
Et0 (MPa)	-0,116	0,720	-0,100	0,757
EM0 (MPa)	0,214	0,504	0,399	0,199

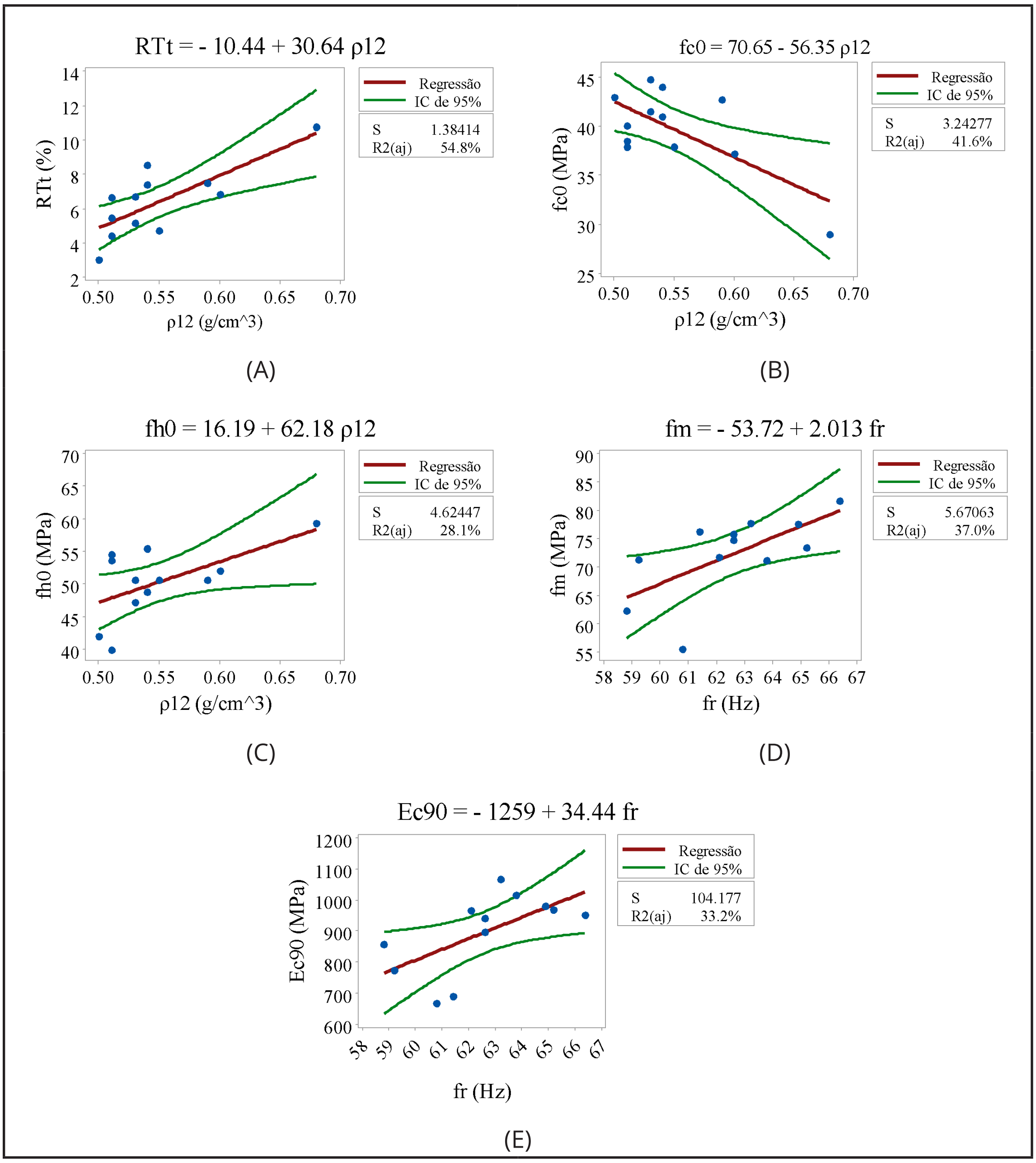
Source: The Authors (2023)

In where: *ρ12 – Apparent density; RRt – Total radial retraction; RTt – Total tangential retraction; fc0 – Resist. there is compression parallel to the fibers; fc90 – Resist. to compression normal to the fibers; ft0 – Resist. to traction parallel to the fibers; ft90 – Resist. to traction perpendicular to the fibers; fv0 – Resist. to shear in the direction parallel to the fibers; fs0 – Resist. to splitting parallel to the fibers; fM – Resist. conventional in the static bending test; fh0 – Hardness parallel to the fibers; fh90 – Hardness perpendicular to the fibers; W – Tenacity; Ec0 – Modulus of elasticity in compression parallel to the fibers; Ec90 – Modulus of elasticity in compression perpendicular to the fibers; Et0 – Modulus of elasticity in traction parallel to the fibers; EM0 – Conventional modulus of elasticity in the static bending test; *underlined terms show significant correlation by ANOVA (p-value < 0.05).

From Table 4, apparent density showed a significant correlation (p-value < 0.05) in only three (RTt, fc0, and fh0) of the 16 other variables compared, and about frequency, only two (fM and Ec90) of the 14 correlations tested were considered significant by the analysis of variance.

Figure 2 illustrates and presents the regression models as well as the adjusted coefficients of determination (R2 aj) referring to the significant correlations indicated in Table 4.

Figure 2 – Linear regression models referring to co-relationships considered significant by ANOVA



Source: Authors (2023)

In Figure 2, the Anderson-Darling test on the ANOVA residuals of the regression models showed normality in all cases (p-value > 0.05), which validates the results of the analysis of variance. Even though the correlations were significant, the adjusted coefficient of determination varied from 28.10% to 54.80%, and this implies inaccurate models to be used in estimating the aforementioned properties. These results can be seen in the noticeable dispersion between the pairs of experimentally determined values and the fitted curves.

In Figure 2 A, the regression model referring to the correlation between apparent density and total tangential retraction, it is possible to verify the existence of a relationship between density and retractability, the higher the density, the greater the retractability, that is, denser wood tends to absorb more water per unit volume, consequently they tend to expand or contract more than those with lower density. Oliveira, Tomazello Filho and Fiedler (2010) explained that denser woods because they have a higher concentration of thicker-walled cells, tend to absorb more water per unit volume and consequently expand or contract more than those of lower density. As a comparative parameter, concerning the adjusted coefficient of determination, Christoforo, Almeida, Almeida, Santos, Panzera and Lahr (2016) studied the possibility of estimating the retractability of five species of native Brazilian wood as a function of apparent density. Four regression models were studied (exponential, linear, quadratic, and cubic). According to the authors, it was possible to estimate volumetric and tangential shrinkage using the quadratic regression model, which showed R^2 values of over 70%.

In Figures 2 B and 2 C, regression models are presented as a function of the correlation between apparent density, compressive strength, and hardness, respectively, both parallel to the fibers. The relationship between apparent density and the strength and hardness properties of wood is well-known and universal. In this context, mechanical strength increases proportionally with increasing density. Denser species are harder and have higher resistance values. However, when evaluating Figure 2 B, a result was found to be inconsistent with the literature, given that the interpretation of the fitted curve allowed us to infer that denser woods imply lower values of compressive strength parallel to the fibers. The inconsistency can be explained by the variability in density due to the small size of the samples and the possibility of them containing different proportions of sapwood and heartwood, which implies that the wood properties behave differently, from a physical, chemical, and morphological point of view (Pereira; Oliveira; Carvalho; Carneiro; Vital; Santos, 2013). These factors make it difficult to establish a direct relationship with the properties obtained from the specimens, and it is worth noting that the wood used to determine the density is not removed from the specimen of the aforementioned associated property, and this further increases the variability in the results. About the adjusted coefficients of determination (R2 aj), Figures 2 B and 2 C, were lower than those obtained in similar studies. Dias and Lahr (2004) carried out a study to estimate the resistance and stiffness properties of forty Brazilian native species (hardwoods) through apparent density, obtaining the relationship between apparent density and compression parallel to the fibers of the order of R^2 equal at 0.77104. Lahr, Aftimus, Arroyo, Almeida, Christoforo, Chahud and Branco (2016) carried out a complete characterization of Angelim Saia wood (Vatairea sp.) by ABNT standard NBR 7190:1997 and, in addition, using regression models, estimated the wood properties using apparent density, with coefficients of determination of over 60% and 70% for resistance to compression parallel to the fibers and hardness parallel to the fibers, respectively. The differences between the values of the studies cited here and the present study are because the authors worked with more than one species, as well as the average values of the properties, making it possible to reduce variability and improve adjustments.

There have been no studies in the literature evaluating the correlation between the natural frequency of the transverse vibration test and the physical-mechanical properties of wood. However, from the analysis of the curves in Figures 2 D and 2 E, it can be inferred that there is a relationship in which higher frequency values imply higher conventional strength results in the static bending test and an increase in the modulus of elasticity in compression perpendicular to the fibers.

Table 5 presents the multiple regression models considering the apparent density and natural frequency of the transverse vibration test as estimators of the other physical and mechanical properties evaluated, to improve the precision achieved by the simple linear regression models.

Table 5 – Quadratic multiple regression models

Models	R2 aj (%)	p-value
$RRt = -63 - 237 \cdot \rho12 + 4{,}12 \cdot fr + 101 \cdot \rho12^2 - 0{,}0401 \cdot fr2 + 1{,}92 \cdot \rho12 \cdot fr$	16,30	0,732
$RTt = -366 + 145 \cdot \rho12 + 10{,}1 \cdot fr + 23 \cdot \rho12^2 - 0{,}069 \cdot fr^2 - 2{,}28 \cdot \rho12 \cdot fr$	76,45	0,064
$fc0 = 201 - 1081 \cdot \rho12 + 4{,}2 \cdot fr - 375 \cdot \rho12^2 - 0{,}137 \cdot fr^2 + 23{,}8 \cdot \rho12 \cdot fr$	80,34	0,039
$fc90 = -203 - 131 \cdot \rho12 + 7{,}85 \cdot fr + 209{,}2 \cdot \rho12^2 - 0{,}0544 \cdot fr^2 - 1{,}70 \cdot \rho12 \cdot fr$	80,11	0,041
$ft0 = -6628 + 14842 \cdot \rho12 + 84 \cdot fr - 6979 \cdot \rho12^2 - 0{,}18 \cdot fr^2 - 112 \cdot \rho12 \cdot fr$	60,71	0,237
$ft90 = -98{,}7 + 491 \cdot \rho12 - 1{,}11 \cdot fr - 106{,}0 \cdot \rho12^2 + 0{,}0352 \cdot fr^2 - 5{,}96 \cdot \rho12 \cdot fr$	61,50	0,226
$fv0 = 345 - 45 \cdot \rho12 - 10{,}7 \cdot fr + 18 \cdot \rho12^2 + 0{,}087 \cdot fr^2 + 0{,}5 \cdot \rho12 \cdot fr$	33,63	0,669
$fs0 = 22{,}6 - 33{,}5 \cdot \rho12 - 0{,}450 \cdot fr - 0{,}00032 \cdot \rho12^2 + 0{,}00127 \cdot fr^2 + 0{,}568 \cdot \rho12 \cdot fr$	60,61	0,238
$fM = -1201 + 488 \cdot \rho12 + 34{,}8 \cdot fr - 1280 \cdot \rho12^2 - 0{,}335 \cdot fr^2 + 15{,}5 \cdot \rho12 \cdot fr$	88,55	0,009
$fh0 = -1351 + 726 \cdot \rho12 + 38{,}1 \cdot fr - 227 \cdot \rho12^2 - 0{,}277 \cdot fr^2 - 6{,}4 \cdot \rho12 \cdot fr$	47,05	0,461
$fh90 = 521 - 766 \cdot \rho12 - 8{,}6 \cdot fr + 226 \cdot \rho12^2 + 0{,}032 \cdot fr^2 + 7{,}9 \cdot \rho12 \cdot fr$	15,30	0,943
$W = 42{,}7 - 61{,}6 \cdot \rho12 - 0{,}843 \cdot fr + 9{,}87 \cdot \rho12^2 + 0{,}00332 \cdot fr^2 + 0{,}824 \cdot \rho12 \cdot fr$	76,70	0,062
$Ec0 = 200260 + 486663 \cdot \rho12 - 10182 \cdot fr - 599178 \cdot \rho12^2 + 64 \cdot fr^2 + 3312 \cdot \rho12 \cdot fr$	71,29	0,108
$Ec90 = -6880 - 17920 \cdot \rho12 + 382 \cdot fr + 4079 \cdot \rho12^2 - 3{,}63 \cdot fr^2 + 195 \cdot \rho12 \cdot fr$	63,07	0,204
$Et0 = -545048 + 1270804 \cdot \rho12 + 6850 \cdot fr - 843401 \cdot \rho12^2 - 38 \cdot fr^2 - 4735 \cdot \rho12 \cdot fr$	45,18	0,494
$EM0 = -448303 - 121785 \cdot \rho12 + 15481 \cdot fr - 179956 \cdot \rho12^2 - 146{,}9 \cdot fr^2 + 5501 \cdot \rho12 \cdot fr$	55,51	0,316

Source: Authors (2023)

In where: *RRt – Total radial retraction; RTt – Total tangential retraction; fc0 – Resist. there is compression parallel to the fibers; fc90 – Resist. there is normal compression to the fibers; ft0 – Resist. to traction parallel to the fibers; ft90 – Resist. to traction perpendicular to the fibers; fv0 – Resist. to shear in the direction parallel to the fibers; fs0 – Resist. to splitting parallel to the fibers; fM – Resist. conventional in the static bending test; fh0 – Hardness parallel to the fibers; fh90 – Hardness perpendicular to the fibers; W – Tenacity; Ec0 – Modulus of elasticity in compression parallel to the fibers; Ec90 – Modulus of elasticity in compression perpendicular to the fibers; Et0 – Modulus of elasticity in traction parallel to the fibers; EM0 – Conventional modulus of elasticity in the static bending test; *Underlined terms refer to regression models significant by ANOVA (p-value < 0.05).

The p-values of the ANOVA residual normality test for all the multiple regression models in Table 5 were greater than 0.05, validating the results of the analysis of variance. Even with the improvement in the precision of the multiple regression models when compared to the simple regression models presented in Figure 2, only three models were considered significant (p-value < 0.05 and R^2aj greater than 80%), which implies that variations in the independent variables do not explain a large part of the variations suffered by the dependent variables, a result that can be improved with the inclusion of new species, and which will consist of the evaluation of future work.

3 CONCLUSIONS

Based on the results obtained and the discussions held, the following conclusions were reached:

The wood of the Cajueiro species studied was classified as medium density and class C30, in the resistance class of dicotyledons (hardwoods), according to ABNT NBR 7190 (1997), and can be used as structural elements in civil construction;

The transverse vibration test proved to be an accurate and reliable technique for assessing the modulus of elasticity of structural parts;

The modulus of elasticity obtained using the transverse vibration method was equivalent to the moduli obtained in the specimens and beams tested in static bending in a non-destructive manner;

The results of the correlation analyses were not superior, possibly due to the number of samples tested, the use of only one species, and the adoption of sample values instead of average values (an approach only possible in research with several species), which resulted in significant linear regression models, but with low precision. Correlations can be improved by increasing the number of samples and including new species, reducing variability, and improving adjustments;

The multiple regression models, generated to improve the precision of the simple linear regression models, presented higher R^2aj than the linear models for only 03 properties (fc0, fc90, and FM) of the 16 evaluated, thus requiring further studies with the objective of verifying such relationships for a greater number of samples and experimental conditions.

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