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TECHNICAL PAPER

APPARENT DENSITY AS AN ESTIMATOR OF WOOD PROPERTIES OBTAINED IN TESTS WHERE FAILURE IS FRAGILE

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KEYWORDS

hardwoods, fragile failure, regression models, analysis of variance.

ABSTRACT

The use of new wood species in construction requires knowledge of their properties for safer and more economical structural sizing. In Brazil, structural projects are carried out according to the standard document ABNT NBR 7190:1997. Tests required by this standard for the complete characterization of species require large machines with high costs, which are present only in large research centers. Considering the lack of experimental determination, this study aimed, with the help of analysis of variance of regression models, to investigate the possibility of estimating, through apparent density, wood properties obtained in tests where failure is considered fragile, allowing the estimation of properties of species still little used. Ten wood species belonging to the hardwood group (cambara, cedro, cedrorana, copaiba, angelim-araroba, castelo, oiticica-amarela, guarucaia, guaicara, and garapa), covering all strength classes established in the standard ABNT NBR 7190:1997, were used. The results showed that shear strength parallel to the grain (f_{v0}) was the only property that could be estimated by apparent density (ρ_{12}), with an R^2 above 50%. Tensile strength normal to the grain (f_{t90}) and splitting strength (f_{s0}) showed poor fit quality.

INTRODUCTION

Wood has been widely used since the dawn of humanity, present in usual human activities, such as overcoming natural obstacles, transportation, agriculture, among others. Being a versatile material, it has always been essential to human needs and its wide availability has been an important factor for a large expansion in its use for constructing structures, bridges, silos, and roofs (Christoforo et al., 2013).

Wood has high strength in relation to its weight, being this ratio three times higher than for steel and ten times higher than for concrete (Calil Júnior & Dias, 1997). It is a biodegradable, reusable, and recyclable material. Wood construction not only requires less energy to obtain the material but also provides low energy consumption over the building's life cycle compared to any other building material. For example, steel and concrete buildings incorporate and consume from 12 to 20% more energy than wood buildings. Building with wood also results in waste reduction, as steel and concrete buildings produce 6 to 16% more solid waste than wood, both in manufacturing and construction (Wang et al., 2014).

Brazil has a significant forest area, either native or planted. According to the Sistema Florestal Brasileiro (2016), the native area has approximately 485.8 million hectares, and the Brazilian Tree Industry (IBÁ, 2017) points out that in 2016 the planted forest area was about 7.84 million hectares. Regarding species diversity, Brazil has about 8,715 tree species in its territory, which corresponds to 14% of the 60,065 species that grow on the planet (Beech et al., 2017).

In Japan, 45% of residential buildings are constructed with wood frame, and, in New Zealand, this percentage is 85%, reaching 90% in North America (Hemstrom, 2016). In Brazil, according to Araujo et al.

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(2018), general industrial costs, tax exemptions, and workforce are the main difficulties encountered for the growth of the wooden housing construction sector. The authors emphasized that it is essential the creation, implementation, and expansion of public policies for the forest products industry, seeking to disseminate sustainable housing as alternatives to the traditional techniques based on non-renewable mineral raw materials, which are currently prevalent in Brazil. Thus, it would be possible to implement significantly cleaner, faster-to-build buildings accessible to all social classes, increasing and improving the production of the entire timber chain and giving this material a high value for its use as a structure in buildings, trying to reach in the future the numbers of European and North-American countries.

Exploring new wood species with the potential to replace those traditionally used in construction is needed, contributing to a more rational consumption and avoiding the increase in prices of the most used species (Lahr et al., 2016). Adequate knowledge of physical and mechanical properties of new wood species is necessary to allow them to be used in the construction of wooden structures and their rational use, contributing to a structural sizing with high safety and economy (Christoforo et al., 2017a).

In Brazil, structural projects are carried out according to the Brazilian Standard ABNT NBR 7190:1997, which guides the structural calculation methods and safety procedures for the sizing of wood structures, also presenting the test methods for the evaluation of the physical and mechanical properties of woods.

Appendix B of the Brazilian Standard presents, on average, fifteen physical and mechanical properties of wood, among which are the tensile strength normal to the grain (f_{t90}), shear strength parallel to the grain (f_{v0}), and splitting strength (f_{s0}). They are determined in tests where failure is considered fragile, as the respective stress-strain diagrams present no yield strength.

Physical and mechanical properties of woods must be determined at 12% moisture, which is the wood equilibrium moisture and, according to ABNT NBR 7190:1997, the standard reference condition for the presentation of experimental results. If the wood has different moisture than the reference, the strength and stiffness values should be corrected in the moisture found for the standard moisture.

The Brazilian Standard presents relationships between the strength values, as provided in item 6.3.3 of NBR 7190, considering usual species and the absence of an experimental determination of all properties. Although Logsdon et al. (2005) have evaluated that there should be a revision of these values to correlate strength properties, this correlation is carried out to facilitate the determination of strengths from a technical point of view, as the complete characterization tests demand the use of more raw material and person-hours, leading to higher costs and, consequently, misuse of material due to lack of knowledge of its properties.

On the other hand, an easily determined property is apparent density. It is defined by the ratio between mass and volume at 12% moisture, requiring a balance and a caliper for its evaluation. Thus, considering that this property is easily determined, several authors have found a relationship between apparent density and wood strength and stiffness properties, such as Christoforo et al. (2017b), who found a significant relationship between compressive strengths parallel and normal to the grain and apparent density. Almeida et al. (2014) also found significant relationships of strength and stiffness properties with apparent density.

Therefore, this study aimed to evaluate, based on the Brazilian Standard ABNT NBR 7190 and regression models based on analysis of variance (ANOVA), the possibility of estimating wood strength properties obtained in tests where failure is fragile, from apparent density.

MATERIAL AND METHODS

Woods from cambara (*Erisma uncinatum* Warm.), cedro (*Cedrela* sp.), cedrorana (*Cedrelinga catenaeformis* Ducke), copaiba (*Copaifera* sp.), angelim-araroba (*Vataireopsis araroba* (Aguiar) Ducke), castelo (*Calycophyllum multiflorum* Griseb.), oiticica-amarela (*Clarisia racemosa* Ruiz & Pav.), guarucaia (*Peltophorum vogelianum* Benth.), guaicara (*Luetzelburgia* sp.), and garapa (*Apuleia leiocarpa* (Vogel) J. F. Macbr.) were adequately stocked and tested in the facilities of the Laboratory of Wood and Wood Structures (LaMEM), São Carlos Engineering School (EESC), University of São Paulo (USP), with moisture contents close to 12%.

Physical and mechanical properties consisted, respectively, of apparent density (ρ_{ap}), tensile strength normal to the grain (f_{t90}), shear strength parallel to the grain (f_{v0}), and splitting strength (f_{s0}), obtained according to the requirements of Appendix B of the Brazilian Standard ABNT NBR 7190 (1997). Twelve specimens were manufactured and tested for each wood species and each property, resulting in 240 experimental determinations. Woods were categorized into strength classes for the hardwood group, according to the characteristic value (Equation 1) obtained from the compressive strength parallel to the grain test (ABNT NBR 7190, 1997).

$$f_{c0,k} = \left(2 \cdot \frac{f_1 + f_2 + f_3 + ... + f_{(n/2)-1}}{(n/2)-1} - f_{n/2} \right) \cdot 1{,}10 \quad (1)$$

The results from Equation 1were placed in ascending order ($f_1 \leq f_2 \leq f_3 \ldots \leq f_n$), disregarding the highest strength value if the number of specimens is odd, not taking for $f_{c0,k}$ a strength value lower than f_1 nor lower than 0.70 of the mean strength value. Table 1 shows the characteristic values and respective framing of the species into the strength classes of the Brazilian Standard.

TABLE 1. Categorization of wood species into strength classes of the hardwood group.

Species	$f_{c0,k}$ (MPa)	Strength class
Cambara (Ca-Ro)	23.71	C20
Cedro (C-Am)	25.64	C20
Cedrorana (Ced)	36.24	C30
Copaiba (Co)	34.86	C30
Angelim-araroba (Ang)	42.92	C40
Castelo (Ca)	45.73	C40
Oiticica-amarela (O-Am)	53.84	C50 (arbitrated)
Guarucaia (Guar)	56.45	C50 (arbitrated)
Guaicara (Gua)	66.40	C60
Garapa (Gar)	63.28	C60

Table 1 shows that woods were chosen according to the criterion of classification into strength classes of the Brazilian Standard, allowing a higher generalization of results. In this sense, the strength class C50 (Oiticica-amarela and guarucaia) was incorporated for the development of this research.

Analysis of variance (ANOVA) and Tukey test, both at a 5% significance level, were used to investigate the influence of factor wood species on the evaluated physical and mechanical properties. To validate both, the normality of residual distribution of ANOVA was tested using the Anderson-Darling test, also at a 5% significance level. Considering the assumptions, a P-value (probability P) equal to or higher than the significance level implies accepting that the residual distribution is normal (acceptance of the null hypothesis – H_0), but not normal (alternative hypothesis – H_1) otherwise (P-value<0.05).

From the Tukey test, A denotes the group with the highest mean value, B denotes the group with the second-highest mean value and so on, and equal letters imply treatments with statistically equivalent means. Two-parameter regression models (Equations 2 to 5) based on ANOVA (at 5% significance level) were used in an attempt to estimate the strength values evaluated as a function of apparent density.

$$Y = \alpha_0 + \alpha_1 \cdot \rho_{ap} + \varepsilon \quad [\text{Linear – Lin}] \tag{2}$$

$$Y = \alpha_0 \cdot e^{\alpha_1 \cdot \rho_{ap}} + \varepsilon \quad [\text{Exponential – Exp}] \tag{3}$$

$$Y = \alpha_0 + \alpha_1 \cdot Ln\left(\rho_{ap}\right) + \varepsilon \quad [\text{Logarithmic – Log}] \tag{4}$$

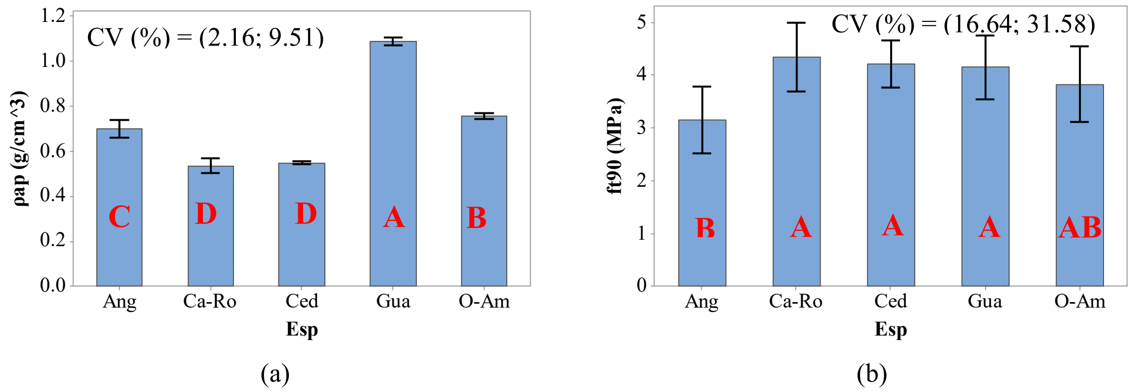
$$Y = \alpha_0 + {\rho_{ap}}^{\alpha_1} + \varepsilon \quad [\text{Geometric – Geo}] \tag{5}$$

From eqs (2) to (5), Y denotes the dependent variable (f_{t0}, f_{v0}, and f_{s0}), α_0 and α_1 are the parameters fit by the least-squares method, and ε is the random error. In addition, regression models were used for each species and the set involving all species.

Fit quality was evaluated by the coefficient of determination (R^2), and model significance was evaluated by the P statistics (P-value). From the hypotheses formulated in the analysis of variance of regression models, a P-value higher than or equal to 5% implies that the fit model (H_0) is not representative, but significant (P-value<0.05) otherwise. The ANOVA approach of regression models makes it possible, regardless of the fit quality (R^2), to show the effective relationship between the compared properties, which is essential for studies involving the analysis of results with wood due to their intrinsic variability (Christoforo et al., 2017a).

RESULTS AND DISCUSSION

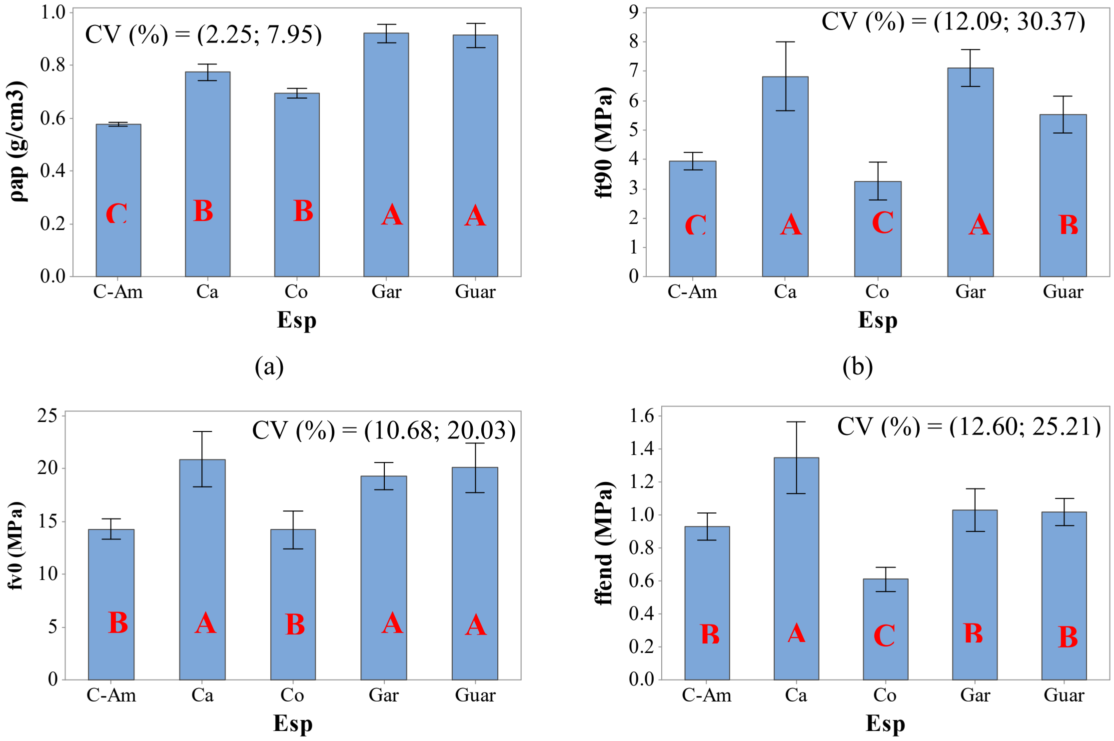
Figure 1 shows the mean values, extreme values of coefficient of variation (CV), confidence intervals of the mean (at 95% confidence level), and results of the Tukey test (factor = wood species - Esp) of physical and mechanical properties investigated as a function of woods from cambara (Ca-Ro), cedrorana (Ced), angelim-araroba (Ang), oiticica-amarela (O-Am), and guaicara (Gua). On the other hand, Figure 2 shows the results for woods from cedro (C-Am), castelo (Ca), copaiba (Co), garapa (Gar), and guarucaia (Guar).



(a) (b)

(c) (d)

FIGURE 1. Results of the evaluated physical and mechanical properties.



(a) (b)

(c) (d)

FIGURE 2. Results of the evaluated physical and mechanical properties.

The P-values of the Anderson-Darling normality test on ANOVA residuals of physical and mechanical properties ranged from 0.107 to 0.673, validating the ANOVA results and, consequently, the Tukey test.

The Tukey test (Figures 1 and 2) showed that cambara and cedrorana, although belonging to distinct strength classes, are statistically equivalent regarding the mean apparent densities, which may negatively affect the estimates generated by the regression models. Similarly, castelo and copaiba showed statistically equivalent apparent densities, even belonging to different strength classes (C40 and C30, respectively). It was also observed for angelim-araroba (C40) and cedro (C20). The species guaicara, garapa, and guarucaia also presented equivalent apparent densities.

The mean values of f_{t90} for the species cambara, cedrorana, guaicara, castelo, and garapa are statistically equivalent. For this same property, the species copaiba and cedro presented equivalence between their mean values, which was also observed for the species angelim-araroba and guarucaia. The species oiticica-amarela showed mean values of f_{t90} statistically equivalent to the woods angelim-araroba, guarucaia, cambara, cedrorana, guaicara, castelo, and garapa.

The species angelim-araroba, cambara, and cedrorana were considered statistically equivalent regarding f_{v0}. The same behavior was observed for guaicara, castelo, garapa, and guarucaia. Oiticica-amarela, cedro, and copaiba also presented equivalent mean shear strengths.

The species angelim-araroba, cambara, cedro, garapa, and guarucaia had equivalent f_{s0}, which was also observed for guaicara and castelo, while cedrorana and oiticica-amarela had an f_{s0} equivalent to the other studied species, except for copaiba, which did not show splitting strength equivalent to other species.

Similar density values were determined by Grobério & Lahr (2002) for cedrorana (570 kg/m^3), angelim-araroba (680 kg/m^3), and guaicara (1090 kg/m^3), Christoforo et al. (2016) and Almeida et al. (2016) for angelim-araroba (690 and 700 kg/m^3, respectively), and Aquino et al. (2018) for copaiba (700 kg/m^3).

Lahr et al. (2016) determined a mean value of apparent density of 680 kg/m^3 for cambara wood. Dias & Lahr (2004) found mean values of apparent density of 566, 674, 756, and 995 kg/m^3 for cedrorana, angelim-araroba, oiticica, and guaicara, respectively.

Araújo (2007) obtained mean values of tensile strength normal to the grain (f_{t90}) of 4.41 MPa for cedrorana wood. Dias & Lahr (2004) found f_{t90} values corresponding to 3.10 MPa for angelim-araroba and cedrorana woods and 3.90 MPa for oiticica and guaicara woods. Aquino et al. (2018) obtained a mean value of f_{t90} corresponding to 3.00 MPa for copaiba wood.

Grobério & Lahr (2002) determined mean values of shear strength parallel to the grain (f_{v0}) of 11.3 MPa for angelim-araroba, 11.90 MPa for cedrorana, and 20.80 MPa for guaicara. Aquino et al. (2018) found an f_{v0} value corresponding to 15 MPa for copaiba wood.

Regarding splitting strength (f_{s0}), Dias & Lahr (2004) found mean values of 0.40, 0.60, 0.70, and 0.60 MPa for angelim-araroba, cedrorana, guaicara, and oiticica, respectively. Grobério & Lahr (2002) obtained mean values of f_{s0} of 0.6 MPa for angelim-araroba and cedrorana woods and 0.7 MPa for guaicara wood. Aquino et al. (2018) found a value of f_{s0} of 0.60 MPa for copaiba wood.

Tables 2 and 3 show the best models (classified by the coefficient of determination) obtained considering the species in isolation, while Table 4 shows the best fit for the group involving all species.

TABLE 2. Best fit obtained by wood species (cambara, cedrorana, angelim-araroba, oiticica-amarela, and guaicara).

Species	Model	R^2 (%)	P-value
Cambara	$f_{t90} = 4.74 + 0.64 \cdot Ln(\rho_{ap})$ [Log]	0.38	0.849
	$f_{v0} = 13.73 + 5.00 \cdot Ln(\rho_{ap})$ [Log]	4.75	0.496
	$f_{fend} = 0.61 - 0.22 \cdot \rho_{ap}$ [Lin]	2.08	0.654
Species	**Model**	**R^2 (%)**	**P-value**
Cedrorana	$f_{t90} = 8.36 + 6.83 \cdot Ln(\rho_{ap})$ [Log]	5.19	0.477
	$f_{v0} = 9.33 \cdot e^{0.36 \cdot \rho_{ap}}$ [Exp]	0.24	0.879
	$f_{fend} = 1.00 + 0.59 \cdot Ln(\rho_{ap})$ [Log]	0.51	0.862
Species	**Model**	**R^2 (%)**	**P-value**
Angelim-araroba	$f_{t90} = 0.04 + 4.43 \cdot \rho_{ap}$ [Lin]	7.64	0.384
	$f_{v0} = -1.19 + 16.63 \cdot \rho_{ap}$ [Lin]	7.94	0.375
	$f_{fend} = 0.67 - 0.13 \cdot \rho_{ap}$ [Lin]	0.47	0.832
Species	**Model**	**R^2 (%)**	**P-value**
Oiticica-amarela	$f_{t90} = 26.96 \cdot {\rho_{ap}}^{7.11}$ [Geo]	37.51	0.034
	$f_{v0} = 3.65 + 18.45 \cdot \rho_{ap}$ [Lin]	3.40	0.566
	$f_{fend} = -1.49 + 2.82 \cdot \rho_{ap}$ [Lin]	5.24	0.474
Species	**Model**	**R^2 (%)**	**P-value**
Guaicara	$f_{t90} = -5.99 + 9.33 \cdot \rho_{ap}$ [Lin]	6.40	0.427
	$f_{v0} = 302.34 \cdot e^{-2.49 \cdot \rho_{ap}}$ [Exp]	40.19	0.027
	$f_{fend} = -0.36 + 0.29 \cdot \rho_{ap}$ [Lin]	3.70	0.549

TABLE 3. Best fit obtained by wood species (cedro, copaiba, castelo, guarucaia, and garapa).

Species	Model	R^2 (%)	P-value
Cedro	$f_{t90} = 25.70 \cdot {\rho_{ap}}^{3.41}$ [Geo]	42.93	0.021
	$f_{v0} = 7.78 \cdot {\rho_{ap}}^{-1.08}$ [Geo]	4.84	0.492
	$f_{fend} = 1.50 \cdot {\rho_{ap}}^{0.88}$ [Geo]	2.11	0.652
Species	**Model**	**R^2 (%)**	**P-value**
Copaiba	$f_{t90} = 228.88 \cdot e^{-6.16 \cdot \rho_{ap}}$ [Exp]	33.77	0.031
	$f_{v0} = 11.52 - 7.03 \cdot Ln(\rho_{ap})$ [Log]	1.11	0.758
	$f_{fend} = 0.44 - 0.54 \cdot Ln(\rho_{ap})$ [Log]	3.54	0.579
Species	**Model**	**R^2 (%)**	**P-value**
Castelo	$f_{t90} = 3.22 + 4.69 \cdot \rho_{ap}$ [Lin]	1.63	0.692
	$f_{v0} = -5.20 + 33.73 \cdot \rho_{ap}$ [Lin]	18.88	0.158
	$f_{fend} = 5.18 \cdot e^{-1.75 \cdot \rho_{ap}}$ [Exp]	13.24	0.244
Species	**Model**	**R^2 (%)**	**P-value**
Guarucaia	$f_{t90} = 3.49 + 2.25 \cdot \rho_{ap}$ [Lin]	2.69	0.610
	$f_{v0} = 21.18 \cdot {\rho_{ap}}^{0,83}$ [Geo]	14.98	0.213
	$f_{fend} = 0.39 \cdot e^{1.07 \cdot \rho_{ap}}$ [Exp]	35.90	0.039

TABLE 3 (CONTINUATION). Best fit obtained by wood species (cedro, copaiba, castelo, guarucaia, and garapa).

Species	Model	R^2 (%)	P-value
Garapa	$f_{t90} = 1.40 + 6.21 \cdot \rho_{ap}$ [Lin]	12.08	0.268
	$f_{v0} = 20.07 \cdot \rho_{ap}^{0.56}$ [Geo]	10.05	0.315
	$f_{fend} = 3.56 - 2.83 \cdot \rho_{ap}$ [Lin]	56.68	0.005

TABLE 4. Best fit obtained for the group with all wood species.

Model	R^2 (%)	P-value
$f_{t90} = 5.39 + 2.37 \cdot Ln\left(\rho_{ap}\right)$ [Log]	10.87	0.002
$f_{v0} = 20.49 + 14.59 \cdot Ln\left(\rho_{ap}\right)$ [Log]	51.27	0.000
$f_{fend} = 0.90 \cdot \rho_{ap}^{0.56}$ [Geo]	11.95	0.000

Tables 2 and 3 show that only six models were considered significant by ANOVA (P-value< 0.05), which consisted of the relationships $f_{t90} = f(\rho_{ap})$ (geometric) for oiticica-amarela ($R^2 = 37.51\%$), $f_{v0} = f(\rho_{ap})$ (exponential) for guaicara ($R^2 = 40.19\%$), $f_{t90} = f(\rho_{ap})$ (geometric) for cedro ($R^2 = 42.93\%$), $f_{t90} = f(\rho_{ap})$ (exponential) for copaiba ($R^2 = 33.77\%$), $f_{s0} = f(\rho_{ap})$ (exponential) for guarucaia ($R^2 = 35.90\%$), and $f_{s0} = f(\rho_{ap})$ (linear) for garapa ($R^2 = 56.68\%$). Aquino et al. (2018) found no significant model for the fragile relationships of copaiba wood.

The three estimated mechanical properties were considered significant for the set involving all species (Figure 3 and Table 4).

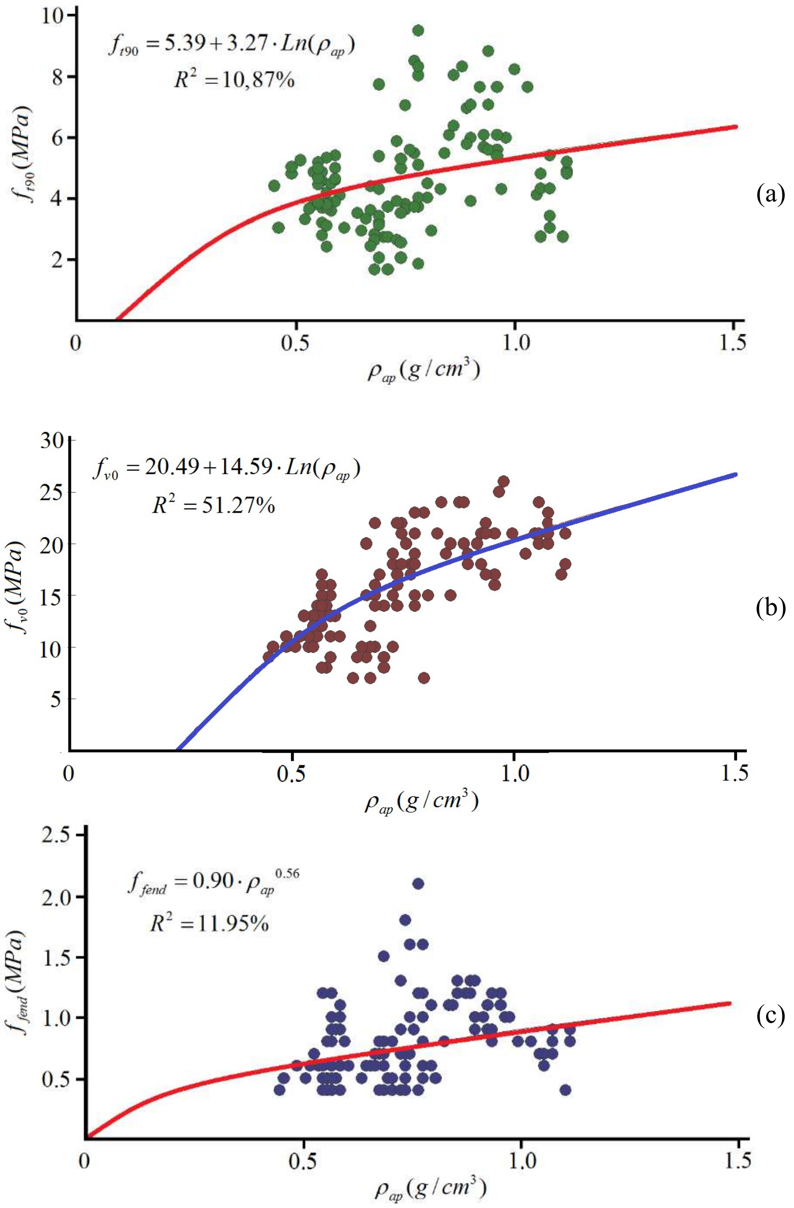


FIGURE 3. Regression models for the set of all species: $f_{t90}(\rho_{ap})$ (a), $f_{v0}(\rho ap)$ (b), and $f_{s0}(\rho_{ap})$ (c).

Table 4 shows all fragile properties estimated as a function of apparent density. The best fit ($R^2 = 10.87\%$) to estimate the tensile strength normal to the grain was the logarithmic model (Figure 3a). The logarithmic model (Figure 3b) obtained for the estimation of shear strength parallel to the grain provided a coefficient of determination equal to 51.27%, while the coefficient of determination of exponential fit (Figure 3c) obtained for the estimation of splitting strength was 11.95%, both being considered significant by ANOVA of regression models.

Lahr et al. (2016) performed the complete characterization of wood species *E. uncinatum*. The possibility of estimating physical and mechanical properties as a function of apparent density (ρ_{ap}) was evaluated. ANOVA provided non-significant results for the regression models of the obtained properties in tests where failure is considered fragile.

Similarly, Christoforo et al. (2017b) performed the complete characterization of wood species *C. multiflorum*. The possibility of estimating physical and mechanical properties as a function of apparent density (ρ_{ap}) was evaluated. This wood was categorized in the strength class D40, according to the Brazilian Standard ABNT NBR 7190 (1997). They found that the fragile strength properties could not be estimated by apparent density. Regression models by ANOVA provided non-significant results with poor fit quality.

Christoforo et al. (2017a) also carried out the complete characterization of *Anadenanthera colubrina*. This wood was categorized into the strength class D40, according to the Brazilian Standard ABNT NBR 7190 (1997). The relationships between apparent density and fragile properties (f_{t90}, f_{v0}, and f_{s0}) were evaluated using regression models. ANOVA indicated non-significant results and poor fit for fragile properties.

Silva et al. (2018) found, from regression models, a relationship between fragile properties (f_{t90}, f_{v0}, and f_{s0}) and apparent density (ρ_{12}). Cupiuba (*Goupia glabra* Aubl.), extracted from three different locations, was classified into strength classes D30, D40, and D50, with each lot classified into a distinct class. Regression models were significant, with coefficients of determination ranging from 64 to 78%.

The analysis relating all woods allowed minimizing the inherent variability of each species (Icimoto et al., 2015; Machado et al., 2013), which corroborated the results obtained in the regression models shown in Table 4.

Moreover, Christoforo et al. (2017a) also found a significant model to estimate shear strength parallel to the grain (f_{v0}) as a function of apparent density. This important property is used to size wooden structures, and its relationship with apparent density reinforces its importance.

The poor quality in fitting tensile strength normal to the grain (f_{t90}) and splitting strength (f_{s0}) may be justified by its failure mode, partly justified by anatomical wood issues. These considerations should be evaluated in future researches, as there are no studies in the literature dealing with these relationships.

CONCLUSIONS

The results obtained with regression models for ten wood species analyzed in this study, which cover all strength classes of the Brazilian Standard ABNT NBR 7190, indicate that the only property that can be estimated as a function of apparent density (ρ_{12}) is the shear strength parallel to the grain (f_{v0}), being the logarithmic model the best fit. The poor fit quality of the other fragile properties (f_{t90} and f_{s0}) may be partly explained by anatomical wood issues, and further studies would be necessary to consider this variable.

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