

Models to Estimate Longitudinal Compressive Strength of Brazilian Hardwood Based on Apparent Density

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As wood is an orthotropic and natural material, there are several properties required for its use in civil construction. The apparent density has been used to estimate physical and mechanical properties of wood, as it is easy to determine experimentally, unlike other determinations, which involve the use of equipment available only in large research centers. Using the Brazilian standard ABNT NBR 7190 and linear and non-linear regression models, this research aimed to evaluate their accuracy in estimating the compressive strength parallel to the fibers (f_{c0}) as well as their characteristic value ($f_{c0,k}$). This study considered 72 tropical wood species from native forests that were divided into the 4 strength classes of this standard. For the set formed by all species, the linear polynomial model was the best fit, resulting in a determination coefficient of just over 70%.

Keywords: Hardwoods; Longitudinal compressive strength; Apparent density; Regression models

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INTRODUCTION

Wood is a material with excellent structural properties, mainly because it has strength in traction and compression. Another important point is that it is a renewable resource, unlike steel and concrete, which are other materials commonly used in construction (Pigozzo *et al.* 2018a). According to Bacha (2017), Brazil stands out on the international scene for its extensive tropical native forests and for planting homogeneous forests with exotic species. Also, Brazil has 493.5 million hectares of forests, which is equivalent to 12% of the world's forests.

The Brazilian standard ABNT NBR 7190 (1997), which establishes the premises and methods for wooden structures design, defines four strength classes for the categorization of any hardwood species for structural purposes. This classification is based on the characteristic compressive strength value in the direction parallel to the fibers ($f_{c0,k}$), as shown in Table 1, where $E_{c0,m}$ consists of the mean value of the elasticity module to compression in the direction parallel to the fibers and $\rho_{12\%}$ is the apparent density relative to the equilibrium moisture content (12%) considered by the standard.

Table 1. Strength Classes of Hardwoods According to ABNT NBR 7190 (1997)

Classes	Range	$E_{c0,m}$ (MPa)	$\rho_{12\%}$ (kg/m ³)
C20	$20 \leq f_{c0,k} < 30$ MPa	9500	650
C30	$30 \leq f_{c0,k} < 40$ MPa	14500	800
C40	$40 \leq f_{c0,k} < 60$ MPa	19500	950
C60	$f_{c0,k} \geq 60$	24500	1000

For designing, it is ideal to know all the material properties of strength and stiffness to be used (Oliveira *et al.* 2019). For wood, an orthotropic material, several tests are necessary to obtain the properties of interest, some of which are performed using specialized equipment, available only in large research centers. In addition to the simplified method contained in ABNT NBR 7190 (1997), an alternative process that establishes relationships between characteristic values of strength to certain stresses consists of estimating the properties (physical or mechanical) using apparent density as a dependent variable (Adamopoulos and Passialis 2010; Pigozzo *et al.* 2018b).

The apparent density is a property that is easily determined experimentally, defined by the ratio between the mass and the volume of the sample at 12% humidity, as indicated in the 1997 standard, ABNT NBR 7190 (Pigozzo *et al.* 2018c). Thus, the estimation of other wood properties with just one simple test is extremely valuable (Almeida *et al.* 2019; Wolenski *et al.* 2020; Almeida *et al.* 2020), allowing the engineer to carry out structural design easily and effectively (Lahr *et al.* 2016).

There are several reports using apparent density as an estimator of physical and mechanical properties of wood from native Brazilian forests (Lahr *et al.* 2016; Almeida *et al.* 2017; Christoforo *et al.* 2017). However, few studies that have considered the number of species (72) evaluated in the present research, which makes it possible to effectively verify the accuracy and generality of the use of apparent density, via regression models, in the estimation of the strength to parallel compression (f_{c0}) and its associated characteristic value ($f_{c0,k}$). It is also noteworthy that, depending on the precision of the models to be obtained, they can be used in the pre-classification of the wood right after its cut (pre-classification in loco) and naturally in the design of structures by incorporating such results (models) in future versions of the Brazilian standard ABNT NBR 7190 (1997).

With that in mind, this research aimed to estimate, using the linear and nonlinear regression models and the Brazilian standard ABNT NBR 7190 (1997), the precision in the estimation of the compressive strength parallel to the fibers (f_{c0}) and the characteristic value ($f_{c0,k}$) by means of the apparent density considering 72 species of hardwood from native Brazilian forests.

EXPERIMENTAL

Materials

The 72 species considered in the present study are shown in Table 2. The wood from homogeneous lots was properly stored in a greenhouse, resulting in a moisture content close to 12% in accordance with ABNT NBR 7190 (1997). Twelve specimens per species were manufactured and tested in parallel compression to the fibers (Fig. 1), and another twelve specimens were used to determine the apparent density values, resulting in 1728 experiments.

Table 2. Wood Species Evaluated

Common Name	RC	Common Name	RC	Common Name	RC
Amescla	C20	Canela Parda	C40	Peroba Mica	C60
Caixeta	C20	Canelão	C40	Umirana	C60
Cajueiro	C20	Casca Grossa	C40	Angelim Ferro	C60
Cambará	C20	Copaíba	C40		
Cambará Rosa	C20	Cupiúba	C40	Angelim Vermelho	C60
Cedro Doce	C20	Goiabão	C40	Angico Preto	C60
Cedro	C20	Louro Verde	C40	Breu Vermelho	C60
Cedroarana	C20	Mirarema	C40	Champanhe	C60
Marupá	C20	Piolho	C40	Cutiúba	C60
		Quaruba Rosinha	C40	Garrote	C60
Quarubarana	C20	Rabo de Arraia	C40	Guajará	C60
Cambará	C30	Angelim Pedra	C60	Ipê	C60
Castanheira	C30			Itaúba	C60
Cedro Amazonense	C30	Angelim Saia	C60		
Cedro	C30	Casca Grossa	C60	Jatobá	C60
Cupiúba	C30	Castelo	C60		
Embireira	C30	Catanudo	C60	Maçaranduba	C60
Tauari	C30	Envira Branca	C60		
		Envira	C60	Mandioqueira	C60
Abiú	C40	Garapa	C60	Oiuchu	C60
Angelim Amargoso	C40	Guaíçara	C60	Quina Rosa	C60
Angelim Araroba	C40	Guanandi	C60	Roxinho	C60
Angico Branco	C40	Guarucaia	C60	Sucupira	C60
Bicuíba	C40	Ipê	C60	Tachi	C60
Branquilho	C40	Louro Preto	C60	Tatajuba	C60
Cafearana	C40	Oiticica Amarela	C60		
Canafistula	C40	Parinari	C60		

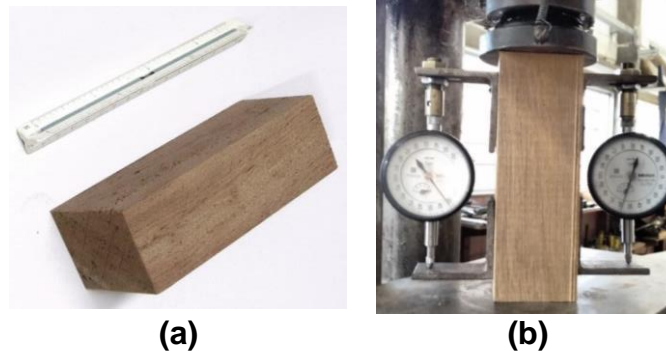


Fig. 1. a) Standardized specimen illustration (5 x 5 x 15 cm -- ABNT NBR 7190, 1997); and b) the apparatus used to perform the compression tests parallel to the grain

The specimens were tested on the universal testing machine (AMSLER, 25-ton load capacity, São Carlos, Brazil). Their moisture content (U) at the test time was obtained using the Marrari M5 contact humidity meter ($10.22\% \leq U \leq 12.73\%$; São Carlos, Brazil).

Methods – Characteristic Strength

With the sample moisture content obtained, the values of strength to parallel compression (f_{c0}) and consequently the characteristic values ($f_{c0,k}$) were corrected to a

moisture content of 12% (Eq. 1), in which $f_{c0,U}$ is the strength of the sample associated with the moisture content U and $f_{c0,12}$ is the strength with 12% moisture.

$$f_{c0,12} = f_{c0,U} \cdot \left[1 + \frac{2 \cdot (U - 12)}{100} \right] \quad (1)$$

Based on the corrected values of compressive strength in the direction parallel to the fibers ($f_{c0,12}$), Eq. 2 was used to determine the characteristic value ($f_{c0,k}$) for wood categorization, where f_1, f_2, \dots, f_n denote the compressive strength values in ascending order of the 12 (n) specimens tested (ABNT NBR 7190 1997).

$$f_{c0,k} = \text{Max} \left\{ \begin{array}{l} f_1 \\ 0.7 \cdot \frac{\sum_{i=1}^n f_i}{n} \\ 1.1 \cdot \left[2 \cdot \left(\frac{f_1 + f_2 + f_3 + \dots + f_{(n/2)-1}}{(n/2) - 1} \right) - f_{n/2} \right] \end{array} \right. \quad (2)$$

Methods – Regression Models

In Eqs. 3 to 7, linear and nonlinear regression models used to estimate the values of f_{c0} and $f_{c0,k}$ as a function of apparent density ($\rho_{12\%}$) are presented, in which $\beta_0, \beta_1,$ and β_2 consist of the parameters to be adjusted by the least squares method.

$$f_{c0}(\rho_{12\%}) = \beta_0 \cdot \rho_{12\%} + \beta_1 \quad (3)$$

$$f_{c0}(\rho_{12\%}) = \beta_0 \cdot \ln(\rho_{12\%} + \beta_1) + \beta_2 \quad (4)$$

$$f_{c0}(\rho_{12\%}) = \beta_0 \cdot \rho_{12\%}^{\beta_1} + \beta_2 \quad (5)$$

$$f_{c0}(\rho_{12\%}) = e^{\left(\beta_0 + \frac{\beta_1}{\rho_{12\%} + \beta_2} \right)} \quad (6)$$

$$f_{c0}(\rho_{12\%}) = (\beta_0 + \beta_1 \cdot \rho_{12\%})^2 \quad (7)$$

For f_{c0} , regression models were generated for each of the four strength classes (Table 1) and also for the set involving the 72 species. For $f_{c0,k}$ a model was obtained considering only the set of all species. It should be noted that $f_{c0,k}$ is the property that categorizes a given species of wood in one of the strength classes of the Brazilian standard. Predictive models were evaluated using the coefficient of variation (CV – Eq. 8), the average absolute percentage error (MAPE – Eq. 9), and the determination coefficient (R^2 – Eq. 10).

$$CV(\%) = 100 \cdot \frac{\sqrt{\frac{\sum_{i=1}^n (Y_{predict_i} - Y_{data_i})^2}{n}}}{\bar{Y}_{data}} \quad (8)$$

$$MAPE(\%) = 100 \cdot \frac{1}{n} \cdot \sum_{i=1}^n \left\| \frac{Y_{predict_i} - Y_{data_i}}{Y_{data_i}} \right\| \quad (9)$$

$$R^2(\%) = 100 \cdot \left(1 - \frac{\sum_{i=1}^n (Y_{predict_i} - Y_{data_i})^2}{\sum_{i=1}^n (Y_{data_i} - \bar{Y}_{data})^2} \right) \quad (10)$$

From Eqs. 8 to 9, n is the considered sample's number, $Y_{predict_i}$ (f_{c0} or $f_{c0,k}$) is the value estimated by the regression model, Y_{data_i} is the experimentally determined value, and \bar{Y}_{data} is the property average value obtained experimentally.

RESULTS AND DISCUSSION

Physical and Mechanical Properties

Figure 2 shows the results of apparent density, compression strength parallel to fibers, and the characteristic value of strength to parallel compression, with CV being the variation coefficient. The CV is presented showing the lowest and highest values obtained in all studied species (20 to 60), proving the quality of the tests performed. The bars represent the confidence intervals of the averages (the average varies from the lowest to the highest value shown in the bars), using 95% reliability.

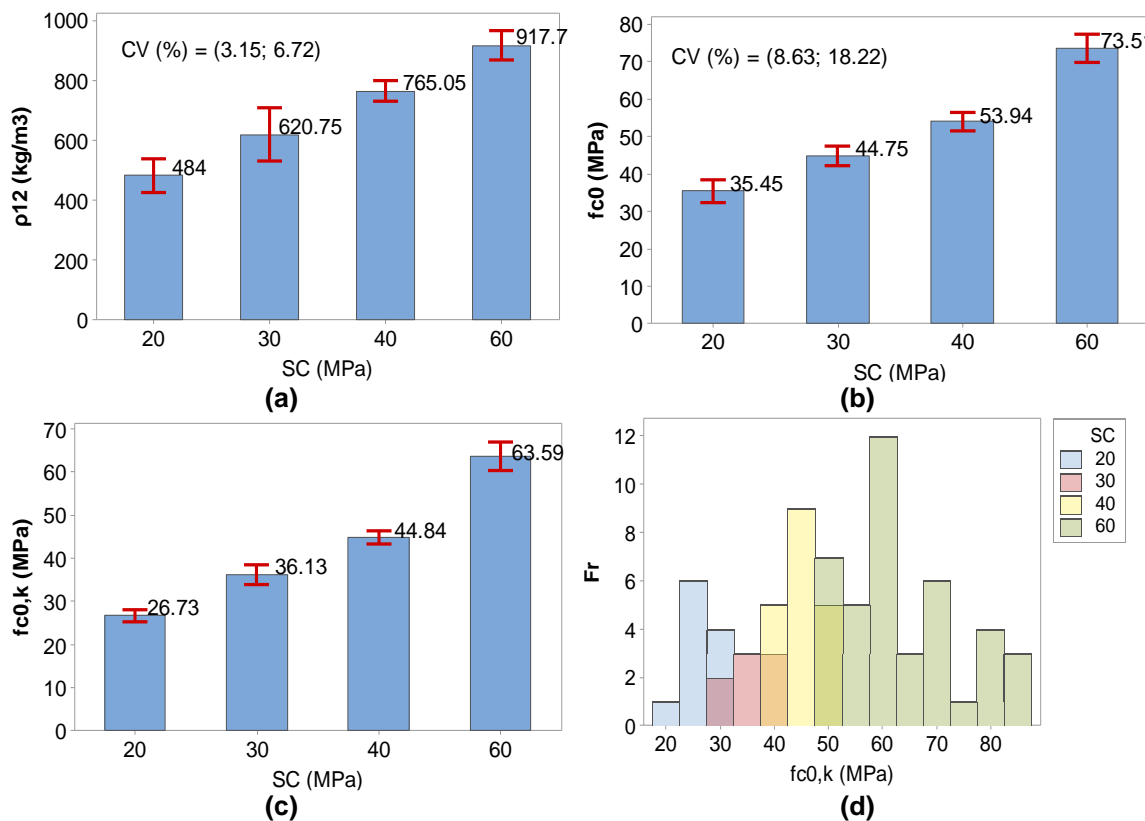


Fig. 2. Results obtained in the tests performed: a) bulk density; b) compression parallel to the fibers; c) shear parallel to the fibers; and d) species frequency by strength class

From Fig. 2, the average values of apparent density by strength classes were all lower than the reference values presented in Table 1. It should be noted that after almost 23 years, the species number considered in this research is surely higher than the species number that gave rise to the results in Table 1. There is a trend of linear relationship when the values of f_{c0} with $\rho_{12\%}$, and $f_{c0,k}$ with $\rho_{12\%}$, are observed.

The compressive strength results clearly increase progressively with the increase in the strength class, evidencing that the variation coefficient was less than 18%, as required by ABNT NBR 7190 (1997) for normal stresses. Of the characteristic values, 13.92% of the species were classified in class C20, 10.13% were class C30, 24.10% were class C40, and 51.85% in class C60.

Regression Models

Table 3 presents the best adjustments (considering Eqs. 3 to 7) by strength class for the estimate of f_{c0} as well as the models of f_{c0} and $f_{c0,k}$ considering the results for the 72 wood species.

Table 3. Better Adjustments by Strength Class and for the Set Considering All Wood Species

SC	Regression Adjustment	CV (%)	MAPE (%)	R ² (%)	R ² adj
20	$f_{c0}(\rho_{12\%}) = e^{\left(3.39 - \frac{41.32}{\rho_{12\%} - 742.13}\right)}$	10.73	9.81	19.97	15.35
30	$f_{c0}(\rho_{12\%}) = 1.96 \cdot \ln(\rho_{12\%} - 496.20) + 36.51$	2.26	2.33	83.76	74.87
40	$f_{c0}(\rho_{12\%}) = e^{\left(3.92 - \frac{62.33}{\rho_{12\%} - 1.25 \cdot 10^3}\right)}$	10.81	8.91	23.44	20.12
60	$f_{c0}(\rho_{12\%}) = 8.36 \cdot \ln(\rho_{12\%} - 643.21) + 33.11$	10.09	8.38	11.45	7.54
All Species	$f_{c0}(\rho_{12\%}) = 0.074 \cdot \rho_{12\%} + 1.80$	14.67	11.19	73.30	65.32
All Species	$f_{c0,k}(\rho_{12\%}) = 0.068 \cdot \rho_{12\%} - 2.562$	16.76	13.54	71.20	64.87

The regression models for the f_{c0} estimate by strength classes, with the exception of C30, showed little precision (less than 23.44%). These results are due to the small variation in density within the strength classes, implying that it is not possible to capture a trend of behavior between $\rho_{12\%}$ and f_{c0} with the increase in apparent density values. Such a result can also be seen by the regression models (best adjustments) not being the same in all strength classes.

For class C30, which corresponds to 10.13% of the total evaluated species, the value of R² (83.76%) is indicative of a strong relationship between anatomy, apparent density, and strength to compression parallel to the fibers (Duarte *et al.* 2020). It should be noted that the same precision degree (R² = 19.97%) was not obtained for class C20, even with a higher number of species (13.92% of the total) when compared to C30.

For the set involving all species, both for the estimate of f_{c0} and $f_{c0,k}$, the linear model consisted of the best fit, resulting in determination coefficients close to 70%, which implies that the error made in these variables is around 30% (Montgomery 2013). As the species number is significant, the failure to obtain even more accurate models is an indication that other variables should be used in wood properties prediction, such as chemical constituents and anatomical parameters. However, it is noteworthy that the essence of this research was to verify the model's accuracy considering only the apparent

density, as it is a property of easy experimental determination, thus collaborating to enable the more rational use of wood in structural projects, results that should be considered in new versions of the Brazilian standard ABNT NBR 7190 (1997).

The research presented by Christoforo *et al.* (2020) also evaluated the apparent density as an estimator of other properties of 10 hardwood species. However, based on just the density data it was not possible to estimate any properties of these woods. Unlike the present study, the authors used only linear, exponential, logarithmic, and geometric models, which may help to account for a bad fit. The same is confirmed in the work of Almeida *et al.* (2017), in which these adjustments were not optimal to estimate most of the properties analyzed. The apparent density was able to estimate only the basic density and anhydrous density, obtaining a quality of 72.9% and 99.7%, respectively, using the geometric model.

Figure 3 shows the adjustments obtained in the estimate of f_{c0} and $f_{c0,k}$ considering the set of all species. It is possible to note that the higher the density of the wood species, the greater its compression strength. This may be due to denser structures having a higher proportion of lignin.

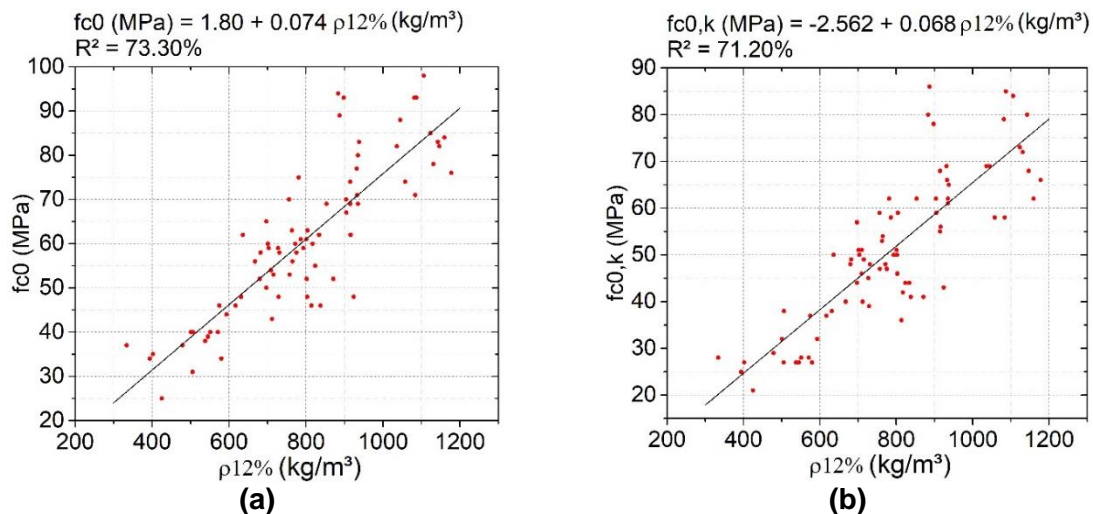


Fig. 3. a) regression model using the apparent density as an estimation of the compressive strength parallel to the fibers; and b) regression model using apparent density as an estimation of the compressive strength parallel to the characteristic fibers.

CONCLUSIONS

1. The small variation in apparent density within a given strength class, with the exception of C30, implies that regression models cannot be used effectively to estimate of compressive strength in the direction parallel to the fibers (f_{c0}) within that class.
2. With all species considered, the linear regression model was the best fit, both for estimating f_{c0} and predicting its characteristic value ($f_{c0,k}$).
3. Because the determination coefficient was close to 70% (slightly higher), the linear regression models obtained in the present study are presented as alternatives in the compressive strength estimation as well as for the pre-classification of a given species. These findings should be taken into consideration in future versions of the Brazilian normative document ABNT NBR 7190 (1997).

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