Estimation of Toughness as a Function of Compression Strength Parallel to the Grain of Tropical Woods

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Tropical species are widely used in construction, and their physical and mechanical properties have been important characteristics with direct impact on the design of structures, especially the strength and stiffness of wood applied in them. Tests to obtain both parameters are conducted under ABNT NBR 7190 (1997) guidelines in Brazil, being rarely found in some research centers because of the higher costs of testing equipment. For instance, the toughness test depends on equipment with a pendulum, whose device requires accuracy and maintenance for reliable analyses. This paper aims to estimate toughness through another property more easily found, given by the compression strength parallel to the grain. For this, 20 tropical wood species of the South American region were used to obtain initial values of these properties. The characteristic values of the compression strength parallel to the grain as well as linear and quadratic regression models were obtained. Statistical analysis was performed and confirmed that a linear model gave better predictions than a quadratic model.

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INTRODUCTION

Because of extensive forests with numerous species, Brazil is among the largest global wood producers. Wood is used in construction due to its adequate performance.

Solid woods, from natural and processed types, are indispensable materials for 17 different timber construction techniques. Timber buildings are produced through a rich possibility of exotic and native woods. About 50 wood species have been commercially utilized in Brazil, including 40 species naturally originating in this tropical region (De Araujo 2021a,b). This diversity justifies the importance of knowing physico-mechanical properties for projects of timber structures (Dias and Lahr 2004).

Testing equipment is usually expensive and available in well-developed research centers. The complete wood characterization is a complex activity, mainly because of the lack of laboratories with the specific machines to perform all the tests and their involved high costs (Christoforo *et al*. 2017). The resistance to compression parallel to the grain (f_{c0}) and toughness (W) are among those important properties of wood for construction.

These structural properties are determined through tests prescribed by the Brazilian standard document for timber structures (ABNT NBR 7190, 1997). Obtaining the compression strength parallel to the grain is performed with a universal testing machine, which is usually available in structural laboratories. Toughness is defined as the energy required to fracture a specimen. This quantity is hard to obtain because the same standard test for its determination must be performed in the radial and tangential directions with the aid of a pendulum machine with a capacity three to five times greater than the energy required to break the specimen by bending.

The use of non-destructive tests can facilitate the prediction and/or attainment of properties (Teles 2014; Chen and Guo 2017). However, performing this type of test also requires the use of unique equipment that is often costly. In this context, several studies have shown that it is possible to estimate a property that is difficult to obtain through another that is more easily obtained by means of regression models with significant adjustments (Almeida *et al*. 2014; Wolenski *et al*. 2020; Lahr *et al*. 2021).

Thus, this work aims to estimate the toughness property (W) as a function of the characteristic compression strength parallel to the grain ($f_{c0,k}$) using 20 tropical wood species through linear and quadratic regression models. The experimental tests to obtain W and $f_{c0,k}$ of the 20 species were performed according to ABNT NBR 7190 (1997) and, therefore, 12 samples were used for each wood species. Subsequently, the models were generated and statistical tests were performed to assess the significance of these.

EXPERIMENTAL

Materials

Twenty commercial tropical wood species were analyzed, four of which having their resistance class already determined by the ABNT NBR 7190 (1997) (Table 1). The wood specimens were prepared according to the recommendations of ABNT NBR 7190 (1997). Twelve specimens per wood species were prepared for each test, totaling 480 specimens. The specimens were manufactured from the wood of the tested species, dried in the air, and preserved with a moisture content close to the equilibrium moisture content, that is, 12%±1%, also by ABNT NBR 7190 (1997), taken from different pieces of wood, away from the edges and free of defects.

Tests were conducted in the Laboratory of Wood and Wood Structures (LaMEM) at the University of São Paulo (USP). For the toughness test, a machine with an energy capacity three times greater than that required to break specimens by bending was used. The specimens used in the tenacity test had a square section of 2 cm on a side and a length along the fibers of 30 cm. For the parallel compressive strength test, the fibers were used as test specimens with a prismatic square section of 5 cm on a side and a length of 15 cm. Test specimens were supported on two axes with a distance of 24 cm between them for the subsequent impact of the pendulum. The universal testing machine (AMSLER®; São Carlos, Brazil) with a load capacity of 25 tons was used to test the compressive strength parallel to grain. Tests were conducted under the guidelines of the ABNT NBR 7190 (1997) to obtain the necessary properties: f_{c0} and W. For each trial, 12 samples per wood species described in Table 1 were used at 12% moisture content as prescribed as the test condition by this standard document, totaling 480 experiments.

Table 1. Twenty Tropical Wood Species under Evaluation

Common Name	Scientific Name	Strength Class	ID
Cambará Rosa	*Erisma uncinatum*	C20	1
Cedrinho	*Erisma* spp.	C20	2
Cedro Doce	*Cedrela* sp.	C20	3
Cedroarana	*Cedrelinga catenaeformis*	C20	4
Copaíba	*Copaifera* spp.	C30	5
Cedro Amargo	*Cedrela odorata*	C30	6
Canafístula	*Peltophorum dubium*	C30	7
Castanheira	*Bertholletia excelsa*	C30	8
Catanudo	*Micropholis* sp.	C40	9
Louro Verde	*Cordia sellowiana*	C40	10
Abiu Casca Grossa	*Pouteria pachycarpa*	C40	11
Angelim Araroba	*Vataireopsis araroba*	C40	12
Angelim Saia	*Parkia* sp.	C50	13
Castelo	*Calycophyllum multiflorum*	C50	14
Guarucaia	*Peltophorum vogelianum*	C50	15
Cupiúba	*Goupia paraensis*	C50	16
Itaúba	*Mezilaurus itauba*	C60	17
Jatobá	*Hymenaea stilbocarpa*	C60	18
Tachi	*Tachigali* sp.	C60	19
Angelim Ferro	*Hymenolobium* spp.	C60	20

Methods

Initially, moisture contents of all 12 samples and all 20 species were obtained to ensure that the other experiments would be performed close to the ideal condition of dry moisture (U = 12%). Thus, tests for the f_{c0} and W were conducted. The values obtained from f_{c0} with moisture contents close to 12% were corrected for the exact moisture content of 12% using Eq. 1, as determined by the ABNT NBR 7190 (1997), in which $f_{c0,U}$ is the strength obtained from the sample's moisture content (%); U is the sample's moisture content (%), and $f_{c0,12}$ is the strength (MPa) corrected at 12% moisture content. The obtained values of $f_{c0,12}$ were used to generate the regression models. Equation 1 is as follows:

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

Through measurements performed during the experiment, the length of the Charpy pendulum arm (L) (m) and the final height that the pendulum reaches after impact with the specimen (L') (m), the toughness of each sample was calculated using Eq 2, where m is the mass (g) of the pendulum and g is the acceleration (9.81 m/s²) due to gravity:

$$W = m \times g \times (L - L') \quad (2)$$

With the f_{c0} values obtained, the characteristic compression strength parallel to the grain ($f_{c0,k}$) (Eq. 3) was calculated, according to ABNT NBR 7190 (1997), not taking a value lower than f_1 and 0.7 of the average value of the resistances obtained, where (f_1... f_n) is the compression strength parallel to the grain of the samples in increasing order, and n is the number of samples.

$$f_{c0,k} = \left(2 \times \frac{f_1 + f_2 + \cdots f_{\frac{n}{2}-1}}{\frac{n}{2}-1} - f_{\frac{n}{2}}\right) \times 1{,}1 \quad (3)$$

Regression models used linear (Eq. 4) and quadratic functions (Eq. 5), in which β_1, β_2 and β_3 are the independent terms to be adjusted by the least squares method. Such models seek to estimate toughness through an easily obtainable property, the compression strength parallel to the grain.

$$W = \beta_0 + \beta_1 \times f_{c0} \quad (4)$$

$$W = \beta_0 + \beta_1 \times f_{c0} + \beta_2 f_{c0}^2 \quad (5)$$

The models were generated using the totality of the species and with the average values of *W* and characteristic compression strength, calculated with 12 samples of each species. Analyzing the efficiency of obtained models, the coefficient of determination (R^2) was calculated using Eq. 6, where *n* is the number of specimens, *Ydata* is the mean value experimentally obtained, and $Ypredict_i$ is the value estimated by regression models. The analysis of variance (ANOVA) (Minitab®, version 19.2020.1, São Carlos, Brazil) was used to confirm the correlation and the significance of the model at a 5%.

$$R^2\ (\%) = 100 \times \left(1 - \frac{\sum_{i=1}^{n}\left(Y_{predict_i} - Y_{data_i}\right)^2}{\sum_{i=1}^{n}\left(Y_{data_i} - \bar{Y}_{data_i}\right)^2}\right) \quad (6)$$

RESULTS AND DISCUSSION

The results of f_{c0} and *W* are presented in Figs. 1 and 2, respectively. The values identified in each bar are the property means for each species, and also the 95% confidence interval (CI) for the mean of each species. The coefficient of variation is also identified (CV), with the highest and lowest values obtained for each species.

For f_{c0} (Fig. 1), it was observed that most tropical species reached a coefficient of variation below the limit stipulated by the ABNT NBR 7190 (1997) of 18% for normal stresses, with the lowest value being 5.12 % and the highest coefficient of variation was 25.42. Three wood species exceeded this limit: *Erisma* spp. (CV = 25.42%), *Vataireopsis araroba* (CV = 22.77%), and *Calycophyllum multiflorum* (CV = 18.88%). These results supported the diversified quality of the samples used in the tests to determine f_{c0}.

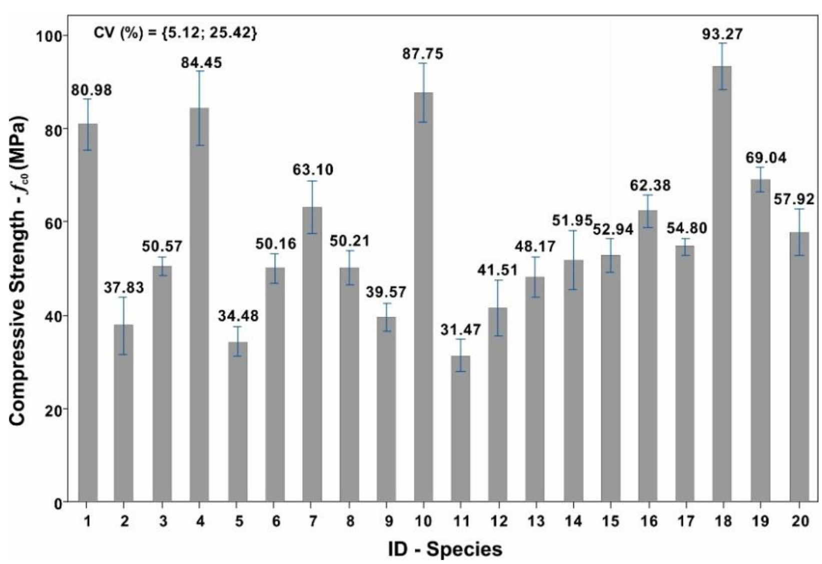

Fig. 1. Average values of compression parallel to grain (f_{c0}) for the 20 tropical woods

For *W* (Fig. 2), nine tropical woods were extrapolated the limit of 28% for tangential efforts of the ABNT NBR 7190 (1997) in their CVs such as *Erisma uncinatum* (CV = 35.26%), *Pouteria pachycarpa* (CV = 39.95%), *Vataireopsis araroba* (CV = 37.97%), *Parkia* sp. (CV = 31.30%), *Goupia Pará* (CV = 36.99%), *Erisma* spp. (CV = 37.93%), *Cedrelinga catenaeformis* (CV = 40.00%), *Bertholletia excelsa* (CV = 36.49%), and *Micropholis* sp. (42.93%). The coefficient of variation ranged from 8.07% to 42.93%.

The $f_{c0,k}$ values are demonstrated in Fig. 3. These values were calculated according to the guidelines of ABNT NBR 7190 (1997), corroborating with that known strength classification of the analyzed tropical wood species, as described in Table 1.

Table 2 shows linear and quadratic models to estimate *W* as a function of the $f_{c0,k}$ for the 20 species. This table demonstrates the p-value evaluating the significance of the model, coefficient of determination (R^2) and the adjusted coefficient of determination (R^2_{adj}), that is, the percentage of the response that is explained by the model obtained.

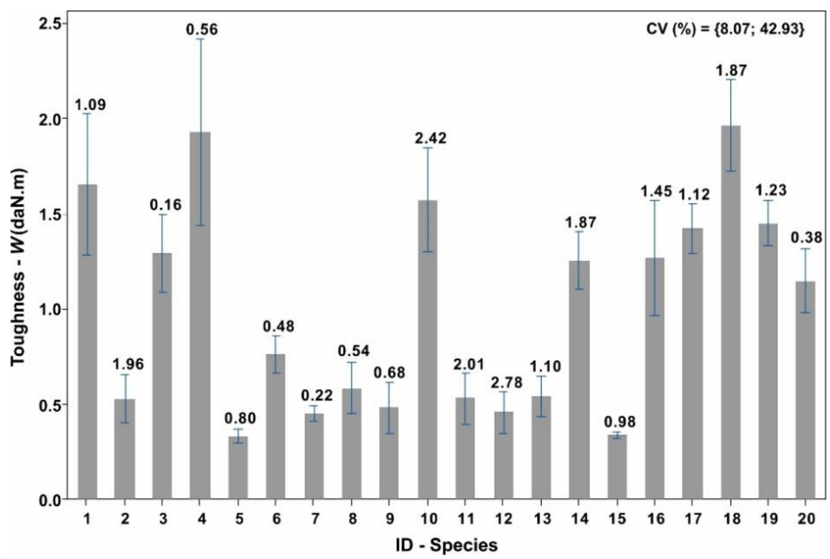

Fig. 2. Average values of toughness (*W*) for the 20 tropical woods

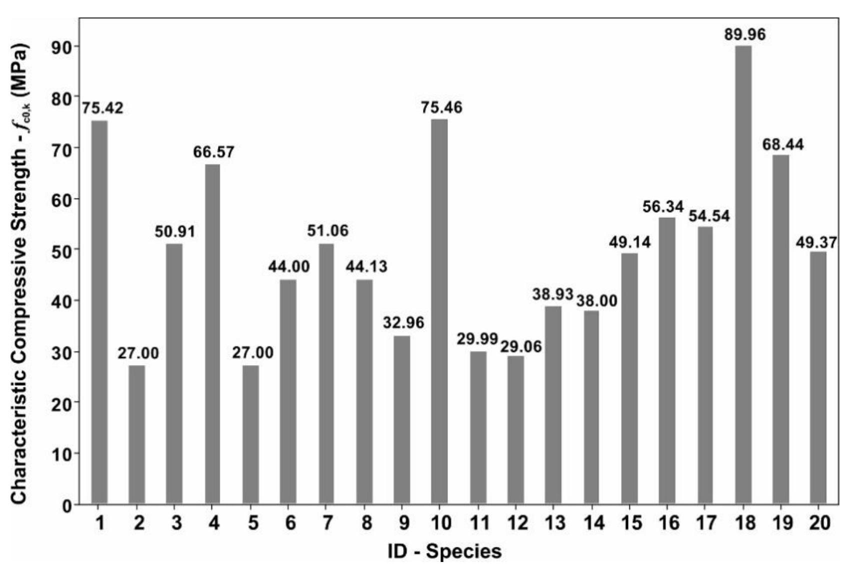

Fig. 3. Characteristic Compressive Strength ($f_{c0,k}$) for the 20 tropical woods

Table 2. Tropical Wood Species: Regression Models and Coefficients per Model

Model	Equation	p-value	R^2 (%)	R^2_{adj} (%)
Linear	$W = - 0.302 + 0.02608 f_{c0,k}$	0.000	71.51	69.93
Quadratic	$W = - 0.271 + 0.0248 f_{c0,k} + 0,000012 f_{c0,k}^2$	0.000	71.51	68.16

For the linear model (Fig. 4), the only term of the model was significant, having a p-value equal to 0.00. The model with $f_{c0,k}$ was capable of estimating toughness with significant accuracy of 71.51%. In the quadratic model (Fig. 4), the coefficient of determination was the same (71.51%) as for the linear model. In this last case, there was no benefit to the model in adding the square of the term of $f_{c0,k}$ as a predictor. This observation respected the ANOVA, in which the p-value found for the term, was equal to 0.956; therefore the square term did not make a significant contribution to the model.

In the research conducted by Almeida *et al*. (2014), the *W* was also estimated through a property with relative ease of attainment, the apparent density (ρ_{ap}). The results also showed a satisfactory correlation between these properties. Moreover, linear model had an adjusted coefficient of determination (R^2_{adj}) of 79.90% as well as the adjusted coefficient of determination was 80.60% for the quadratic model, which implies that both models are satisfactory in the estimation of toughness. Although the models obtained by Almeida *et al*. (2014) have R^2_{adj} greater than those obtained for the models with f_{c0}, the results demonstrate a correlation between the f_{c0} and *W*; and because they have a coefficient of determination (R^2) greater than 70% - this indicates an adequate quality of the obtained adjustments, according to Montgomery (2005).

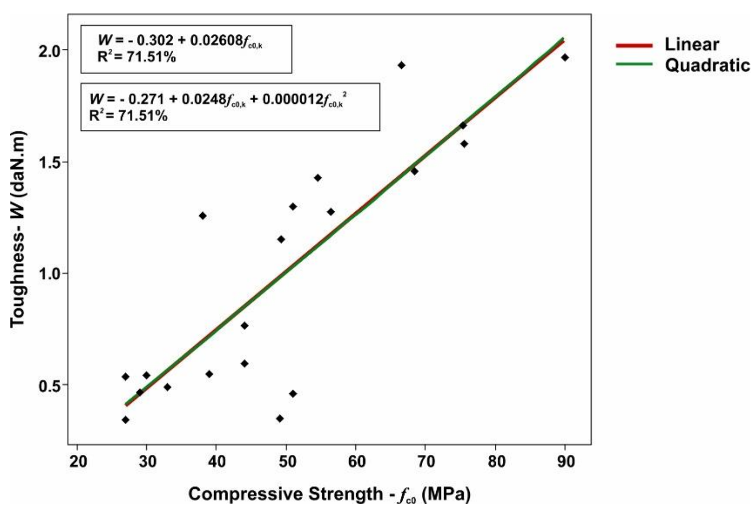

Fig. 4. Linear and quadratic regression models

CONCLUSIONS

1. The experimental results for the f_{c0} and *W* showed good distribution of the sample to obtain the proposed regression models.
2. The linear regression model proved to be significant, as well as all its predictor terms, in the estimation of *W* as a function of $f_{c0,k}$, because both coefficient of determination (R^2) and the adjusted coefficient of determination (R^2_{adj}) were around 70%.

3. The quadratic regression model also demonstrated significance in estimating *W*. However, the quadratic term proved not to be significant to the model and therefore the adjusted coefficient of determination obtained was lower (68.16%) for this model compared to the previous one.
4. The linear model presented the best choice, according to the results of the statistical analysis, implying that it is possible to estimate the wood toughness with significant precision through this model for tropical species, using experimental results of the compression strength parallel to the grain.

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