Estimation of Compression and Shrinkage Properties of Brazilian Tropical Timber through Porosimetry Analysis by Mercury Intrusion

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Wood is a natural material with properties that are strongly influenced by anatomical characteristics, so studies that aim to correlate properties through empirical equations in search of simplification to obtain the values of their characteristics are essential. In this context, this work aims to generate multiple regression models to estimate the properties of shrinkage and compression parallel and normal to the grain of Brazilian tropical woods as a function of the values of porosity, density, and for both properties, with porosity being obtained by mercury intrusion porosimetry. As a result, the radial (RRT) and total tangential (RTT) shrinkage could be estimated through porosity. However, it was not possible to estimate them considering only density as an independent variable. All the models that were used were able to accurately estimate the modulus of resistance and modulus of elasticity values ($f_{c,0}$, $E_{c,0}$, $f_{c,90}$, and $E_{c,90}$).

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INTRODUCTION

Wood is a natural material, and its properties are strongly influenced by anatomical characteristics. Therefore, studies that aim to define the interaction between properties through empirical equations in search of simplification to obtain the values of their characteristics are essential (Almeida *et al.* 2015). In this context, researchers including Almeida *et al.* (2014, 2015), Cavalheiro *et al.* (2016), Almeida *et al.* (2017), Christoforo *et al.* (2020), and Lahr *et al.* (2021), among others, have evaluated the possibility of estimating various wood properties through density using regression models. These studies have found promising results.

Cavalheiro *et al.* (2016) evaluated the possibility of estimating the wood dimensional stability as a function of density. Wood species from the coniferous and dicotyledonous groups were analyzed. The results indicated the absence of a behavior pattern between the density and dimensional stability properties, making it impossible to establish significant relationships in the adoption of density as an estimator of these properties. The authors concluded that the differences in anatomical characteristics between species may be the responsible factor for the lack of a behavior pattern between the densities and dimensional stability properties.

Dias *et al.* (2019) studied the influence of the apparent density on the values of radial and tangential shrinkage of wood species. For this, 43 species of Brazilian tropical wood were evaluated, and linear and exponential regression models were applied, with significance and adjustment assessment through analysis of variance (ANOVA). As a result, a low dependence between these variables was shown, not admitting a correlation between the apparent density and the radial and tangential retractions of the species.

Duarte *et al.* (2020) evaluated the possible correlation between the apparent density (AD) of 10 tropical wood species, with densities between 0.4 and 1.1 g/cm^3, and the porosity (P), which was determined using the mercury intrusion technique. Through statistical analysis, they managed to develop the equation "AD = -1.18P + 1.34," which related the AD with the P with R^2 equal to 0.88, a value that allowed considering the porosity as good density estimator. However, due to the occurrence of pore obstructions in the technique execution due to mercury intrusion, the validity of the hypothesis could invalidate the correlation equation obtained through this analysis. Thus, Duarte *et al.* (2020) suggested future research that investigated a greater variety of wood species.

Wood shrinkage occurs due to loss of moisture and some wood species tend to collapse their cells during drying. In other words, in addition to normal and tangential shrinkage, these woods undergo shrinkage due to the collapse of their anatomical elements due to the negative tension of water in the wood during the initial stages of the conventional drying oven (Yang and Liu 2021). The tendency to collapse occurs in most wood species, including softwood species, although hardwood species exhibit the most severe collapse (Kaumann 1964a,b; Yang and Liu 2018). Thus, shrinkage constitutes an important factor in the wood industrialization process.

In this context, where it is evident that the density is unable to predict the physical-mechanical properties of wood with great precision, there is a need to include another variable related to certain intrinsic characteristics of each species such as porosity. Therefore, this work aims to use regression models adopting porosity and apparent density as estimation properties (independent variables) of shrinkage and compression parallel and normal to the grains (dependent variables) of Brazilian tropical woods. Multiple variable regression models will also be analyzed to estimate these properties, that is, using porosity and apparent density in the same equation, instead of separately. It is worth noting that the porosity was obtained through the analysis of porosimetry by mercury intrusion.

EXPERIMENTAL

Materials

This work analyzed eight species of Brazilian tropical wood: Cedro-Amazonense (*Cedrela spp.*; basic density =0.44 g/cm^3; shaft diameter ≤1.5 m), Cedroarana (*Cedrelinga catenaeformis* Ducke; basic density =0.53 g/cm^3; shaft diameter ≤2 m), Cambará (*Erisma* *uncinatum* Warm; basic density =0.48 g/cm^3; shaft diameter ≤0.8 m), Tatajuba (*Bagassa guianensis;* basic density =0.68 g/cm^3; shaft diameter ≤1.8 m), Cupiúba (*Goupia glabra;* basic density =0.71 g/cm^3; shaft diameter ≤1.2 m), Jatobá (*Hymenaea spp.;* basic density =0.75 g/cm^3; shaft diameter≤ 2 m), Angelim-vermelho (*Dinizia excelsa* Ducke; basic density =0.82 g/cm^3; shaft diameter ≤2 m) and Champanhe (*Dipteryx odorata;* basic density =0.82 g/cm^3; shaft diameter ≤1.2 m) (Instituto de Pesquisas Tecnológicas 2021). The wooden pieces, over 50 years of age, were supplied by the Northern Timber Industries Union of the State of Mato Grosso, SINOP, Brazil.

Methods

All the tests that were carried out to determine the physical and mechanical properties of the wood samples were performed at the Wood and Timber Structures Laboratory (LaMEM), of the Structural Engineering Departments, of the Sao Carlos School of Engineering (EESC/USP), State of São Paulo, Brazil. The eight species that were investigated came from homogeneous lots, and they were duly stocked in compliance with the NBR 7190 (1997) in Annex B, which provides, among other points, the positioning of sawn wood in a way that facilitates the passage of air between the pieces in a place protected from sun and rain, as well as humidity control until parts reach levels close to twelve percent. Obtaining the properties of apparent density ($\rho_{12\%}$), modulus of elasticity (E_{c0}) and resistance (f_{c0}) to compression parallel to the grains, normal compression to the grain (modulus of elasticity (E_{c90}) and resistance (f_{c0}), total radial shrinkage (RRT), and total tangential shrinkage (RTT) of these species were obtained as recommended in Appendix B "Determination of the properties of wood for structural design", of the ABNT standard NBR 7190 (1997).

It should be noted that the characteristic value obtained on the set of compressive strength values in the direction parallel to the fibers (f_{c0}) is responsible for placing the wood species in one of the 4 strength classes [C20 (20 ≤ f_{c0k} < 30 MPa), C3 (30 ≤ f_{c0k} <40 MPa), C40 (40 ≤ f_{c0k} < 60 MPa), C60 (f_{c0k} ≥ 60 MPa)] for the hardwood group. In equation 1, f_1, f_2 to f_n denote the compressive strength values in ascending order of the 12 (n) test specimens tested for each species.

$$f_{c0k} = Max \begin{cases} f_1 \\ 0.7 \cdot \sum_{i=1}^{n} f_1 / n \\ 1.1 \cdot (2 \cdot \left[\frac{f_1 + f_2 + \cdots + f_{\left(\frac{n}{2}\right)-1}}{\left(\frac{n}{2}\right)-1} \right] \end{cases} \tag{1}$$

The moisture content (U) of the specimens at the time of the tests was obtained using the Marrari M5 contact moisture meter (10.73 ≤ U ≤ 12.22%). The resistance and stiffness properties were corrected to the standard moisture content of wood of 12%, as prescribed in the referred regulation. Thus, 12 specimens were tested for each investigated property, in addition to the porosity values (Por), in which two determinations were made per wood species. Due to material availability, the E_{c90} and f_{c0} values were not measured for the Cedroarana, Tatajuba, and Cupiúba wood species. The mechanical tests were performed on an Amsler universal testing machine (São Carlos, Brazil), with a capacity of 25 tons.

The tests for the porosity determination were conducted in a 9320 Micromeritics PoreSizer 9320 (Norcross, GA, USA), with a pressure capacity of 200 MPa. The PoreSizer was owned by the Sao Carlos Institute of Physics, USP. The parameters used in the test consisted of mercury with a surface tension of 0.494 g/cm², a density 13.533 g/mL, a contact angle of forward and reverse at 130°, and a balance time between low and high pressure of 10 s. The 130° angle was adopted for the forward and reverse contact angle, as suggested by the Micromeritics equipment software. Two samples were tested per batch. The samples were 2 cm in height and 1 cm² in area, and they were dried in an oven for 24 h at 50 °C with air circulation prior to testing.

The test results were evaluated with the aid of the Mathcad software version 15 (Cambridge, MA, USA). The regression models (linear and non-linear) comprised a free variable and to two (β_0, β_1) and three ($\beta_0, \beta_1, \beta_2$) parameters, expressed by Eqs. 2 to 9. These were used to estimate the six other properties (Y) that were investigated in this study.

$$Y = \beta_0 \cdot X + \beta_1 \tag{2}$$

$$Y = \beta_0 \cdot \ln(X + \beta_1) + \beta_2 \tag{3}$$

$$Y = \beta_0 + \beta_1 \cdot \ln(X) \tag{4}$$

$$Y = \beta_0 \cdot X^{\beta_1} + \beta_2 \tag{5}$$

$$Y = \beta_0 \cdot X^{\beta_1} \tag{6}$$

$$Y = \beta_0 \cdot e^{\beta_1 \cdot X} \tag{7}$$

$$Y = (\beta_0 + \beta_1 \cdot X)^2 \tag{8}$$

$$Y = \beta_0 + \beta_1 \cdot X^2 + \beta_2 \cdot X^3 \tag{9}$$

The mean absolute percentage error (MAPE), calculated by Eq. 10, was used as the criterion (lowest error) for choosing the most accurate model (2 out of 9) by estimated property. The regression variation coefficient (CV) was obtained with Eq. 11 and the coefficient of determination (R^2) was obtained by Eq. 12, the latter measuring the adjustment quality.

$$\mathrm{MAPE}(\%) = 100 \cdot \frac{1}{n} \cdot \sum_{i=1}^{n} \left\| \frac{\mathrm{Ypredito_i} - \mathrm{Ydata_i}}{\mathrm{Ydados_i}} \right\| \tag{10}$$

$$\mathrm{CV}(\%) = 100 \cdot \frac{\sqrt{\sum_{i=1}^{n} \frac{(\mathrm{Ypredito_i} - \mathrm{Ydata_i})^2}{n}}}{\bar{\mathrm{Y}}\mathrm{data}} \tag{11}$$

$$\mathrm{R}^2(\%) = 100 \cdot \left(1 - \frac{\sum_{i=1}^{n} (\mathrm{Ypredito_i} - \mathrm{Ydata_i})^2}{\sum_{i=1}^{n} (\mathrm{Ydata_i} - \bar{\mathrm{Y}}\mathrm{data})^2}\right) \tag{12}$$

In Eqs. 10 to 12, n is the samples number considered, $Ypredito_i$ is the value estimated by the regression model, $Ydata_i$ is the experimentally determined value and $\bar{Y}_{data}$ is the average value of the experimentally determined results.

This study tested models that were dependent on a single free variable ($\rho_{12\%}$ or Por), which made it possible to identify the causes for a given property. With the objective of better precision adjustments, multiple linear regression models were used according to Eq. 13, where Y represents the estimated properties.

$$Y = \beta_0 + \beta_1 \cdot \rho_{12\%} + \beta_2 \cdot \mathrm{Por} \tag{13}$$

RESULTS AND DISCUSSION

Table 1 presents the properties that were evaluated for the eight wood species as well as the results from the statistical analysis.

Table 1. Average Values (X_m) and the CV for the Studied Properties of the Jatobá, Champanhe, Angelim-vermelho, Tatajuba, Cambará, Cedroarana, Cupiúba and Cedro Amazonense Wood Species

Properties	Jatobá		Champanhe		Angelim-vermelho		Tatajuba	
	X_m	CV (%)	X_m	CV (%)	X_m	CV (%)	X_m	CV (%)
$\rho_{12\%}$ (g/cm³)	1.08	3.61	1.09	3.08	1.13	9.75	0.94	6.07
RRT (%)	3.63	18.01	3.95	20.85	5.1	11.81	4.28	10.8
RTT (%)	6.71	10.44	6.38	16.94	8.38	7.97	5.78	10.24
f_{c0} (MPa)	93.37	11.24	93.16	5.45	77.53	7.54	80.16	18.56
E_{c0} (MPa)	21403	13.62	23002	10.94	16695	17.82	18238	15.11
f_{c90} (MPa)	19.75	15.88	23.92	21.05	25.53	8.98	-	-
E_{c90} (MPa)	1117	15.14	1269	14.7	1251	28.48	-	-
Por (%)	22.4	-	19.6	-	16.4	-	35.8	-

Properties	Cambará		Cedroarana		Cupiúba		Cedro Amazonense	
	X_m	CV (%)	X_m	CV (%)	X_m	CV (%)	X_m	CV (%)
$\rho_{12\%}$ (g/cm³)	0.56	4.17	0.57	7.44	0.85	2.77	0.58	2.26
RRT (%)	3.7	14.06	3.51	25.23	4.6	9.61	3.77	8.95
RTT (%)	7.1	11.54	6.45	17.54	7.58	6.93	6.08	10.36
f_{c0} (MPa)	43.44	12.84	41.52	22.77	57.36	14.07	46.33	5.39
E_{c0} (MPa)	10380	16.72	10394	12.81	12970	15.35	12952	14.76
f_{c90} (MPa)	6.14	24.01	-	-	-	-	11.33	20.72
E_{c90} (MPa)	520	17.78	-	-	-	-	564	22.95
Por (%)	64.2	-	66.8	-	40.6	-	65.9	-

The average values of the tested properties were, for the most part, close to those of literature such as Almeida *et al.* (2019), Lahr *et al.* (2016), and the Instituto de Pesquisas Tecnológicas (2021). Any differences were due to differences in the wood species lots and in the sample's moisture content (Segundinho *et al.* 2017).

The strength classes were defined according to the characteristic compressive strengths parallel to the grains ($f_{c0,k}$) obtained for each wood species, being: Jatobá C60 ($f_{c0,k} = 79.86$ MPa), Champanhe C60 ($f_{c0,k} = 96.58$ MPa), Angelim-Vermelho C60 ($f_{c0,k} = 72.38$ MPa), Tatajuba C60 ($f_{c0,k} = 60.06$ MPa), Cambará C40 ($f_{c0,k} = 38.94$ MPa), Cedroarana C30 ($f_{c0,k} = 29.05$ MPa), Cupiúba C50 ($f_{c0,k} = 51.04$ MPa), and Cedro Amazonense ($f_{c0,k} = 46{,}64$ MPa) (NBR 7190 1997).

Equation 14 expresses the best adjustment obtained for the estimation of porosity (Por - dimensionless) as a function of apparent density (g/cm³), considering the set of all wood species. It is noteworthy that the CV, the MAPE, and the R² values were equal to 3.31%, 2.73%, and 99.54%. This illustrated the excellent precision obtained in the Por estimate by $\rho_{12\%}$ for the species with densities between 0.56 and 1.13 g/cm³.

$$\text{Por} = -0.864 \cdot \rho_{12\%} + 1.15 \tag{14}$$

Tables 2 and 3 show the results (best adjustments by property) of the regression models considering the apparent density and porosity as an estimator, respectively. The multiple regression models that were obtained are shown in Table 4.

Table 2. Regression Models Results Considering the Apparent Density as an Estimator of the Other Properties

Models	MAPE (%)	R² (%)
$RRT = -1.731 \cdot 10^{-3} \cdot \rho_{12\%}^{-10.5337} + 4.3139$	7.36	37.15
$RTT = 6.552 \cdot \rho_{12\%}^{2} - 9.886 \cdot \rho_{12\%} + 10.121$	9.67	8.61
$f_{c0} = (3.65 + 5.199 \cdot \rho_{12\%})^2$	8.05	88.52
$E_{c0} = 1.694 \cdot 10^4 \cdot \rho_{12\%} + 1.349 \cdot 10^4$	12.01	75.62
$f_{c90} = 3.437 \cdot ln(\rho_{12\%} - 0.559) + 25$	4.99	95.75
$E_{c90} = 1.237 \cdot 10^3 \cdot \rho_{12\%} - 188.76$	3.12	98.49

The models that were generated for the shrinkage estimation had R^2 values of less than 50%, while the R^2 values for the properties' estimation of f_{c0}, E_{c0}, f_{c90}, and E_{c90} from the apparent density varied between 75.62% and 98.49%. These results confirmed that the apparent density was a good estimator of the wood species properties.

Table 3. Regression Models Results Considering the Porosity as an Estimator of the Other Properties

Models	MAPE (%)	R² (%)
$\mathrm{RRT} = -0.032 \cdot \ln(\mathrm{Por} - 0.164) + 3.867$	6.53	57.82
$\mathrm{RTT} = -0.049 \cdot \ln(\mathrm{Por} - 0.164) + 6.506$	6.23	54.96
$f_{c0} = -37.751 \cdot \mathrm{Por}^2 - 62.482 \cdot \mathrm{Por} + 100.542$	8.96	86.78
$E_{c0} = 1.984 \cdot 10^3 \cdot \mathrm{Por}^2 - 2.097 \cdot 10^4 \cdot \mathrm{Por} + 2.403 \cdot 10^4$	13.14	73.46
$f_{c90} = 182.2066 \cdot \mathrm{Po}^2 - 184.9342 \cdot \mathrm{Por} + 51.999$	12.77	95.77
$E_{c90} = 1.9342 \cdot 10^3 \cdot \mathrm{Por}^2 - 3.1002 \cdot 10^3 \cdot \mathrm{Por} + 1.7409 \cdot 10^3$	4.00	98.72

The regression models that considered porosity as a shrinkage estimator had R^2 values greater than 50%, and it can be said that it is possible to estimate the shrinkage through the wood porosity values. The shrinkage values are directly influenced by the anatomical characteristics of the wood species. Based on the determination coefficients obtained, porosity is the best estimator for these properties. The properties estimation of f_{c0}, E_{c0}, f_{c90}, and E_{c90} through the porosity showed R^2 values greater than 78%.

Table 4. The Results of Multiple Linear Regression Models

Models	MAPE (%)	R² (%)
$RRT = 12.870 - 8.55 \cdot Por - 6.181 \cdot \rho_{12\%}$	8.82	34.80
$RTT = 48.118 - 36.67 \cdot Por - 30.694 \cdot \rho_{12\%}$	6.33	48.41
$f_{c0} = -238.92 + 204.204 \cdot Por + 259.676 \cdot \rho_{12\%}$	8.33	90.57
$E_{c0} = -5.802 \cdot 10^4 + 5.164 \cdot 10^4 \cdot Por + 6.157 \cdot 10^4 \cdot \rho_{12\%}$	11.09	78.06
$f_{c90} = -29.262 + 19.562 \cdot Por + 44.133 \cdot \rho_{12\%}$	16.10	91.58
$E_{c90} = 1.748 \cdot 10^3 - 1.691 \cdot 10^3 \cdot Por - 187.422 \cdot \rho_{12\%}$	4.71	98.45

The models that were generated to estimate the properties of f_{c0}, E_{c0}, f_{c90}, and E_{c90} through the porosity and bulk density had high R^2 values (78.06% to 98.45%). The apparent density caused the models generated for the RRT and RTT estimates to present lower determination coefficients when compared to the models that considered only porosity as a shrinkage estimator.

CONCLUSIONS

1. The apparent density was a good estimator of the f_{c0}, E_{c0}, f_{c90}, and E_{c90} properties. However, it was not possible to estimate the shrinkage considering only density as an independent variable.
2. All properties that were evaluated in this research could be estimated considering porosity as an independent variable, where it was possible to estimate the shrinkage values, which are directly linked to the wood anatomical factors. Up to this point, researchers have not achieved such precision in their estimates.
3. It was not possible to estimate the shrinkage considering the apparent density and the porosity. The other properties could be estimated using multiple linear regression models.
4. The estimates of properties such as the dimensional stability and the normal compression of the grain, which characterize a fragile rupture mode, should consider anatomical factors such as porosity to achieve the maximum precision degree. Further research on this subject is recommended so that even more accurate models are obtained.

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