Floresta e Ambiente 2022; 29(2): e20220019
https://doi.org/10.1590/2179-8087-FLORAM-2022-0019
ISSN 2179-8087 (online)

Floram Floresta e Ambiente

ORIGINAL ARTICLE – Forest Products Science and Technology

Influence of Moisture on Physical and Mechanical Properties of *Pouteria Pachycarpa* Wood

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Abstract

According to the Brazilian standard for wooden structures, strength and stiffness increase linearly with decreasing moisture; however, as wood is a natural, heterogeneous and anisotropic material, certain strength and stiffness properties may not be affected even by large differences in moisture. Therefore, this work aims to evaluate the reliability of the resistance and rigidity transformation equations as a function of moisture, used to correct the properties when the test was not performed at 12% moisture. Furthermore, it was checked whether the humidity affects the properties of the studied species. Of the 15 properties analyzed, 2 did not show changes when analyzed at the fiber saturation point and at 12% moisture. Additionally, the correction equations of the Brazilian standard showed errors of up to 24% in the estimation of properties at 12% moisture. Thus, the need to correct the Brazilian standard for wooden structures is evident.

Keywords: Casca Grossa, ANOVA, NBR 7190.

1. INTRODUCTION AND OBJECTIVES

Wooden structures can be used in both low buildings, i.e., residences, and even tall buildings, i.e., buildings (Lahr et al. 2017). Its advantage over other commonly used materials (i.e., steel and concrete) is its high tensile and compressive strength and a low density-strength ratio (Almeida et al. 2018). Another advantage, considered by many as the main one (Aquino et al. 2021; Lahr et al. 2021) following the precepts set forth in the Brazilian standard NBR 7190 (ABNT 1997), as well as to evaluate the possibility of estimating physical and mechanical properties, using the analysis of variance (ANOVA), is its renewable source. Through reforestation, it is possible to use this material in structures without harming the environment and with an unlimited source of raw material always available (Christoforo et al. 2017).

Brazil, due to its large forest area (9 million hectares in 2019), has great potential to further explore the use of wood in construction, especially in structural systems (Couto et al. 2020). Aiming at the best use and adequate utilization, it is necessary to know the properties and the behavior of wood when subjected to acting efforts (Dias et al. 2016). In Brazil, NBR 7190 (ABNT 1997) governs the premises for the design and execution of wooden structures.

According to NBR 7190 (ABNT 1997), to characterize a wood species, several laboratory tests are necessary. As some tests are difficult to perform, some authors have sought other ways of characterization, e.g., the use of regression models. In agreement with Lahr et al. (2021) 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 NBR 7190 (ABNT 1997) 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}, it is possible to estimate the compressive strength parallel to the fibers through wood density, which is an easily obtained property. In line with Aquino et al. (2021) following the precepts set forth in the Brazilian standard NBR 7190 (ABNT 1997), as well as to evaluate the possibility of estimating physical and mechanical properties, using the analysis of variance (ANOVA), density was also able to estimate the tensile strength parallel to the fiber, besides the compressive strength parallel to the fiber being a good estimator of the modulus of elasticity property in compression and tension parallel to the fiber.

On the other hand, NBR 7190 (ABNT 1997) presents a simplified method, in which it is possible to estimate the properties of wood only with the compressive strength test parallel to the fibers. In this method, the standard displays relationships between strengths and compression. However, according to Couto et al. (2020), the simplified method is outdated and needs to be revised. In his study, using 10 Brazilian wood species covering all hardwood normative strength classes (C20 to C60), the ideal ratio between compression and shear, both parallel to the fibers, is 0.22 and not 0.12 as shown in this standard.

As can be seen, NBR 7190 (ABNT 1997) is the standard used for the characterization of wood species and many authors seek other forms of characterization, besides checking the reliability of the values and conditions presented, since its current version is 24 years old and new wood species were studied. In this context, it is important to highlight that, for the design of wood structures, it is necessary to perform property tests at a moisture of 12%. If it has not been performed under this condition, it is necessary to correct the values obtained. However, since wood is a natural (i.e., affected by soil and climate conditions, among others), heterogeneous and anisotropic material, certain strength and stiffness properties may not be affected even by large differences in moisture (Almeida et al. 2019; Fragiacomo et al. 2010; Menis et al. 2012). However, the standard shows that the strength and stiffness values are highly affected by the moisture, showing the need for studies on the influence of moisture on wood properties (Carvalho et al. 2021; Stolf et al. 2014).

Thus, the present paper aims to evaluate whether 15 properties of *Pouteria pachycarpa* wood are affected by moisture. For this, experimental tests with 12% moisture and higher than this value (U%) were performed. After obtaining the properties at the two moistures, analyses based on ANOVA and Anderson-Darling test, with a significance level of 0.05, were used to investigate whether or not there was a change in the properties with the moisture's variation. In addition, it was sought to verify whether the equations of transformation of strength and stiffness as a function of moisture (U% for 12%) presented by the standard have an acceptable error for the species studied.

2. MATERIALS AND METHODS

The pieces of Casca Grossa (*Pouteria pachycarpa*) wood, from the south of Roraima (Brazil), were supplied by a lumber company located in São Carlos (Brazil, SP), being green and air dried. The homogeneous lot was about 1 m³, with nominal dimensions of 6 cm × 16 cm × 330 cm.

The physical and mechanical properties were determined according to the premises of the Brazilian standard NBR 7190 (ABNT 1997) "Design of wooden structures." Twelve samples were tested per property analyzed and for each moisture (12% and U%), resulting in 360 samples. The tested properties are shown in Table 1.

Table 1. Physical and mechanical properties evaluated.

Abbreviation	Properties
ρ_{12} (g/cm³)	Apparent density
εrt (%)	Radial shrinkage
εtt (%)	Tangential shrinkage
f_{c0} (MPa)	Compression strength parallel to the fibers
f_{t0} (MPa)	Tensile strength parallel to the fibers
f_{t90} (MPa)	Tensile strength normal to the fibers
f_{v0} (MPa)	Shear strength parallel to the fibers
f_{s0} (MPa)	Resistance to fiber splitting parallel to the fibers
f_{tm} (MPa)	Conventional strength in static bending test
E_{c0} (MPa)	Elastic modulus in compression parallel to the fibers
E_{t0} (MPa)	Modulus of elasticity in tension parallel to the fibers
E_{tm} (MPa)	Conventional modulus of elasticity in the static bending test
f_{h0} (MPa)	Hardness parallel to the fibers
f_{h90} (MPa)	Hardness normal to the fibers
W (daN·m)	Toughness

The samples moisture (U%) was determined according to the Brazilian standard NBR 7190 (ABNT 1997), as presented in Equation 1. From this equation, m_i is the wet sample mass and m_s is the dry sample mass, measured every 6 hours and using a maximum temperature of 103±2 °C. After the mass has no more change, the dry mass is determined.

$$U\% = \frac{m_i - m_s}{m_s} \cdot 100 \tag{1}$$

With the moisture values defined, the tests were performed on the samples at 12% moisture and U%. In order to characterize the species in the hardwood group (C20, C30, C40, and C60), the characteristic fiber parallel compressive strength ($f_{c0,k}$) was obtained using Equation 2, where f_n is the value for 12% moisture ($f_{c0,12\%}$). In this equation, f_1, f_2 to f_n denote the compressive strength values at 12% moisture in increasing order of the n specimens tested (n = 12 in this case). (ABNT NBR 7190, 1997)

$$f_{c0,k} \geq \begin{cases} f_1 \\ 0.70 \cdot \frac{\sum_{i=1}^{n} f_i}{n} \\ 1.10 \cdot \left[2 \cdot \frac{f_1+f_2+\cdots+f_{(n/2)-1}}{(n/2)-1}\right] - f_{n/2} \end{cases} \tag{2}$$

Finally, besides performing the experimental tests at 12% moisture, Equations 3 and 4 of the Brazilian standards were used to correct the values for strength (f_{12}) and stiffness (E_{12}), respectively, with moisture values higher than 12%. It should be noted that the use of such expressions is recommended for moisture values between 12% and 20%. Thus, knowing the experimental values of the properties of strength and stiffness at 12%, it is possible to verify the error of these equations, comparing experimental and corrected f_{12} and E_{12}.

$$f_{12} = f_U \cdot \left[1 + \frac{3 \cdot (U - 12)}{100}\right] \tag{3}$$

$$E_{12} = E_U \cdot \left[1 + \frac{2 \cdot (U - 12)}{100}\right] \tag{4}$$

Analysis of variance (ANOVA) with a significance level of 0.05 was used to verify the influence of varying moisture (from 12% to the associated moisture of U%) on the investigated properties. By ANOVA, a p-value (probability p) less than the significance level implies a significant difference in the means of a given property caused by the variation in moisture, and not significance otherwise. The Anderson-Darling test, also evaluated at the 0.05 significance level, was used to verify normality in the distribution of residuals and equality of variances. A p-value equal to or greater than the significance level implies validation of the ANOVA model.

3. RESULTS AND DISCUSSION

Table 2 shows the results of the mean and coefficient of variation (CV) of the physical and mechanical properties of *Pouteria pachycarpa* wood related to the moisture of 12% and the U%. It is worth saying that the average moisture values before correction (U%) were 19.75%. After drying, the samples had a moisture of 12.45% for U12%, a value close to the 12% required by the Brazilian standard (ABNT NBR 7190, 1997). In addition to these results, the p-values from ANOVA and the Anderson-Darling (A-D) test are shown. Finally, the error of Equations 3 and 4 and the estimated mean values (Est.) of the strength and stiffness properties are shown in Table 3.

Table 2. Result of the physical and mechanical properties of *Pouteria pachycarpa* wood.

Property	$U_{12\%}$		U%		ANOVA	A-D	$U_{12\%}$/U%
	$\bar{x}$	*CV* (%)	$\bar{x}$	*CV* (%)	P-value	P-value	
ρ (g/cm³)	0.80	6.92	1.13	8.84	0.000	0.058	0.71
εrt (%)	5.09	8.68	-	-	-	-	-
εtt (%)	11.37	9.12	-	-	-	-	-
f_{c0} (MPa)	58.82	16.10	36.82	14.69	0.000	0.507	1.60
f_{t0} (MPa)	135.46	15.32	93.27	13.70	0.000	0.058	1.45
f_{t90} (MPa)	4.42	18.09	3.47	26.83	0.011	0.651	1.27
f_{v0} (MPa)	13.36	18.18	9.89	12.91	0.000	0.283	1.35
f_{s0} (MPa)	0.93	18.28	0.67	20.54	0.001	0.071	1.40
f_{tm} (MPa)	108.24	17.67	74.82	10.89	0.000	0.158	1.45
E_{c0} (MPa)	17029.81	19.53	13891.52	23.21	0.013	0.013	1.23
E_{t0} (MPa)	16999.19	13.04	15349.99	16.07	0.102	0.555	1.11
E_{tm} (MPa)	16401.98	10.52	13977.42	20.71	0.008	0.052	1.17
f_{h0} (MPa)	100.14	15.22	51.54	19.23	0.000	0.209	1.94
f_{h90} (MPa)	65.21	8.21	36.16	16.19	0.000	0.833	1.80
W (daN·m)	1.16	22.92	0.94	26.68	0.050	0.955	1.24

Table 3. Average result of the normative estimates of strength and stiffness.

Property	Experimental	Est.	Dif. = Experimental – Est.	Error (%)
f_{c0} (MPa)	58.82	44.68	13.25	24.04
f_{t0} (MPa)	135.46	113.60	19.90	16.14
f_{t90} (MPa)	4.42	4.21	0.11	4.73
f_{v0} (MPa)	13.36	12.02	1.12	10.05
f_{s0} (MPa)	0.93	0.81	0.10	12.75
f_{tm} (MPa)	108.24	91.10	15.81	15.83
E_{c0} (MPa)	17029.81	16556.39	184.69	2.78
E_{t0} (MPa)	16999.19	18399.95	-1564.77	-8.24
E_{tm} (MPa)	16401.98	16702.11	-503.33	-1.83

Through the characteristic fiber parallel compressive strength (Equation 2), this species is classified in class C40 (ABNT NBR 7190, 1997). Also, with the premises of this standard, the CV met the limits of 18% and 28% for normal and tangential properties, respectively, evidencing the quality of the tests performed. As can also be seen, the CVs of the properties obtained for the moisture equal to U% were different from the CVs of the properties determined at U12%. This variation occurs because wood properties are affected by the type of species, fiber direction, magnitude of the applied loading, among other conditions (Fragiacomo et al. 2010).

According to the ANOVA results, all 6 strength properties investigated (f_{c0}, f_{v0}, f_{t0}, f_{t90}, f_{s0} and f_{tm}) were significantly affected by the variation in moisture. The difference between the results at U% was 27% to 60% greater when compared to the results at 12% moisture. Therefore, it is evidenced the need to use Equation 3 to correct these PSF properties to 12%. However, through the errors analyzed in Table 3, it is clear that the proposed equations need to be revised, since an error of up to 24% can be obtained. Through the Anderson-Darling test, the ANOVA used on these properties were valid.

Analyzing the 3 stiffness properties (E_{c0}, E_{t0} and E_{tm}), only the modulus of elasticity in tension parallel to the fibers was not significantly affected, which differs from the model in equation 4. In this equation, the modulus of elasticity increases linearly with the decrease in moisture. The average value of this property for the 12% moisture condition was 11% higher than the value of this property for the wood in the saturated condition. The modulus of elasticity in compression parallel to the fibers and the conventional modulus of elasticity in the static bending test were affected by the variation in moisture. Analyzing E_{c0} and E_{tm}, Equation 4 obtained an error of only 2.78% and 1.83%, respectively, showing its effectiveness, differently observed in the resistance equation (Equation 3). Through the Anderson-Darling test, the ANOVA used in these properties were valid.

Regarding the other 4 properties analyzed (ρ, f_{h0}, f_{h90} and W), only the toughness (W) was not significantly affected by the variations in moisture. A difference of 24% between U% and 12% moisture was determined. The other properties (ρ, f_{h0} and f_{h90}) were significantly affected, with a difference between the results of 71% to 94%. Analogously to strength and stiffness, using the Anderson-Darling test, the ANOVA's used on these properties were valid.

Through Table 3, if the expressions of the Brazilian standard NBR 7190 (ABNT 1997) are used for values of U close to 20%, estimated values are still expected to be significantly different from experimental values, which calls attention to the development of new research on the subject. As can be seen from the errors found in these equations, the Brazilian standard underestimates timber structures, as it estimates strengths up to 24% lower. Additionally, other works also concluded that the standard needs revision, presenting an error in its equations. As shown by Lahr et al. (2021), the ratio between shear and compressive strength parallel to the fibers should be 0.24 instead of 0.12, as shown by the standard. Moreover, Couto et al. (2020) and Matos and Molina (2016) also concluded this error in their research, obtaining values 83% and 93%, respectively, when compared with the normative values.

4. CONCLUSIONS

The results of this research allow us to conclude that:

i Through the CV's, the results quality obtained is proven, since they are below the 18% and 28% limit imposed by the Brazilian standard NBR 7190 (ABNT 1997) for wooden structures;

ii Eight out of ten properties of strength and stiffness was significantly affected by the variation in moisture, as predicted in the equations for estimating the strength and stiffness of wood proposed by the Brazilian standard;

iii Among the 15 properties analyzed, only two (E_{t0} and W) were not significantly affected by moisture, contrary to the equations for estimating wood strength and stiffness proposed by the Brazilian standard; and

iv Through the calculated errors, it is evident the need to revise the correction equation, since it brought errors of up to 24% in the estimation of properties when transformed from a moisture higher than 12% to 12% moisture.

As can be seen, the Brazilian standard is correct in linearly reducing most of the properties of strength and stiffness, being wrong only in the modulus of elasticity in tension parallel to the fibers and toughness. However, the equations of the Brazilian standard erroneously predict the transformation of strength and stiffness from a moisture higher than 12% to 12%. Thus, research involving other species is essential to reach more precise conclusions about the effects of varying moisture, as well as the accuracy of the equations proposed by the standard.

ACKNOWLEDGEMENTS

The research was carried out with the support of the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) - Financing Code 001.

SUBMISSION STATUS

Received: 22 Feb. 2022

Accepted: 25 Apr. 2022

Associate editor: João Vicente de Figueiredo Latorraca

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