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ANALYSIS OF MOISTURE CONTENT VARIATION ON STRENGTH AND STIFFNESS PROPERTIES OF *CEDRELLA ODORATA* WOOD SPECIES

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ABSTRACT

In order to analyze the influence of moisture content variation on *Cedrella odorata* wood specie on strength and stiffness properties, considering 12% moisture content up to fiber saturation point (FSP). Most of strength and stiffness properties analyzed were significantly influenced by moisture content according statistical analysis. ANOVA, Anderson Darling and Multiple comparison tests were used at 5% significance level. Considering that most of properties were affected by moisture content, the equations to estimate wood properties according moisture decrease are quite precise, but most of estimations were higher than experimental values at 12% moisture content, indicating the need of a standard review for such estimators, which may lead to an unsafe timber structure design.

KEYWORDS: Mechanical properties, fiber saturation point, equilibrium moisture content.

INTRODUCTION

The use of natural materials on civil construction, such wood, has increased along the years. Used since ancient times for tools an shelters and nowadays the utilization of versatile material on furniture, sports equipment, structural and non-structural use on buildings (Almeida et al. 2013, Christoforo et al. 2017, Ferro et al. 2019, Lahr et al. 2017, Aquino et al. 2021a).

Brazil owns the largest number of wood tree flora (8715 wood species), with 4333 species being endemic of the Brazilian country (Beech et al. 2017, Steege et al. 2020). Also, 58% of Brazilian territory is covered by vegetation (493 million hectares), with 7.84 million hectares being covered by reforestation wood species (pine and eucalyptus), showing the abundance of such natural material in the country (CONAB 2019, IBÁ 2019).

For timber structures design and wood characterization is standardized by the Brazilian standard ABNT NBR 7190: 1997, similar to the International standard ISO 13061: 2017, using small clear wood specimens. For an appropriate and complete wood characterization, which consist on determining 12 physical and mechanical properties, big equipment available only on research centers.

In order to ease the wood characterization of unknown and well-known wood species, the Brazilian code establishes the minimal and simplified characterization, respectively. The minimal characterization consists on the determination of compressive, tensile and shear strength parallel to the grain and apparent density at 12% moisture content. The simplified characterization consists on determine compressive strength parallel to the grain and estimate other mechanical properties using standardized relations.

Also, the Brazilian standard ABNT NBR 7190: 1997 establishes the standard moisture content at 12% for wood. If the physical and mechanical property is obtained with wood on a different moisture content, the property must be corrected for the standard humidity (12%) using standardized equations. Considering that, the standard is not reviewed for 24 years (since 1997) and wood, as an orthotropic and natural material, affected by edaphoclimatic factors (Aquino et al. 2021b, Lahr et al. 2016, Lima et al. 2018, Silva et al. 2018, Teixeira et al. 2021), strength and stiffness properties should not be affected by moisture content, do not requiring a correction to the standard moisture content. Such procedure may lead to increase of wood properties, conducing to a non-secure timber structure design.

Then, the objective of the present research was to analyze if 15 physical and mechanical properties of *Cedrella odorata* are affected by moisture content comparing property values at standard moisture content (12%) and fiber saturation point. After properties determination, analysis of variance (ANOVA) and Anderson-Darling test were performed to check if there were differences considering moisture content. Also, strength and stiffness regression models as a function of moisture content (12% and fiber saturation point) owns an acceptable error for the present wood specie.

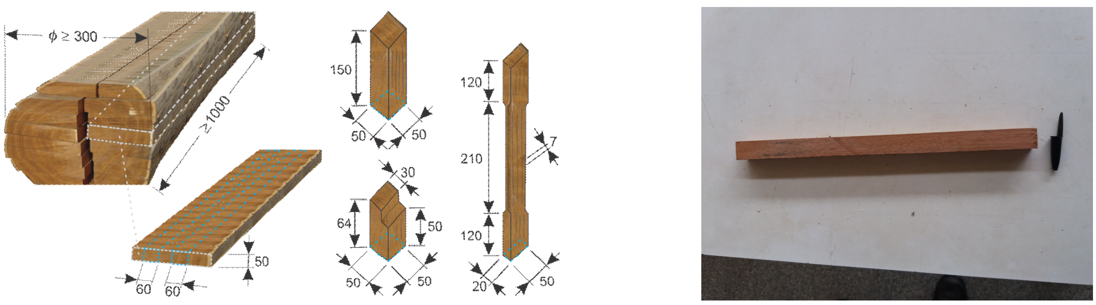
MATERIAL AND METHODS

The specimens of wood *Cedrella odorata* (Cedro amargo), from the south of Roraima (Brazil), were supplied by a company in the wood sector located in São Carlos (Brazil). The homogeneous batch presented around 1 m^3, with pieces containing nominal dimensions of 60 x 160 x 3300 mm.

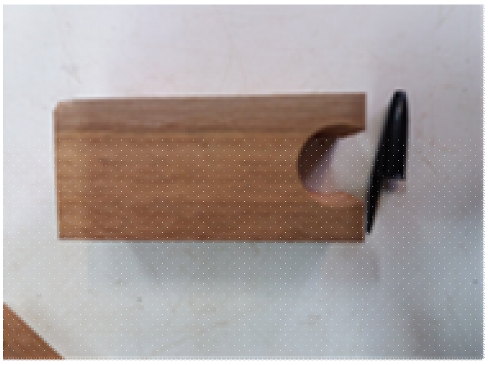
The physical and mechanical properties were determined according to ABNT NBR 7190: 1997. Twelve samples were tested per property analyzed and for both moisture content (12% and fiber saturation point), resulting in 180 samples (physical and mechanical properties) for moisture content at 12% and 180 specimens (physical and mechanical properties) at moisture at fiber saturation point, being a total of 360 specimens. The tested properties are displayed in the Tab. 1. On Fig. 1 wood specimens are described according ABNT NBR 7190: 1997.

Tab. 1: Evaluated physical and mechanical properties.

Abbreviation	Properties
ρ_{12} ($g \cdot cm^{-3}$)	Apparent density at 12% moisture content
ρ_{FSP} ($g \cdot cm^{-3}$)	Apparent density at fiber saturation point
$\varepsilon_{R,2}$ (%)	Radial shrinkage
$\varepsilon_{T,3}$ (%)	Tangential shrinkage
f_{c0} (MPa)	Compressive strength parallel to the fibers
f_{t0} (MPa)	Tensile strength parallel to the fibers
f_{t90} (MPa)	Tensile strength perpendicular to the fibers
f_{v0} (MPa)	Shear strength parallel to the fibers
f_{s0} (MPa)	Splitting strength
f_M (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 tensile parallel to the fibers
E_M (MPa)	Modulus of elasticity in the static bending test
f_{h0} (MPa)	Hardness parallel to the fibers
f_{h90} (MPa)	Hardness perpendicular to the fibers
W (N·m)	Toughness



(a) (b)



(c)

(d)

Fig. 1: (a) Dimension of wood specimens for compression, tension, shear strength and hardness and description of their extraction on timber (dimension in mm) (Morando et al. 2019); (b)toughness impact specimen; (c) splitting strength specimen; (d) normal tensile strength specimen.

As the samples had moisture content close to the equilibrium moisture content (12%), the strength (f_{12}) and stiffness (E_{12}) values were corrected with the aid of Eqs. 1 and 2, respectively, where f_U and E_U are the samples strength and stiffness associated with the U moisture content. It should be noted that the use of such expressions is recommended for moisture content values between 12% and 20%.

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

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

where: U - the moisture content (%).

Knowing the values of strength and stiffness properties in the moisture content associated with the fiber saturation point and also close to equilibrium moisture (≈12%), Eqs. 1 and 2 were also used to estimate such properties for 12% moisture starting from the moisture content of the fiber saturation point determined experimentally, measuring the error of Eqs. 1 and 2 proposed by the Brazilian standard ABNT NBR 7190: 1997.

Seeking the species characterization in the hardwood group (C20, C30, C40 and C60), the characteristic value of compressive strength parallel to the fibers ($f_{c0,k}$) was obtained through Eq. 3, based on the prescriptions of Brazilian Code NBR 7190: 1997 and using the corrected value for 12% moisture ($f_{c0,12\%}$). In this equation, f_1, f_2, …, f_n denote the compressive strength values with 12% moisture in ascending order of the n test specimens tested, noting that 12 samples were executed (n = 12).

$$f_{c0,k} \geq \begin{cases} f_1 \\ 0.70 \cdot \dfrac{\sum_{i=1}^{n} f_n}{n} \\ \left(2 \cdot \dfrac{f_1 + f_2 + f_3 + ... + f_{(n/2)-1}}{(n/2)-1} - f_{n/2} \right) \cdot 1{,}10 \end{cases} \quad (3)$$

Analysis of variance (ANOVA), at a 5% significance level, was used to verify the influence of moisture content variation (from 12% to moisture associated with the fiber saturation point) on the investigated properties. From ANOVA, p-value (probability p) lower than the level of significance implies a significant difference in the means of a given property caused by the variation in moisture content, and non-significance otherwise.

The Anderson-Darling and multiple comparison test, also assessed at a 5% 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.

RESULTS AND DISCUSSION

On Tab. 2 the results of *Cedrella odorata* are presented considering the moisture content of 12% and fiber saturation point. It is important to highlight that mean values of moisture content obtained on fiber saturation point (FSP) and equilibrium moisture content, according Brazilian standard – 12%, were equal to 24.31% and 12.14%, respectively.

Tab. 2: Results of physical and mechanical properties for Cedrella odorata wood specie.

Prop.	MC – 12%		MC - FSP		p-value	12%/FSP
	$\bar{x}$	CV (%)	$\bar{x}$	CV (%)		
ρ ($g{\cdot}cm^{-3}$)	0.50	4.12	0.77	12.98	<u>0.000</u>	0.65
$\varepsilon_{R,2}$ (%)	4.05	11.09	-	-	-	-
$\varepsilon_{R,3}$ (%)	5.66	16.04	-	-	-	-
f_{c0} (MPa)	39.58	12.04	26.58	10.33	<u>0.000</u>	1.49
f_{t0} (MPa)	59.93	23.97	58.36	21.47	0.736	1.03
f_{t90} (MPa)	3.09	22.17	2.37	20.01	<u>0.006</u>	1.30
f_{v0} (MPa)	10.65	17.07	8.75	14.72	<u>0.007</u>	1.22
f_{s0} (MPa)	0.53	14.36	0.51	19.60	0.649	1.04
f_M (MPa)	66.68	14.06	52.06	11.40	<u>0.000</u>	1.28
E_{c0} (MPa)	9604	12.97	8573	18.77	0.093	1.12
E_{t0} (MPa)	10167	14.82	8462	21.41	<u>0.020</u>	1.20
E_M (MPa)	9371	8.61	8542	17.54	0.105	1.10
f_{h0} (MPa)	57.67	22.25	36.83	16.53	<u>0.000</u>	1.57
f_{h90} (MPa)	36.97	37.37	25.43	16.22	<u>0.011</u>	1.45
W (N·m)	4.80	42.93	8.70	22.76	<u>0.000</u>	0.55

MC- moisture content;. $\bar{x}$ - mean value of presented property; FSP – fiber saturation point.

Also, on Tab. 2 is displayed the ratio values between obtained properties for corrected moisture content to 12% and fiber saturation point (12%/FSP) and ANOVA results (5% significance level). The p-values of Anderson Darling and Multiple Comparison tests ranged between 0.123 to 0.531 and 0.092 to 0.643, respectively, validating ANOVA results.

Observing the values of CV for 12% moisture content and fiber saturation point (FSP), for most properties the CV for 12% MC was lower than FSP values. According the literature, such behavior is caused by the decrease of wood strength with moisture increase until fiber saturation. After this, wood properties remains constant, justifying the decrease of CV values for FSP values (Almeida et al. 2020, Claisse 2016, Logsdon 1998).

The Brazilian standard NBR 7190: 1997 establishes reference values of CV equal to 18% for normal efforts and 28% for tangential efforts to consider the characterization adequate, i.e, to have statistical significance without further analysis. Only f_{t0} passed such value. Such fact may happen considering the variability in tensile strength test and failure form, which is fragile and irregular rupture plane, leading to such great variability (Christoforo et al. 2020b, Morando et al. 2019, Pertuzzatti et al. 2018).

The characteristic compressive strength parallel to the grain ($f_{c0,k}$) on 12% moisture content was 32.95 MPa. Then, *Cedrella odorata* wood specie can be classified on C30 strength class according the Brazilian Standard NBR 7190: 1997. Such classification are found on the literature for *Cedrella odorata* wood specie (Dias and Lahr 2004). Checking the ANOVA results for strength properties, only two properties (f_{t0} and f_{s0}) were not affected significantly by moisture content, which can be considered independent of moisture content. For f_{c0}, f_{t90}, f_{v0}, f_M, the difference between 12% moisture properties and FSP properties ranged between 22% to 49%, being a significant variation.

For stiffness properties, only modulus of elasticity in tensile parallel to the fibers were affected significantly for moisture content. The difference for 12% moisture value and FSP value was 20%. E_{c0} and E_M were not influenced by moisture content, which properties may be considered constant regardless moisture content.

For toughness property, such property was changed significantly by moisture content, with a reduction of 45% from 12% moisture value to FSP value, countering the behavior observed in other properties. On the literature, the relation between toughness and apparent density at 12% moisture shows an increase on toughness W with apparent density enhance (Christoforo et al. 2020a).

On Tab. 3, the results of estimated mean values (Est.) for strength and stiffness properties at FSP moisture content using Eqs. 1 and 2 and associated error to the estimation. For the strength properties not affected by moisture content (f_{t0} and f_{s0}), the error on the estimates are more pronounced than the other which moisture were significant. Such behavior indicates the revision need on Eq. 1, performing and adjustment for each strength property.

Considering stiffness properties, the only property significantly influenced by moisture content presented a lower error when compared with E_{c0} and E_M, differently from strength properties. The indication for review of Eq. 2 are also necessary.

Tab. 3: Regression models based on apparent density as an estimator of the other properties.

Prop.	Exp.	Est.	Dif. = Exp. – Est.	Er. (%)
f_{c0} (MPa)	39,58	36,40	3,18	8,04
f_{t0} (MPa)	59,93	79,91	-19,98	33,34
f_{t90} (MPa)	3,09	3,25	-0,16	5,02
f_{v0} (MPa)	10,65	11,98	-1,33	12,50
f_{s0} (MPa)	0,53	0,70	-0,17	31,76
f_M (MPa)	66,68	71,29	-4,61	6,91
E_{c0} (MPa)	9604	10683	-1079	11,24
E_{t0} (MPa)	10167	10545	-378	3,72
E_M (MPa)	9371	10645	-1274	13,60

Exp. - the experimental value at 12% moisture; Est.- the estimated property at 12% moisture using the experimental property at FSP (24,31%); Er. - the associated error to the estimate.

In general, for most of estimated strength and stiffness properties, such values are higher than the experimental values, leading to unsecure estimates and an unsafe design of timber structures, highlighting the demand for review of Eqs. 1 and 2 on Brazilian standard. Even though such equations are valid for moisture content below 20%, such performance should not change much on equation boundary and accuracy should be preserved. But there was an increase on properties with moisture content reduction.

Such performance were observed for *Cedrelinga catenaeformis* (Soares et al. 2021). The authors investigated the influence of moisture content variation (12% to FSP) on this wood specie, characterizing 12 mechanical properties, with a FSP equal to 27,11%. Two strength properties and one stiffness property were significantly influenced by moisture content. As occurred in this research, associated error on non-affected properties by moisture content was higher than influenced properties.

CONCLUSIONS

(1) Most of strength and stiffness properties analyzed in this research were influenced by moisture content rise from 12% to FSP, indicating some precision on how to consider moisture content reduction on properties. *(2)* Estimation using equations disposed on Brazilian standard presented inaccurate predictions, which may lead to unsafe timber design project, indicating the demand for a standard review. *(3)* The only property which estimate were lower than experimental value was f_{c0}, the main property on wood, used for classification on strength classes. *(4)* In order for a better comprehension of the effect of moisture on strength and stiffness properties, further researches with other tropical wood species must be carried out.

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