Evaluation of moisture content variation on strength and stiffness properties of *Cedrella* sp. wood specie

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Abstract

In order to evaluate the influence of moisture content on wood physical and mechanical properties, the present research analyzed the influence of moisture content variation on *Cedrella* sp. on 12 strength and stiffness properties, considering 12% moisture content up to Fiber Saturation Point (FSP) were considered. Brazilian Standard consider a correction on wood properties obtained on moisture content different of 12%, reducing the properties. Eight properties from these twelve were significantly influenced by moisture content according to statistical analysis (5% significance level). 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 to moisture decrease are quite precise, but most of estimations were higher than the 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. For a conclusive consideration of moisture content variation influence on wood products, further researches with other tropical wood species are required.

Keywords: mechanical properties, fiber saturation point, equilibrium moisture content.

1. Introduction

The use of natural materials for civil construction, such as wood, has increased along the years. Used since ancient times for tools and shelters, and nowadays, for furniture, sports equipment, as well as structural and non-structural use in buildings (Almeida *et al*., 2013; Christoforo *et al*., 2017; Lahr *et al*., 2017).

Brazil has the largest number of wood tree flora (8715 wood species), with 4333 species being endemic of the Brazilian country (Beech *et al*., 2017). Also, 58% of the Brazilian territory is covered by vegetation (493 million hectares), with 7.84 million hectares being covered by reforested wood species (pine and eucalyptus), showing the abundance of such natural material within the country (CONAB, 2019; Ibá, 2019).

Timber structure design and wood characterization is standardized by the Brazilian Standard ABNT NBR 7190 (ABNT, 1997), similar to the International Standard ISO 13061 (ISO, 2017), using small clear wood specimens. For an appropriate and complete wood characterization, which consists of determining 12 physical and mechanical properties, requires big equipment, available only in 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 of determining the compressive, tensile and shear strength parallel to the grain and apparent density at 12% moisture content. The simplified characterization consists of determining the compressive strength parallel to the grain and estimation of the other mechanical properties using standardized relationships.

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

Then, the objective of the present research was to analyze if 15 physical and mechanical properties of *Cedrella* sp. are affected by moisture content comparing property values at standard moisture content (12%) and fiber saturation point. After property determination, analysis of variance (ANOVA) and the 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 species.

2. Material and methods

The specimens of wood *Cedrella* sp. (cedar), 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 m³, with pieces containing nominal dimensions of 6 cm x 16 cm x 330 cm.

The physical and mechanical properties were determined according to the premises of the Brazilian standard NBR 7190 (ABNT, 1997). Twelve samples were tested per property analyzed, as well as the moisture content (12% and fiber saturation point) of each, resulting in 360 samples. The tested properties are displayed in Table 1. In Figure 1, wood specimens' dimensions are described.

Table 1 – Evaluated physical and mechanical properties.

Abbreviation	Properties
ρ_{12} (g/cm³)	Apparent density at 12% moisture content
ρ_{FSP} (g/cm³)	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

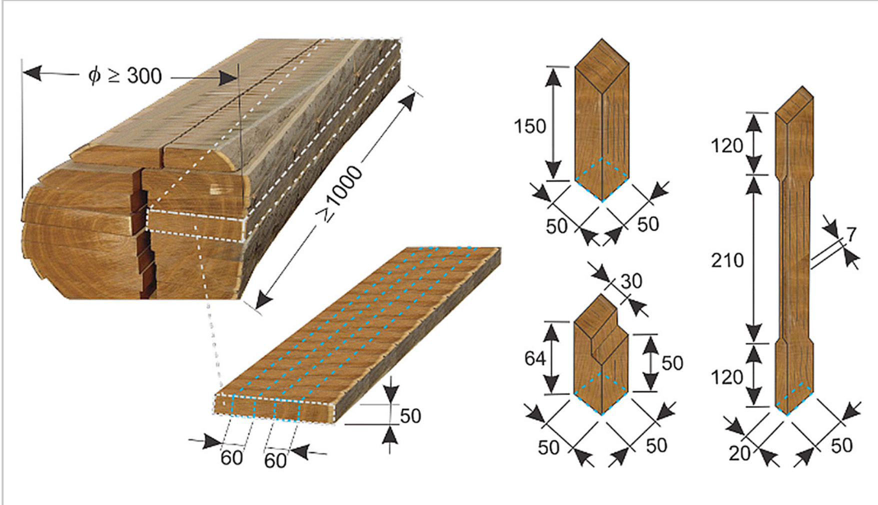

Figure 1 - Dimension of wood specimens and description of their extraction (Dimension in mm). Source: Morando *et al.* (2019).

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 equations 1 and 2, respectively, where f_U and E_U are the sample's 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%.

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

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

With U the moisture content, in percentage (%).

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%), Equations 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 Equations 1 and 2 proposed by the Brazilian standard ABNT NBR 7190 (ABNT, 1997). The moisture content was evaluated using the mass method, drying on oven until reach the dried mass and the difference of mass is the moisture content.

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 Equation 3, based on the prescriptions of Brazilian Code NBR 7190 (ABNT, 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).

$$f_{c0,k} \geq \begin{cases} f_1 \\ 0.70 \cdot \dfrac{\sum_{i=1}^{n} f_n}{n} \\ \left(2 \cdot \dfrac{f_1 + f_2 + f_3 + \ldots + f_{(n/2)-1}}{(n/2) - 1} - f_{n/2}\right) \cdot 1.10 \end{cases} \tag{3}$$

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, a 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 (Anderson-Darling test) and equality of variances (Multiple Comparison test). A p-value equal to or greater than the significance level implies validation of the ANOVA model. The ANOVA evaluated if the properties are equivalent at 12% moisture content and at fiber saturation point (FSP).

3. Results

In Table 2, the results of *Cedrella* sp. 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 to the Brazilian Standard – 12%, were equal to 25.34% and 12.06%, respectively.

Also, in Table 2, the ratio values between obtained properties for corrected moisture content to 12% and fiber saturation point (12%/FSP) and ANOVA results (5% significance level) are displayed. 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.

Table 3 displays the results of estimated mean values (Est.) for strength and stiffness properties at FSP moisture content using Equations 1 and 2 and associated error to the estimation.

Table 2 – Results of physical and mechanical properties for *Cedrella* sp. wood specie.

Prop,	MC – 12%		MC - FSP		p-value	12%/FSP
	$\bar{X}$	CV (%)	$\bar{X}$	CV (%)		
ρ (g/cm³)	0.50	5.34	0.59	5.33	0.000	0.85
$\varepsilon_{R,2}$ (%)	3.45	24.13	-	-	-	-
$\varepsilon_{R,3}$ (%)	5.02	19.32	-	-	-	-
f_{c0} (MPa)	31.48	17.88	27.92	14.36	0.088	1.13
f_{t0} (MPa)	67.23	22.79	51.75	38.83	0.045	1.30
f_{t90} (MPa)	2.84	26.90	2.31	22.58	0.058	1.23
f_{v0} (MPa)	9.21	24.41	9.22	24.62	0.993	1.00
f_{s0} (MPa)	0.46	32.83	0.51	16.28	0.340	0.90
f_M (MPa)	56.58	20.46	62.00	27.68	0.372	0.91
E_{c0} (MPa)	8353	14.09	8895	23.58	0.443	0.94
E_{t0} (MPa)	9523	20.20	9154	17.67	0.617	1.04
E_M (MPa)	8716	19.85	9286	20.94	0.456	0.94
f_{h0} (MPa)	48.51	35.78	41.50	22.02	0.229	1.17
f_{h90} (MPa)	32.18	25.01	32.17	19.78	0.998	1.00
W (N·m)	5.30	39.95	7.80	27.67	0.010	0.68

- From ANOVA, evaluated at 5% significance level, p-value below to 0.05 implies on nonequivalence of properties mean values, and equivalence otherwise.

Table 3 – Estimate results fo strength and stiffness properties mean values.

Prop,	Exp,	Est,	Dif, = Exp, – Est,	Er, (%)
f_{c0} (MPa)	31.48	38.23	-6.75	21.44
f_{t0} (MPa)	67.23	70.86	-3.63	5.40
f_{t90} (MPa)	2.84	3.16	-0.32	11.38
f_{v0} (MPa)	9.21	12.62	-3.41	37.08
f_{s0} (MPa)	0.46	0.70	-0.24	51.81
f_M (MPa)	56.58	84.90	-28.32	50.05
E_{c0} (MPa)	8353	11084.95	-2731.95	32.71
E_{t0} (MPa)	9523	11407.71	-1884.71	19.79
E_M (MPa)	8716	11572.21	-2856.21	32.77

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

4. Discussion

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 to 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

(ABNT, 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. The properties f_{t0}, f_{v0}, f_{s0} passed such value. Such fact may happen considering the variability in tensile strength test and failure form, which is a fragile and irregular rupture plane, leading to such great variability (Christoforo *et al*., 2020a; Morando *et al*., 2019; Pertuzzatti *et al*., 2018).

The characteristic compressive strength parallel to the grain ($f_{c0,k}$) with 12% moisture content was 30.00 MPa. Then, the *Cedrella* sp. wood species can be classified in the C30 strength class according the Brazilian Standard NBR 7190 (ABNT, 1997). Such classification is found in literature for *Cedrella* sp. wood specie (Dias and Lahr, 2004).

Checking the ANOVA results for strength properties, only two properties (f_{t0} and W) were affected significantly by moisture content, which can be considered dependent on moisture content. For fc0, the difference between 12% moisture properties and FSP properties were 30%, being a significant variation. The other properties that were not influenced by moisture content presented a difference ranging between a reduction of 10% from 12% moisture to FSP moisture property value to an increase of 23%.

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, whose properties may be considered constant regardless of moisture content.

For the toughness property, such property was changed significantly by moisture content, with a reduction of 32% from 12% moisture value to FSP value, countering the behavior observed in other properties. In literature, the relationship between toughness and apparent density at 12% moisture shows an increase in W with apparent density enhancement (Christoforo *et al*., 2020b).

Observing Table 3, for the strength property affected by moisture content (f_{t0}), the error in the estimates are more pronounced than the other, where moisture was significant. Such behavior indicates the revision need for Equation 1, performing and adjustment for each strength property considering that Brazilian Standard considers a linear increase on strength properties with moisture content decrease. For *Cedrella* sp. such consideration does not reflect on wood performance.

Considering stiffness properties, no property was significantly influenced by the moisture content, presenting an average 30% error. The indication for review of Equation 2 are also necessary, in order to achieve an appropriate correlation between moisture content and stiffness property values, as observed for strength properties.

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

Such behavior was observed for Cedrelinga catenaeformis (Soares *et al*., 2021). The authors investigated the influence of moisture content variation (12% to FSP) on this wood species, 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, indicating that the estimation demands review.

5. Conclusions

- Eight of twelve strength and stiffness properties were influenced by moisture content rise from 12% to FSP, indicating some precision on how to consider moisture content reduction on properties;
- Estimation using Equations disposed on Brazilian Standard presented inaccurate predictions, which may lead to an unsafe timber design project, indicating the demand for a standard review;
- The only property whose estimate was lower than the experimental value was fc0, the main property on wood, used for classification of strength classes;
- 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 in order to obtain a conclusive consideration.

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