Critical analysis of the mechanical properties of Dinizia *excelsa* wood in relation to moisture variations: implications for ABNT NBR 7190:2022

Análise crítica das propriedades mecânicas da madeira de Dinizia *excelsa* em relação às variações de umidade: implicações para a ABNT NBR 7190:2022

DOI: 10.54033/cadpedv21n1-117

Recebimento dos originais: 12/12/2023
Aceitação para publicação: 15/01/2024

Iuri Fazolin Fraga
Master in Civil Engineering
Institution: Universidade Federal de São Carlos
Address: Rod. Washington Luiz, s/n, São Carlos – SP, CEP: 13565-905
E-mail: iurifraga@outlook.com

Felipe Nascimento Arroyo
Master in Civil Engineering
Institution: Universidade Federal de São Carlos
Address: Rod. Washington Luiz, s/n, São Carlos – SP, CEP: 13565-905
E-mail: lipe.arroyo@gmail.com

Fernando Júnior Resende Mascarenhas
Master in Civil Engineering
Institution: Universidade de Coimbra
Address: R. Luís Reis Santos, Pólo II, Coimbra, Portugal, CEP: 3030-788
E-mail: fer.jr.resende@hotmail.com

Heloiza Candeia Ruthes
Doctor in Civil Engineering
Institution: Universidade Federal de São Carlos
Address: Rod. Washington Luiz, s/n, São Carlos – SP, CEP: 13565-905
E-mail: heloruthes@gmail.com

Larissa Soriani Zanini Ribeiro Soares
Doctor in Civil Engineering
Institution: Instituto Federal de Educação, Ciência e Tecnologia do Triângulo Mineiro
Address: Av. Dr. Randolfo Borges Jr., 2900, Uberaba – MG, Brasil,
CEP: 38064-300
E-mail: larissazanini@iftm.edu.br

Vinícius Borges de Moura Aquino
Doctor in Civil Engineering
Institution: Universidade Estadual Paulista "Júlio de Mesquita Filho"
Address: Alm. Bahia, 550, Ilha Solteira – SP, Brasil, CEP: 15385-000
E-mail: aquino.vini@hotmail.com

André Luis Christoforo
Doctor in Civil Engineering
Institution: Universidade Federal de São Carlos
Address: Rod. Washington Luiz, s/n, São Carlos – SP, CEP: 13565-905
E-mail: christoforoal@yahoo.com.br

Francisco Antonio Rocco Lahr
Doctor in Civil Engineering
Institution: Universidade de São Paulo
Address: Av. Trabalhador São Carlense, 400, São Carlos – SP, CEP: 13566-590
E-mail: frocco@sc.usp.br

ABSTRACT
Brazil possesses an extensive forested territory conducive to the prevalence of numerous tree species, including *Dinizia excelsa*, commonly known as Angelim-Vermelho. The utilization of a wood species in a structural system necessitates a comprehensive analysis of its physical-mechanical properties. In this context, a crucial variable for study is the moisture content, the variations of which, *a priori*, can significantly impact wood properties. Although the Brazilian code prescribes specific models to adjust strength and stiffness concerning the reference moisture, allowing a linear increase as moisture content decreases, this phenomenon may not universally apply to all wood species. Some species may exhibit statistically constant or even decreased values, contradicting code predictions. Therefore, by employing analysis of variance (ANOVA) at a 5% significance level, this research aims to examine the impact of moisture content variation (ranging from 12% to the fiber saturation point – FSP) on 12 mechanical properties of *Dinizia excelsa* wood. Each type of test involved the creation of 12 specimens, totaling 360 determinations. Among the 12 mechanical properties examined, four showed no significant variations between 12% moisture and the FSP. This suggests that the code formulation inadequately addresses all properties for all wood species. Furthermore, the study revealed that correction models can result in strength values higher than experimentally obtained, thus overestimating structural capacities, and compromising safety. Therefore, a critical reassessment of the existing Brazilian code is imperative.

Keywords: *Dinizia excelsa*, moisture content adjustments, analysis of variance, mechanical properties.

RESUMO
O Brasil possui um extenso território florestal propício à prevalência de inúmeras espécies de árvores, incluindo a *Dinizia excelsa*, comumente conhecida como

Angelim-Vermelho. A utilização de uma espécie de madeira em um sistema estrutural requer uma análise abrangente de suas propriedades físico-mecânicas. Nesse contexto, uma variável crucial para o estudo é o teor de umidade, cujas variações, *a priori*, podem impactar significativamente as propriedades da madeira. Embora a norma brasileira prescreva modelos específicos para ajustar a resistência e a rigidez em relação à umidade de referência, permitindo um aumento linear à medida que o teor de umidade diminui, esse fenômeno pode não se aplicar universalmente a todas as espécies de madeira. Algumas espécies podem apresentar valores estatisticamente constantes ou até mesmo decrescentes, contradizendo as previsões normativas. Portanto, por meio da análise de variância (ANOVA) a um nível de significância de 5%, esta pesquisa visa examinar o impacto da variação do teor de umidade (variando de 12% até o ponto de saturação das fibras – PSF) em 12 propriedades mecânicas da madeira de *Dinizia excelsa*. Cada tipo de teste envolveu a confecção de 12 espécimes, totalizando 360 determinações. Entre as 12 propriedades mecânicas examinadas, quatro não apresentaram variações significativas entre 12% de umidade e o PSF. Isso sugere que a formulação da norma aborda inadequadamente todas as propriedades para todas as espécies de madeira. Além disso, o estudo revelou que modelos de correção podem resultar em valores de resistência superiores aos obtidos experimentalmente, superestimando assim as capacidades estruturais e comprometendo a segurança. Portanto, uma reavaliação crítica da norma brasileira existente é imperativa.

Palavras-chave: *dinizia excelsa*, ajustes de teor de umidade, análise de variância, propriedades mecânicas.

1 INTRODUCTION

Wood, as a natural and renewable material, has been manipulated by humans since ancient times. In contemporary contexts, its widespread use in civil construction, especially in the structural systems of buildings, is notable on a global scale. The significance of wood usage is particularly evident in countries in the Northern Hemisphere, where the wood-frame system is extensively employed in the construction of single-family homes (Araujo *et al*., 2016; Pan *et al*., 2019; Yuan *et al*., 2023).

Like other materials employed in structural applications, wood offers distinct advantages, including excellent mechanical properties (Christoforo *et al*., 2020) and a favorable strength-to-weight ratio (Ramage *et al*., 2017; Izzi *et al*., 2018; Hayes *et al*., 2023). This characteristic contributes to the construction of buildings that are comparatively lightweight when contrasted with conventional systems. In recent years, there has been notable progress in the development of wood-derived products, primarily sourced from planted forests (Seng Hua *et al*., 2022; Punhagui & John, 2022). This trend has captivated consumers interested in environmentally sustainable products, while also fostering a movement toward the rationalization of construction practices.

An additional advantage worth highlighting is the flexibility to use various wood species in the processing of wood products. Brazil stands out as one of the main global repositories of forest potential, with an estimated tree diversity exceeding 15,000 species in the Amazon Rainforest alone (Sousa-Baena *et al*., 2014; Daly & Martinez-Habibe, 2019; Ter Steege *et al*., 2020). Among these species, *Dinizia excelsa*, colloquially known as Angelim-Vermelho, is native. Classified in the hardwood group, *Dinizia excelsa* wood exhibits notable density (950-1000 kg/m^3 under standard reference conditions, i.e., 12% moisture content), hardness, excellent dimensional stability, and high resistance to deterioration (Loureiro *et al*., 2000; Mesquita *et al*., 2009; Iwakiri *et al*., 2016). Furthermore, these wood species are prevalent in regions or countries where the Amazon Rainforest is present (Loureiro *et al*., 2000; Mesquita *et al*., 2009; Iwakiri *et al*., 2016).

For a wood species to be considered suitable for structural applications, it is imperative to have a comprehensive understanding of its physical and mechanical properties. This knowledge enables a thorough analysis of its behavior under various load conditions and assists in establishing standardized values, including strength and stiffness classes. Consequently, this process simplifies the identification of more suitable applications in civil construction (Lima *et al*., 2018; Soares *et al*., 2021[b]).

During the characterization process, a critical variable studied is the moisture content (MC) within the wood. This property, *a priori*, significantly influences the physical and mechanical attributes of the material (Kretschmann, 2008). In the Brazilian context, the criteria for the design, testing, and characterization of timber structures must adhere to the parameters established in the ABNT NBR 7190 (2022) code. This code, in turn, provides models to adjust the strength and stiffness properties of wood based on the reference moisture.

The purpose of these equations is to adjust the values of mechanical properties obtained in experimental tests to comply with a standardized moisture content of 12%. The prescribed approach involves considering a linear increase in the variation of strength and stiffness properties as the moisture content decreases (ABNT NBR 7190, 2022).

However, in the next chapter, research will be presented that highlights a gap in this code premise. Instead of observing a linear increase in the values of the physical-mechanical properties of wood with the reduction of moisture content, some investigations point out the non-significance of the values or even an inverse relationship – i.e., mechanical property values are directly proportional to the moisture content. Given this scenario, the need for a meticulous analysis of code accuracy becomes evident.

2 INFLUENCE OF MOISTURE CONTENT ON THE MECHANICAL PROPERTIES OF HARDWOODS

According to the exposition presented in the Introduction, this chapter is dedicated to presenting research efforts that have sought to assess the influence exerted by moisture content on the properties of different wood species belonging to the hardwood group.

Lahr *et al*. (2016) investigated the influence of moisture content on 15 physical-mechanical properties of Jatobá wood (*Hymenaea stilbocarpa* Hayne), sourced from different regions of the Amazon. This species was classified as C60 by the then ABNT NBR 7190 (1997), indicating a characteristic compressive strength parallel to the grain $f_{c0,k} \geq 60$ MPa. The results revealed that the extraction region of the test specimens did not significantly affect the evaluated physical-mechanical properties. Concerning the influence of moisture content, when comparing the fiber saturation point (FSP) with the reference moisture content of 12%, the authors observed significant variations in eight out of the 15 analyzed properties. Notably, at a moisture content of 12%, mean values were higher than the FSP in properties such as compression, tension, and shear strength parallel to the grain, as well as in the modulus of elasticity in bending and in compression parallel to the grain. These results align with the models proposed by the then ABNT NBR 7190 (1997), which predict a linear increase in mechanical properties with a reduction in moisture content.

However, due to wood being a natural, heterogeneous, and anisotropic material (Brémaud *et al*., 2011; Ozyhar *et al*., 2012), certain strength and stiffness properties may not be significantly affected even in the presence of variations in moisture content, as demonstrated by Soares *et al*. (2021[a]). In their study on the *Cedrelinga catenaeformis* species, classified as C20 according to the then ABNT NBR 7190 (1997) ($20 \leq f_{c0,k} < 30$ MPa), the authors noted that toughness increased by approximately 59% at the FSP compared to the 12% moisture content. Additionally, eight out of the 12 evaluated properties showed no significant variations, contrary to code predictions.

Aquino *et al*. (2021) investigated the influence of moisture content in a species belonging to class C30 ($30 \leq f_{c0,k} < 40$ MPa), namely *Cedrella odorata*. By contrasting the saturated condition (FSP) with the reference moisture content of 12%, in contrast to the findings of Soares *et al*. (2021[a]), the researchers observed that most of the analyzed strength and stiffness properties were significantly affected by moisture content, as indicated by statistical analysis. Given this scenario, the study concluded that code equations for estimating wood properties, considering the decrease in moisture, are quite accurate. However, it is relevant to note that most estimates showed values higher than the experimental ones with a moisture content of 12%, resulting in an overestimation of structures and compromising safety.

Ruthes *et al*. (2022) reached a conclusion analogous to that of Soares *et al*. (2021[a]). Most of the evaluated mechanical properties of *Vatairea sp*. (class C40, i.e., $40 \leq f_{c0,k} < 60$ MPa) exhibited insignificant variations. Furthermore, the most significant errors in the estimates were observed for properties that were notably influenced by moisture content, once again highlighting inaccuracies in code models.

The ABNT NBR 7190 (1997) did not initially cover the C50 strength class within the hardwood group. This gap was addressed in the 2022 version. Despite not previously including this class, Arroyo *et al*. (2022) conducted a comparative analysis of 15 physical and mechanical properties in both saturated and reference moisture conditions (12%), focusing on the species *Pouteria Pachycarpa* (50 ≤ $f_{c0,k}$ < 60 MPa). Out of the 15 evaluated properties, two showed no variations when analyzed at both the FSP and 12% moisture. Furthermore, the authors noted that the correction equations stipulated by the Brazilian code exhibited errors of up to 24% in estimating properties at 12% moisture.

Finally, it is worth highlighting the study conducted by Fraga *et al*. (2022), dedicated to the analysis of the species *Dipteryx odorata* (class C60, i.e., $f_{c0,k}$ ≥ 60 MPa). When examining the 12 specific mechanical properties, the researchers identified that four of them (tensile strength parallel to the grain – f_{t0}, shear strength parallel to the grain – f_{v0}, conventional bending strength parallel to grain – f_m, and toughness – W) showed no significant variations between 12% moisture and the FSP. This finding led to the conclusion that the code formulation does not encompass all properties for all species. Additionally, it was observed that the correction models stipulated by the code result in strength values higher than those obtained experimentally, leading to an overestimation of structures, and compromising safety.

Analyzing the discussed research, the following considerations stand out:

- **Limited applicability of ABNT NBR 7190 (1997) equations:** The correction equations for mechanical properties established by ABNT NBR 7190 (1997) were formulated based on a limited number of wood species, encompassing various mechanical characteristics through only two adjustment equations.
- **Lack of uniform behavior across species:** The absence of a uniform behavioral pattern among species is observed. In some studies, the code model demonstrates effectiveness. On the other hand, some research indicates that the same models do not provide reliable estimates of wood mechanical properties, resulting in comparisons with reduced significance or even behavior contrary to that advocated by the code.
- **Impact of revised codes:** All mentioned studies were conducted based on the 1997 version of ABNT NBR 7190 (1997). This code has been revised and has been in effect since 2022. However, the prediction models for mechanical properties remain unchanged since then, emphasizing

once again the importance of new research, encompassing different species, to enrich the bibliographic foundation for future code adjustments.

Given such limitations and considering the absence of studies at this level for the species *Dinizia excelsa* in the literature, the main objective of this study is to investigate the influence of moisture content variation, ranging from fiber saturation point (FSP) to the reference condition of 12%, on twelve specific mechanical properties of the mentioned species. To conduct this analysis, the analysis of variance (ANOVA) technique is employed, with a significance level of 5%. Simultaneously, the research aims to validate the appropriateness of the correction equations prescribed by ABNT NBR 7190 (2022).

3 MATERIAL AND METHODS

Experimental research for the characterization of the physical and mechanical properties of wood samples was conducted at the Wood and Timber Structures Laboratory (LaMEM – Laboratário de Madeira e Estruturas de Madeira) of the Department of Civil Engineering at the São Carlos School of Engineering (EESC – Escola de Engenharia de São Carlos), University of São Paulo (USP – Universidade de São Paulo).

The wood samples used were all derived from *Dinizia excelsa* (Angelim-Vermelho), harvested in the southern region of the state of Roraima, Brazil. These samples were provided in both green and air-dried conditions by a lumber company located in São Carlos, Brazil. The nominal dimensions of the tested pieces were 6 × 16 × 335 cm, constituting a homogeneous batch of approximately 1.0 m^3.

Table 1 presents the physical and mechanical properties determined according to the specifications and methods of the Brazilian code ABNT NBR 7190-3 (2022). Twelve specimens were made available for each type of test (ABNT NBR 7190-3, 2022) and for each moisture content (12% and fiber saturation point – FSP), totaling 360 determinations.

Table 1 – Physical and mechanical properties evaluated

Variable	Description
ρ (kg/m³)	Apparent density
ε_{rt} (%)	Total radial shrinkage
ε_{tt} (%)	Total tangential shrinkage
f_{c0} (MPa)	Compression strength parallel to the grain
f_{t0} (MPa)	Tension strength parallel to the grain
f_{t90} (MPa)	Tension strength perpendicular to the grain
f_{v0} (MPa)	Shear strength parallel to the grain
f_{s0} (MPa)	Cleavage strength parallel to the grain
f_{m} (MPa)	Conventional bending strength parallel to grain
E_{c0} (MPa)	Modulus of elasticity in compression parallel to the grain
E_{t0} (MPa)	Modulus of elasticity in tension parallel to the grain
E_{m} (MPa)	Conventional modulus of elasticity in bending
f_{h0} (MPa)	Hardness parallel to the grain
f_{h90} (MPa)	Hardness perpendicular to the grain
W (N·m)	Toughness

Source: Prepared by the authors (2023).

As established by ABNT NBR 7190-3 (2022), the wood moisture content (U) is calculated as the ratio of the mass of water contained in the wood to the mass of dry wood, expressed by Equation 1. Both standard moisture contents (12%) and the fiber saturation point (FSP) were obtained through precise control of the sample masses.

$$U(\%) = \frac{m_i - m_s}{m_s} \cdot 100 \quad (1)$$

Being:

m_i is the initial mass of the wood, in grams;
m_s is the mass of dry wood, in grams.

After reaching a moisture content (MC) of approximately 12%, the strength (f) and stiffness (E) values of the samples were adjusted to this specific moisture content (f_{12}; E_{12}). These corrections were made using Equations 2 and 3, as recommended by the ABNT NBR 7190-1 (2022) code. Here, f_U and E_U represent, respectively, the strength and modulus of elasticity of the samples associated with the moisture content U. It is important to note that the application of these expressions is advised for moisture contents ranging between 12% and 20%.

$$f_{12} = f_U\left(1 + \frac{3(U-12)}{100}\right) \tag{2}$$

$$E_{12} = E_U\left(1 + \frac{2(U-12)}{100}\right) \tag{3}$$

Upon obtaining knowledge of the strength and stiffness values at the moisture content (MC) associated with the fiber saturation point (FSP) and near the reference moisture content (approximately 12%), Equations 2 and 3 were applied to estimate these properties for a moisture content of 12%, based on the experimentally determined FSP moisture content.

After correcting the values (from about 12% to exactly 12%) of the compressive strength parallel to the grain (f_{c0}), Equation 4 (ABNT NBR 7190-3, 2022) was used to determine the characteristic value ($f_{c0,k}$) and, consequently, categorize the wood into one of the strength classes of the hardwood group. In this equation, f_1, f_2 to f_n represent the compressive strength values (f_{c0}) in ascending order for the "n" tested specimens (n = 12, per evaluated wood species).

$max(f_{c0,1}; 0{,}7 f_{c0,\text{mean}}) \leq f_{c0,k} \leq f_{c0,\text{mean}}$, being

$$f_{c0,k} = \left(2\frac{\sum_{i=1}^{\frac{n}{2}-1} f_{c0,i}}{\frac{n}{2}-1} - f_{c0,\frac{n}{2}}\right)1{,}1 \tag{4}$$

Analysis of variance (ANOVA), applied at a significance level of 5%, was employed to examine the influence of moisture content variation (MC), ranging from 12% to the MC associated with the FSP, on the investigated properties. In the context of ANOVA, a p-value (probability p) below the significance level indicates a statistically significant difference in the means of a particular property, attributed to the variation in moisture content. Conversely, non-significance suggests the absence of this effect.

To ensure the validity of the ANOVA model, the Anderson-Darling test was employed, also at a significance level of 5%. This test aims to verify the normality in the distribution of residuals and equality of variances. Obtaining a p-value equal to or higher than the significance level confirms the model's compliance with normality and homoscedasticity requirements, reinforcing the reliability of the results obtained by ANOVA.

4 RESULTS AND DISCUSSION

Table 2 displays the results of evaluated properties for the species *Dinizia excelsa* (Angelim-Vermelho) concerning a moisture content of 12% (corrected values) and the fiber saturation point (FSP), accompanied by the coefficient of variation (CV). It is noteworthy that the mean moisture content values (MC) obtained at the FSP and those near the reference condition of 12% (as per ABNT NBR 7190-3, 2022) were 19.94% and 12.29%, respectively.

Table 2 – Results of physical and mechanical properties of Dinizia excelsa wood

Variable	MC – 12%		MC – FSP		p-value ANOVA	p-value A-D	12%/ FSP
	$\bar{x}$	CV (%)	$\bar{x}$	CV (%)			
ρ (kg/m³)	1147.69	11.95	1254.71	11.02	0.082	0.422	0.91
ε_{rt} (%)	5.18	13.86	---	---	---	---	---
ε_{tt} (%)	8.49	9.29	---	---	---	---	---
f_{c0} (MPa)	78.80	11.81	66.41	10.48	0.002	0.550	1.19
f_{t0} (MPa)	103.04	17.21	80.76	14.42	0.003	0.174	1.26
f_{t90} (MPa)	4.76	26.65	4.05	26.68	0.131	0.252	1.20
f_{v0} (MPa)	17.86	21.68	13.79	15.95	0.001	0.965	1.37
f_{s0} (MPa)	0.92	13.09	0.82	17.04	0.082	0.409	1.12
f_m (MPa)	112.07	16.39	99.85	10.98	0.071	0.926	1.12
E_{c0} (MPa)	16883.70	17.17	14502.88	16.19	0.046	0.302	1.16
E_{t0} (MPa)	17181.54	17.09	14207.40	12.80	0.009	0.288	1.21
E_m (MPa)	16750.52	10.16	14311.82	11.00	0.002	0.459	1.17
f_{h0} (MPa)	147.78	14.51	107.57	11.03	0.000	0.903	1.37
f_{h90} (MPa)	138.56	13.76	101.27	14.17	0.000	0.434	1.37
W (N·m)	19.90	26.32	18.30	25.43	0.450	0.922	1.09

Source: Prepared by the authors (2023).

In Table 2, the ratios between properties obtained for the moisture content corrected to 12% and the FSP (12%/FSP) are presented, along with the results of ANOVA and the Anderson-Darling test (A-D), both at a 5% significance level.

Using Equation 4, the characteristic compressive strength parallel to the grain ($f_{c0,k}$) was calculated at 70.55 MPa, placing the studied species in the D60 class, belonging to the hardwood group. In the most recent classification of ABNT NBR 7190-1 (2022), the prefix "D" denotes "Dicotyledon", while 60 refers to the characteristic compressive strength parallel to the grain ($f_{c0,k} \geq 60$ MPa).

To validate the obtained results at a 12% moisture content, they will be contrasted with those obtained by Couto *et al*. (2018), who conducted a comprehensive characterization of the species *Dinizia excelsa*. The comparative parameters, along with the calculated confidence intervals (CI), are detailed in Table 3.

Table 3 – Comparison between the experimental results (mean values) and literature data

Variable	This research		Couto et al. (2018)		CI (95%)
	$\bar{x}$	CV (%)	$\bar{x}$	CV (%)	
ρ (kg/m^3)	1147.69	11.95	1130.00	10.00	[1073; 1222]
ε_{rt} (%)	5.18	13.86	5.10	12.00	[5; 6]
ε_{tt} (%)	8.49	9.29	8.42	8.00	[8; 9]
f_{c0} (MPa)	78.80	11.81	78.00	8.00	[74; 84]
f_{t0} (MPa)	103.04	17.21	105.00	33.00	[93; 113]
f_{t90} (MPa)	4.76	26.65	4.80	28.00	[4; 6]
f_{v0} (MPa)	17.86	21.68	19.00	23.00	[17; 21]
f_{s0} (MPa)	0.92	13.09	0.90	12.00	[0.86; 0.99]
f_m (MPa)	112.07	16.39	110.00	14.00	[102; 122]
E_{c0} (MPa)	16883.70	17.17	16695.00	18.00	[15308; 18459]
E_{t0} (MPa)	17181.54	17.09	17024.00	17.00	[15585; 18778]
E_m (MPa)	16750.52	10.16	15632.00	9.00	[15826; 17676]
f_{h0} (MPa)	147.78	14.51	146.00	14.00	[136; 159]
f_{h90} (MPa)	138.56	13.76	137.00	15.00	[128; 149]
W (N·m)	19.90	26.32	19.80	35.00	[17; 23]

Source: Prepared by the authors (2023).

As evidenced in Table 3, there is an equivalence noted between the experimental data obtained in this study and the findings of Couto *et al*. (2018). The mean values show significant proximity, all within their respective 95% confidence intervals.

Analyzing Table 2, among the 12 evaluated mechanical properties, eight showed lower coefficients of variation (CV) when the moisture content (MC) equaled the fiber saturation point (FSP). As indicated by Kretschmann (2008) and Bodig & Jayne (1993), wood strength tends to decrease with increasing moisture content until reaching the FSP, beyond which a stabilization in values is observed. This phenomenon justifies the reduction in coefficients of variation from the FSP.

Regarding the Anderson-Darling test, the validity of the ANOVA test was confirmed for all investigated strength and stiffness properties, as the values remained above 5%.

Examining Table 2, the ANOVA results indicated that, of the six investigated strength properties, only three (f_{c0}, f_{t0}, f_{v0}) were significantly affected by moisture content variation, with p-values below 5% (0.05). Compressive strength parallel to the grain (f_{c0}) at 12% moisture content was about 19% higher than the corresponding value at the FSP (MC = 19.94%). In contrast, tensile and shear strengths parallel to the grain (f_{t0}, f_{v0}) were 28% and 30% higher, respectively, at the 12% moisture condition.

The other strength properties (f_{t90}, f_{s0}, f_m) did not suffer a significant influence from moisture content, suggesting that, for these, the values can be considered constant or independent of associated moisture content. This result differs from the linear variation model proposed by Equation 2, extracted from ABNT NBR 7190-1 (2022), indicating that these properties depend less on moisture variation than on anatomical aspects, given that the observed failures in the three tests are of the "brittle" type, indicating that anatomy has a more predominant influence than moisture conditions (Marcolin *et al*., 2021).

Regarding the other four analyzed properties (ρ, f_{h0}, f_{h90}, and W), only the apparent density (ρ) and toughness (W) were not significantly affected by variations in moisture content, showing a negligible difference between the results at 12% moisture and those at the FSP of 19.94%. The other properties (f_{h0}, f_{h90}) were significantly affected, showing a 37% increase in hardness parallel and perpendicular to the grain, all associated with the 12% moisture condition.

Considering these results, it is evident not only the absence of standardization in the results among wood species of different classes but also the divergence among species within the same class. The findings presented here disagree with both the conclusions of Lahr *et al*. (2016) and those of Fraga *et al*. (2022), who also investigated species classified as belonging to the C60 or D60 class.

Regarding the three evaluated stiffness properties, all of them (E_{c0}, E_{t0}, E_m) were significantly affected by moisture content variation, with p-values below

5% (0.05). For the 12% moisture condition, the mean stiffness values (E_{c0}, E_{t0}, E_m) were, respectively, 16%, 21%, and 17% higher than the values for these properties at the FSP with a moisture content of 19.94%. These results corroborate with the predictions of Equation 3.

Simultaneously with the data presented in Table 2, Table 4 illustrates the errors of Equations 2 and 3, calculated from the estimated mean values of strength and stiffness properties, determined according to the previously mentioned equations. These results complement the analysis by providing a detailed view of the accuracy of the estimates in relation to the observed values.

Table 4 – Results of the estimation of mean values of strength and stiffness

Variable	Experimental	Estimation	Exp. – Est.	Error (%)
f_{c0} (MPa)	78.80	82.23	-3.43	4.35
f_{t0} (MPa)	103.04	100.00	3.04	2.95
f_{t90} (MPa)	4.76	5.03	-0.27	5.76
f_{v0} (MPa)	17.86	17.07	0.79	4.43
f_{s0} (MPa)	0.92	1.02	-0.09	10.19
f_m (MPa)	112.07	123.63	-11.55	10.31
E_{c0} (MPa)	16883.70	16805.94	77.76	0.46
E_{t0} (MPa)	17181.54	16463.53	718.00	4.18
E_m (MPa)	16750.52	16584.53	165.99	0.99

Source: Prepared by the authors (2023).

Analyzing Table 4, it is observed that the errors range from 0.46% to 4.18% for the three modulus of elasticity, demonstrating the effectiveness of Equation 3 for these three properties. Additionally, it is noteworthy that the three modulus of elasticity experienced reductions compared to the experimental results, promoting safety.

Another relevant aspect in Table 4 is the estimated values of strength and stiffness, calculated from Equations 2 and 3. For the estimated values of compressive strength parallel (f_{c0}), tensile strength perpendicular (f_{t90}), parallel shear (f_{s0}), and conventional strength in static bending test (f_m), the code equations led to values higher than the experimental ones. If the expressions of the Brazilian code ABNT NBR 7190-1 (2022) are applied to moisture contents around 20%, considering that these expressions are intended for a moisture content (MC) ranging between 10% and 20%, some mechanical properties may have estimated values higher than the experimental values, degrading safety.

5 CONCLUSIONS

The study assessed the mechanical properties of *Dinizia excelsa* wood at a moisture content under standard conditions of 12% and at the fiber saturation point (FSP). Among the six examined strength properties, three (f_{t90}, f_{s0}, f_m) were not significantly affected by variations in moisture content, challenging the strength estimation proposed by the Brazilian code. Regarding stiffness, moisture content impacted all three properties, demonstrating precision in the code in this case, with errors below 4.18%. Remarkably, apparent density (ρ) and toughness (W) remaining statistically unchanged. Furthermore, using the code equations to estimate mechanical properties, it was observed that compressive, tensile, and flexural strengths (f_{c0}, f_{t90}, f_m) exceeded experimental values, which could compromise safety in structural designs. The study concludes by advocating for a systematic review of correction equations to enhance the safety of structural designs and minimize the impact of generalized normative equations.

ACKNOWLEDGEMENTS

The authors express their gratitude to the Brazilian National Council for the Improvement of Higher Education (CAPES), finance code 001, Brazilian National Council for Scientific and Technological Development (CNPq) for their invaluable support and contributions to this research.

REFERENCES

ABNT. NBR 7190. **Projeto de estruturas de madeira**. Rio de Janeiro: Associação Brasileira de Normas Técnicas, 1997.

ABNT. NBR 7190. **Projeto de estruturas de madeira**. Rio de Janeiro: Associação Brasileira de Normas Técnicas, 2022.

ABNT. NBR 7190-1. **Projeto de estruturas de madeira – Parte 1**: Critérios de dimensionamento. Rio de Janeiro: Associação Brasileira de Normas Técnicas, 2022.

ABNT NBR 7190-3. **Projeto de estruturas de madeira – Parte 3**: Métodos de ensaio para corpos de prova isentos de defeitos para madeiras de florestas nativas. Rio de Janeiro: Associação Brasileira de Normas Técnicas, 2022.

AQUINO, V. B. M.; SOARES, L. S. Z. R.; RUTHES, H. C.; *et al*. Analysis of moisture content variation on strength and stiffness properties of *Cedrella odorata* wood species. **Wood Research**, v. 67, n. 2, p. 231–240, 2021.

ARAUJO, V. A.; CORTEZ-BARBOSA, J.; GAVA, M.; *et al*. Classification of wooden housing building systems. **BioResources**, v. 11, n. 3, p. 7.889–7.901, 2016.

ARROYO, F. N.; FRAGA, I. F.; SOARES, L. S. Z. R.; *et al*. Influence of moisture on physical and mechanical properties of *Pouteria Pachycarpa* wood. **Floresta e Ambiente**, v. 29, p. e20220019, 2022.

BODIG, J.; JAYNE, B. A. **Mechanics of wood and wood composites**. reprint ed. New York: Van Nostrand Reinhold Company Inc, 1993.

BRÉMAUD, I.; GRIL, J.; THIBAUT, B. Anisotropy of wood vibrational properties: dependence on grain angle and review of literature data. **Wood Science and Technology**, v. 45, n. 4, p. 735–754, 2011.

CHRISTOFORO, A. L.; ALMEIDA, D. H.; VARANDA, L. D.; PANZERA, T. H.; LAHR, F. A. R. Estimation of wood toughness in Brazilian tropical tree species. **Engenharia Agrícola**, v. 40, n. 2, p. 232–237, 2020.

COUTO, N. G.; AQUINO, V. B. M.; ALMEIDA, J. P. B.; *et al*. Determination of physical and mechanical properties of wood specie *Dinizia excelsa* Ducke. **International Journal of Materials Engineering**, v. 8, n. 6, p. 158–161, 2018.

DALY, D. C.; MARTINEZ-HABIBE, M. C. Ten new species of *Dacryodes* from Amazonia and the Guianas. Studies in neotropical Burseraceae XXIII. **Brittonia**, v. 71, n. 2, p. 201–224, 2019.

FRAGA, I. F.; ARROYO, F. N.; SOARES, L. S. Z. R.; *et al*. Influência do teor de umidade em propriedades físicas e mecânicas da madeira de *Dipteryx odorata*. **Matéria (Rio de Janeiro)**, v. 27, p. e20220084, 2022.

HAYES, B. N.; KOLIOU, M.; VAN DE LINDT, J. W. Seismic behavior of balloon frame Cross-Laminated Timber connections. **Journal of Structural Engineering**, v. 149, n. 9, p. 04023115, 2023.

IWAKIRI, S.; TRIANOSKI, R.; FONTE, A. P. N.; *et al*. Potencial de uso de madeiras de *Dinizia excelsa* Ducke e *Protium puncticulatum* J.F.Macbr para produção de painéis EGP. **Scientia Forestalis**, v. 44, n. 111, p. 709–717, 2016.

IZZI, M.; CASAGRANDE, D.; BEZZI, S.; *et al*. Seismic behaviour of Cross-Laminated Timber structures: A state-of-the-art review. **Engineering Structures**, v. 170, p. 42–52, 2018.

KRETSCHMANN, D. E. Influence of juvenile wood content on shear parallel, compression, and tension transverse to grain strength and mode I fracture toughness for loblolly pine. **Forest Products Laboratory**, v. 58, n. 7–8, p. 89–96, 2008.

LAHR, F. A. R.; CHRISTOFORO, A. L.; SILVA, C. E. G.; ANDRADE JUNIOR, J. R.; PINHEIRO, R. V. Avaliação de propriedades físicas e mecânicas de madeiras de Jatobá (*Hymenaea stilbocarpa* Hayne) com diferentes teores de umidade e extraídas de regiões distintas. **Revista Árvore**, v. 40, n. 1, p. 147–154, 2016.

LIMA, T. F. P.; ALMEIDA, T. H.; ALMEIDA, D. H.; CHRISTOFORO, A. L.; LAHR, F. A. R. Physical and mechanical properties of Tatajuba wood specie (*Bagassa guianensis*) from two different Brazilian regions. **Matéria (Rio de Janeiro)**, v. 23, n. 3, p. e12185, 2018.

LOUREIRO, A. A.; FREITAS, J. A.; RAMOS, K. B. L.; FREITAS, C. A. A. **Essências madeireiras da Amazônia**. 4º ed. Manaus: Instituto Nacional De Pesquisas Da Amazônia (INPA), 2000.

MARCOLIN, L. A.; MORITANI, F. Y.; RODEGHERI, P. M.; LAHR, F. A. R. Properties relationship evaluation and plasticity analytical model approach for Brazilian tropical species. **European Journal of Wood and Wood Products**, v. 79, n. 2, p. 477–485, 2021.

MESQUITA, M. R.; FERRAZ, I.; CAMARGO, J. L. Angelim-vermelho *Dinizia excelsa* Ducke Fabaceae. **Manual de Sementes da Amazônia**. 1º ed, p.1–11, 2009. Manaus: Instituto Nacional De Pesquisas Da Amazônia (INPA).

OZYHAR, T.; HERING, S.; NIEMZ, P. Moisture-dependent elastic and strength anisotropy of European beech wood in tension. **Journal of Materials Science**, v. 47, n. 16, p. 6141–6150, 2012.

PAN, Y.; VENTURA, C. E.; FINN, W. D. L.; XIONG, H. Effects of ground motion duration on the seismic damage to and collapse capacity of a mid-rise woodframe building. **Engineering Structures**, v. 197, p. 109451, 2019.

PUNHAGUI, K. R. G.; JOHN, V. M. Carbon dioxide emissions, embodied energy, material use efficiency of lumber manufactured from planted forest in Brazil. **Journal of Building Engineering**, v. 52, p. 104349, 2022.

RAMAGE, M. H.; BURRIDGE, H.; BUSSE-WICHER, M.; *et al*. The wood from the trees: The use of timber in construction. **Renewable and Sustainable Energy Reviews**, v. 68, p. 333–359, 2017.

RUTHES, H. C.; MASCARENHAS, F. J. R.; SOARES, L. S. Z. R.; *et al*. Influence of moisture content on physical and mechanical properties of *Vatairea sp.* wood. **Revista Árvore**, v. 46, p. e4606, 2022.

SENG HUA, L.; WEI CHEN, L.; ANTOV, P.; KRISTAK, L.; MD TAHIR, P. Engineering wood products from *Eucalyptus spp.* **Advances in Materials Science and Engineering**, v. 2022, n. 8000780, 2022.

[a]SOARES, L. S. Z. R.; FRAGA, I. F.; PAULA, L. S.; *et al*. Influence of moisture content on physical and mechanical properties of *Cedrelinga catenaeformis* wood. **BioResources**, v. 16, n. 4, p. 6758–6765, 2021.

[b]SOARES, L. S. Z. R.; SILVA, D. A. L.; PANZERA, T. P.; *et al*. Estimativa de propriedades da madeira Mandioqueira pela frequência natural de vibração e pela densidade aparente. **Matéria (Rio de Janeiro)**, v. 26, p. e13051, 2021.

SOUSA-BAENA, M. S.; GARCIA, L. C.; PETERSON, A. T. Completeness of digital accessible knowledge of the plants of Brazil and priorities for survey and inventory. **Diversity and Distributions**, v. 20, n. 4, p. 369–381, 2014.

TER STEEGE, H.; PRADO, P. I.; LIMA, R. A. F.; *et al*. Biased-corrected richness estimates for the Amazonian tree flora. **Scientific Reports**, v. 10, n. 1, p. 10130, 2020.

YUAN, X.; LI, L.; ZHANG, H.; *et al*. Machine learning-based seismic damage assessment of residential buildings considering multiple earthquake and structure uncertainties. **Natural Hazards Review**, v. 24, n. 3, p. 04023024, 2023.