UFSM

Ciência Florestal

ISSN 1980-5098
OPEN ACCESS

Ci. Fl., Santa Maria, v. 33, n. 3, e70446, p. 1-12, July/Sept. 2023 • https://doi.org/10.5902/1980509870446
Submitted: 23rd/05/2022 • Approved: 11th/07/2023 • Published: 15th/09/2023

Artigos

Influence of moisture content on physical and mechanical properties of *Calophyllum* sp wood

Influência do teor de umidade nas propriedades físicas e mecânicas da madeira *Calophyllum* sp

Felipe Nascimento Arroyo[I], Iuri Fazolin Fraga[I], Heloiza Candeia Ruthes[I], Larissa Soriani Zanini Ribeiro Soares[II], Vinícius Borges de Moura Aquino[III], André Luis Christoforo[I], Francisco Antonio Rocco Lahr[IV]

[I]Federal University of São Carlos, São Carlos, SP, Brazil
[II]University of Uberaba, Uberaba, MG, Brazil
[III]São Paulo State University, Ilha Solteira, SP, Brazil
[IV]University of São Paulo, São Carlos, SP, Brazil

ABSTRACT

Due to its excellent resistance to traction and compression, wood is regularly used in furniture, window frames and in structures and sealing of homes and buildings. Due to the anisotropy and complexity of the material, its properties vary depending on its intrinsic anatomical characteristics and external factors, such as species, moisture content, acting requests, among others. The Brazilian standard provides linear models for estimating and correcting all strength and stiffness properties as a function of the moisture content of the wood. However, due to its characteristics, there may not be a linear variation of the physical and mechanical properties in relation to the moisture content. Thus, this research aims to evaluate and analyze the influence of moisture content on 15 properties of *Calophyllum* sp. The reliability of the Brazilian standard equation for correcting strength and stiffness values as a function of humidity (U% to 12%) was evaluated, in addition to analyzing, through ANOVA, whether there is a change in the properties when they are at the saturation point of the fiber and 12% moisture. Of the 15 properties analyzed, 4 did not change, contrary to the linear models set out in the Brazilian standard. In addition, it was possible to note that the Brazilian standard can estimate with an error of up to 76% when correcting the humidity to 12%.

Keywords: Catanudo; Moisture content; Linear model

RESUMO

A madeira por possuir excelente resistência à tração e compressão é comumente utilizada em móveis, esquadrias e em estruturas e vedação de residências e edifícios. Devido à anisotropia e complexidade do material, suas propriedades variam em função de suas características anatômicas intrínsecas e de fatores externos, como a espécie, teor de umidade, solicitações atuantes, dentre outros. A norma brasileira traz modelos lineares para a estimativa e correção de todas as propriedades de resistência e de rigidez em função do teor de umidade da madeira. Porém, devido às suas características, pode não haver variação linear das propriedades físicas e mecânicas em relação ao teor de umidade. Assim, esta pesquisa tem como objetivo avaliar e analisar a influência do teor de umidade em 15 propriedades da madeira *Calophyllum* sp. Foi avaliada a confiabilidade da equação da norma brasileira para corrigir os valores de resistência e rigidez em função da umidade (U% para 12%), além de analisar, por meio de ANOVA, se há alteração nas propriedades quando estão no ponto de saturação da fibra e 12% de umidade. Das 15 propriedades analisadas, 4 não sofreram alteração, contrariando os modelos lineares dispostos na norma brasileira. Além disso, foi possível notar que a norma brasileira pode estimar com erro de até 76% ao corrigir a umidade para 12%.

Palavras-chave: Catanudo; Teor de umidade; Modelo linear

1 INTRODUCTION

Wooden structures can be used both in low-rise buildings, e.g., residences and tall buildings (LAHR; CHRISTOFORO; VARANDA; CHAHUD; ARAÚJO; BRANCO, 2017). Its advantage over other commonly used materials is its high tensile and compression strength and a low density-resistance ratio (ALMEIDA; SOUZA; MARTINS; CHRISTOFORO; ALMEIDA; LAHR, 2018). Another advantage, considered by many as the main one (LAHR; ARROYO; RODRIGUES; ALMEIDA; AQUINO; WOLENSKI; SANTOS; FERRAZ; CHAHUD; MOLINA; PINHEIRO; CHRISTOFORO, 2021; AQUINO; FREITAS; VASCONCELOS; ALMEIDA; ARROYO; RODRIGUES; CHRISTOFORO; ALMEIDA; SILVA; SILVA; PINHEIRO; LAHR, 2021), 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; ARROYO; SILVA; PANZERA; LAHR, 2017).

Brazil, due to its large forest area (9 million hectares in 2019), has great potential to better explore the use of wood in civil construction, especially in structural systems

(IBA, 2020). Aiming at the best and proper use, it is necessary to know the properties and behavior of wood when requested to active efforts (DIAS; ALMEIDA; ARAÚJO; PANZERA; CHRISTOFORO; LAHR, 2016). In Brazil, NBR 7190 (ABNT, 1997) governs the premises for the design and execution of wooden structures.

The tree of the species *Calophyllum* sp. occurs in the states of Mato Grosso and Pará, Brazil. The wood from this tree belongs to hardwood resistance class C40, according to NBR 7190 (ABNT, 2022), since its resistance to compression parallel to the fiber's ranges from 40 MPa to 50 MPa. In addition, it has easy workability and durability, essential characteristics for application in structures, furniture, and frames.

The Brazilian standard NBR 7190 (ABNT, 1997) contains guidelines for characterizing woody species. However, many authors seek other forms of characterization, in addition to verifying the reliability of the presented values and conditions. In this context, it is necessary to implement property tests with a moisture content of 12%. If it has not realized in this condition, the Brazilian standard recommends that the values be corrected for the equilibrium moisture content, of 12%, through an equation that linearly relates the physical and mechanical properties with the moisture content of the wood.

However, as wood is a natural material (affected by edaphoclimatic conditions), heterogeneous and anisotropic, some particular strength and stiffness properties may not be affected even by considerable differences in moisture content (ALMEIDA; ALMEIDA; ARROYO; ARAÚJO; CHAHUD; BRANCO; PINHEIRO; CHRISTOFORO; LAHR, 2019; FRAGIACOMO; MENIS; MOSS; CLEMENTE; BUCHANAN, 2010), or vary non-linearly, contrary to what is specified by the standard, in which strength and stiffness values are directly proportional to moisture content (ABNT NBR 7190, 1997).

Thus, the present work aims to evaluate whether 15 properties of *Calophyllum* sp wood are affected by moisture content, through experimental tests with 12% of moisture content and at the fiber saturation point. After obtaining the properties, analyses based on ANOVA and the Anderson-Darling test with 5% significance were used to investigate whether or not there was change in the properties with the variation of moisture content. In addition, we sought to verify whether the equations for transforming strength and stiffness as a function of moisture (saturation point for 12%) present acceptable error for the studied species.

2 MATERIALS AND METHODS

The pieces of Catanudo wood (*Calophyllum* sp), originating in the northeast of Mato Grosso, were supplied by a wood company located in the city of São Carlos (Brazil, SP), being green and air-dried. The homogeneous lot presented around 1m³, 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). Twelve specimens were tested per analyzed property and for each moisture content (12% and at the fiber saturation point), resulting in 360 samples. The analyzed properties are shown in Table 1.

Table 1 – Physical and Mechanical properties analyzed

Abbreviation	Properties
ρ_{12} (g/cm³)	Apparent density
ρ_{FSP} (g/cm³)	Density at fiber saturation point
εrt (%)	Radial shrinkage
εtt (%)	Tangential shrinkage
f_{c0} (MPa)	Compressive strength parallel to the fibers
f_{t0} (MPa)	Tensile strength parallel to the fibers
f_{t90} (MPa)	Normal tensile strength to fibers
f_{v0} (MPa)	Shear strength parallel to the fibers
f_{s0} (MPa)	Cracking resistance
f_{tm} (MPa)	Conventional strength in static bending test
E_{c0} (MPa)	Longitudinal modulus of elasticity in compression parallel to the fibers
E_{t0} (MPa)	Longitudinal modulus of elasticity in traction 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)	Normal fiber hardness
W (daN·m)	Tenacity

Source: Authors (2022)

With the results of the properties with 12% moisture and at the fiber saturation point, it was possible, through statistical analysis, to verify if there were differences in the values obtained. For this, the 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. For this test, Minitab software was used.

The Anderson-Darling test, also assessed at a 5% significance level and using de Minitab software, 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.

Subsequently, it was also possible to verify the reliability of equations proposed by the Brazilian standard (ABNT NBR, 1997). These equations are used to correct strength - Equation (1) - and stiffness values - Equation (2) - when the test is not performed on the specimen with a moisture content of 12%. Thus, through the values obtained in the tests at the fiber saturation point (i.e., humidity higher than 12%), they were corrected through equations (1) and (2) and compared with the values obtained in the tests of specimens with 12% humidity. Thus, the quality of these equations was measured by the absolute error, Equation (3).

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

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

$$Error = \frac{P_{estimated} - P_{experimental}}{P_{experimental}} \cdot 100 \tag{3}$$

Where: $P_{estimated}$ is the estimated (i.e., corrected) value of the properties obtained in the equations (1) and (2); $P_{experimental}$ is the real value of the properties obtained in the tests with 12% of humidity.

Seeking the species characterization in the hardwood group (C20, C30, C40 and C60), the compressive strength parallel to the characteristic fibers value ($f_{c0,k}$) was obtained through Equation (4), based on the premises of ABNT NBR 7190 (1997) “Project of wooden structures” and using the corrected value for 12% moisture ($f_{c0.12\%}$). In this equation, f_1, f_2 to f_n denote the compressive strength values with 12% moisture in ascending order of the n test specimens tested (n = 12, in this case).

$$f_{c0,k} \geq \{f_1 \; 0.70 \cdot \frac{\sum_{i=1}^{n} f_i}{n} \; 1.10 \cdot \left[2 \cdot \left(\frac{f_1 + f_2 + \cdots + f_{\left(\frac{n}{2}\right)-1}}{\left(\frac{n}{2}\right) - 1}\right) - f_{\frac{n}{2}}\right] \quad (4)$$

3 RESULTS AND DISCUSSIONS

Table 2 shows the average results of physical and mechanical properties of *Calophyllum* sp wood related to moisture content of 12% and fiber saturation point (FPS), in addition to the coefficient of variation (CV). It should be noted that the average moisture values, before correction (Equations 1 and 2), were 19.75% and 12.45% for the FSP and 12% moisture, respectively. In addition to these results, the p-values of the ANOVA (5% significance) and the Anderson-Darling test (A-D) are shown. Finally, the errors of Equations 1 and 2 are shown in Table 3, showing the estimated mean values (Est.) of the strength and stiffness properties using these equations.

Due to the characteristic compressive strength parallel to the fibers (Equation 3), this species is classified in class C30 (ABNT NBR 7190, 1997). Still with the premises of this standard, the CV met the limits of 18% and 28% for normal and tangential deformations, respectively, demonstrating the quality of the tests performed. As can also be seen, the CVs of the properties obtained for the moisture content equal to the saturation point of the fibers were different from the CVs of the properties determined at 12%. This variation occurs because wood properties are affected by sample moisture, in addition to the species type, fiber direction, magnitude of applied load, among other conditions (FRAGIACOMO; MENIS; MOSS; CLEMENTE; BUCHANAN, 2010).

Table 2 – Results of physical and mechanical properties of *Calophyllum* sp

Prop.	12%		FSP		ANOVA	A-D	12%/FSP
	$\bar{x}$	CV (%)	$\bar{x}$	CV (%)	p-value	p-value	
ρ (g/cm³)	0.82	9.07	1.02	8.83	0.000	0.183	0.80
εrt (%)	5.50	17.03	-	-	-	-	-
εtt (%)	8.49	13.03	-	-	-	-	-
f_{c0} (MPa)	51.42	12.06	36.37	9.27	0.000	0.621	1.41
f_{t0} (MPa)	63.43	18.03	46.21	15.90	0.000	0.669	1.37
f_{t90} (MPa)	4.88	16.43	4.95	17.59	0.890	0.326	0.99
f_{v0} (MPa)	15.88	17.67	10.83	17.15	0.000	0.890	1.47
f_{s0} (MPa)	0.61	27.54	0.88	14.21	0.004	0.727	0.70
f_{tm} (MPa)	89.71	14.84	61.35	17.54	0.000	0.383	1.46
E_{c0} (MPa)	11404.51	14.14	11867.76	24.03	0.050	0.899	1.21
E_{t0} (MPa)	15116.60	16.00	12266.87	15.93	0.004	0.606	1.23
E_{tm} (MPa)	14971.25	14.92	12326.14	13.24	0.003	0.663	1.21
f_{h0} (MPa)	85.89	10.15	84.78	15.65	0.810	0.784	1.01
f_{h90} (MPa)	30.10	10.94	78.24	18.55	0.001	0.508	0.77
W (daN·m)	1.31	24.09	1.34	30.22	0.841	0.745	0.98

Source: Authors (2022)

Table 3 – Results of the estimated (Est.) mean values of strength and stiffness

Prop.	Exper.	Est.	Dif. = Exper. – Est.	Error (%)
f_{c0} (MPa)	51.42	44.82	6.59	12.83
f_{t0} (MPa)	63.43	56.96	6.47	10.20
f_{t90} (MPa)	4.88	6.09	-1.21	-24.87
f_{v0} (MPa)	15.88	13.35	2.53	15.92
f_{s0} (MPa)	0.61	1.08	-0.47	-75.87
f_{tm} (MPa)	89.71	75.61	14.10	15.72
E_{c0} (MPa)	11404.51	13737.26	697.24	4.84
E_{t0} (MPa)	15116.60	14168.24	948.36	6.27
E_{tm} (MPa)	14971.25	14236.69	734.55	4.91

Source: Authors (2022)

According to the ANOVA results, 5 investigated strength properties (f_{c0}, f_{t0}, f_{v0}, f_s and f_{tm}) were significantly affected by the variation in moisture content. The difference between the results at the saturation point was 30% to 70% greater when compared to the results at 12% humidity. Therefore, it is evident that it is necessary to use Equation 1 to correct these properties. However, from the errors analyzed in Table 3, it is clear that the proposed equations need to be revised, since an error of up to 76% can be obtained, approximately. Through the Anderson-Darling test, the ANOVA used in these properties was valid.

Analyzing the stiffness properties (E_{c0}, E_{t0} and E_{tm}), the modulus of elasticity in compression parallel to the fibers was not significantly affected by the moisture content, which differs from the model in Equation 2. The average value of this property for the 12% moisture condition was 21% higher than the value of this property for the wood in the saturated condition. The modulus of elasticity in the traction parallel to the fibers and the conventional modulus of elasticity in the static bending test were affected by the variation in the moisture content. Analyzing E_{t0} and E_{tm}, Equation 2 obtained an error of only 6.27% and 4.91%, respectively, showing its effectiveness. Equally analysis of strength properties, the Anderson-Darling test validates the ANOVA used in these properties.

Regarding the other 4 properties analyzed (ρ, f_{h0}, f_{h90} and W), the toughness (W) and hardness parallel to the fibers (f_{h0}) were not significantly affected by variations in moisture content, with a difference between the results at the point of saturation and 12% humidity of 2% and 1%, respectively. The other properties (ρ and f_{h90}) were significantly affected, with a difference between the results of 20% and 23%, respectively. Analogous to strength, the need for moisture correction is evidenced in only two of these properties.

According to Table 3, if the expressions of the Brazilian standard NBR 7190 (ABNT, 1997) are used to correct U values close to 20%, the equations bring errors from 5% to 76%, approximately, which draws attention to the development of new research on the subject. As can be seen in the errors found in these equations, the Brazilian standard is underestimating 7 properties, with an error of up to 16%, approximately, and overestimating 2 properties, with an error of up to 76%, approximately.

4 CONCLUSIONS

The results of this research allow us to conclude that:

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

ii. Two of the nine properties of strength and stiffness were not significantly affected by the variation in moisture content, contrary to what was predicted in the equations for estimating wood strength and stiffness proposed by the Brazilian standard NBR 7190 (ABNT, 1997);

iii. Through the calculated errors, the need to revise the correction equation is evident, since it brought errors of up to 76% in the estimation of properties when transformed from a moisture above 12% to 12%; and

iv. The Brazilian standard is underestimating 7 properties and overestimating 2 properties, bringing values up to 16% lower and 76% higher.

In conclusion, it is evident that only 4 of the 15 properties of this species were affected by moisture. Furthermore, the equations of the Brazilian standard for wood structures NBR 7190 (ABNT, 1997) erroneously predict the transformation of strength and stiffness of a moisture greater than 12% to 12%. Thus, research involving other species is essential to reach more precise conclusions regarding the effects of varying the moisture content, 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.

REFERENCES

ALMEIDA, T. H.; SOUZA, A. M.; MARTINS, A. S. M.; CHRISTOFORO, A. L.; ALMEIDA, D. H.; LAHR, F. A. R. Effect of service temperature on shear strength of Pinus wood for roof structures. **Acta Scientiarum. Technology**, v. 40, n. 6, 2018. DOI: https://doi.org/10.4025/actascitechnol.v40i1.30913

ALMEIDA, T. H.; ALMEIDA, D. H.; ARROYO, F. N.; ARAÚJO, V. A.; CHAHUD, E.; BRANCO, L. A. M. N.; PINHEIRO, R. V.; CHRISTOFORO, A. L.; LAHR, F. A. R. Time of exposure at 60°C service temperature: influence on strength and modulus of elasticity in compression parallel to the grain of hardwood species. **BioResources**, v. 14, n. 1, p. 207-219, 2019. DOI: https://doi.org/10.15376/biores.14.1.207-219

AQUINO, V. B. M.; FREITAS, M. V. P.; VASCONCELOS, C. Q.; ALMEIDA, J. P. B.; ARROYO, F. N.; RODRIGUES, E. F. C.; CHRISTOFORO, A. L.; ALMEIDA, D. H.; SILVA, S. A. M.; SILVA, D. A. L.; PINHEIRO, R. V.; LAHR, F. A. R. Physical and mechanical characterization of Planchonella Pachycarpa wood species for use in structural purpose. **Wood Research**, v. 66, n. 2, p. 267-276, 2021. DOI: https://doi.org/10.37763/wr.1336-4561/66.2.267276

BRAZILIAN ASSOCIATION OF TECHNICAL STANDARDS. **NBR 7190**: Design of wooden structures. Rio de Janeiro, p. 107. 1997. (in Portuguese)

BRAZILIAN ASSOCIATION OF TECHNICAL STANDARDS. **NBR 7190**: Design of wooden structures. Rio de Janeiro, p. 107. 2022. (in Portuguese)

CHRISTOFORO, A. L.; ARROYO, F. N.; SILVA, D. A. L.; PANZERA, T. H.; LAHR, F. A. R. Full characterization of Calycophyllum multiflorum wood specie. **Engenharia Agrícola**, v. 37, n. 4, 2017. DOI: https://doi.org/10.1590/1809-4430-Eng.Agric.v37n4p637-643/2017

COUTO, N. G.; ALMEIDA, J. P. B.; GOVONE, J. S.; CHRISTOFORO, A. L.; LAHR, F. A. R. Relationship between shear strength and compressive strength parallel to grains of hardwoods. **Ambiente Construído**. v. 20, n. 4, p. 319-327, 2020. DOI: https://doi.org/10.1590/s1678-86212020000400475 (in Portuguese)

DIAS, F. M.; ALMEIDA, T. H.; ARAÚJO, V. A.; PANZERA, T. H.; CHRISTOFORO, A. L.; LAHR, F. A. R. Influence of the apparent density on the shrinkage of 43 tropical wood species. **Acta Scientiarum. Technology**, v. 41, n. 7, 2016. DOI: https://doi.org/10.4025/actascitechnol.v41i2.30947

FRAGIACOMO, M.; MENIS, A.; MOSS, P. J.; CLEMENTE, I.; BUCHANAN, A. H. Numerical and experimental thermal-structural behavior of laminated veneer lumber (LVL) exposed to fire. **Proceedings [...]**, WCTE 2010, v. 4, n. 3, p. 3047-3056, 2010. ISSN 9781622761753. DOI: https://doi.org/10.1260/2040-2317.1.3.145

IBA. **Brazilian Tree Industry**: Annual Report IBA 2020. 2020. Available at: https://iba.org/datafiles/publicacoes/relatorios/relatorio-iba-2020.pdf. Accessed on: July 20, 2021. (in Portuguese)

LAHR, F. A. R.; CHRISTOFORO, A. L.; VARANDA, L. D.; CHAHUD, E.; ARAÚJO, V. A.; BRANCO, L. A. M. N. Shear and longitudinal modulus of elasticity in wood: relations based on static bending tests. **Acta Scientiarum**, v. 39, n. 4, p. 433-437, 2017. DOI: https://doi.org/10.4025/actascitechnol.v39i4.30512

LAHR, F. A. R.; ARROYO, F. N.; RODRIGUES, E. F. C.; ALMEIDA, J. P. B.; AQUINO, V. B. M.; WOLENSKI, A. R. V.; SANTOS, H. F.; FERRAZ, A. L. N.; CHAHUD, E.; MOLINA, J. C.; PINHEIRO, R. V.; CHRISTOFORO, A. L. Models to estimate longitudinal compressive strength of Brazilian hardwood based on apparent density. **BioResources**, v. 16, n. 1, p. 1373-1381, 2021. DOI: https://doi.org/10.15376/biores.16.1.1373-1381

Authorship Contribution

1 Felipe Nascimento Arroyo

Master's degree

https://orcid.org/0000-0001-8226-172X • lipe.arroyo@gmail.com

Contribution: Formal analysis; Writing – original draft; Writing – review & editing

2 Iuri Fazolin Fraga

Master's degree

https://orcid.org/0000-0003-0310-0237 • iurifraga@outlook.com

Contribution: Data curation; Software; Visualization

3 Heloiza Candeia Ruthes

Master's degree

https://orcid.org/0000-0002-8198-5934 • heloruthes@gmail.com

Contribution: Funding acquisition; Resources

4 Larissa Soriani Zanini Ribeiro Soares

PhD

https://orcid.org/0000-0001-6722-535X • larissazanini@iftm.edu.br

Contribution: Investigation; Software

5 Vinícius Borges de Moura Aquino

PhD

https://orcid.org/0000-0003-3483-7506 • aquino.vini@hotmail.com

Contribution: Methodology; Validation

6 André Luis Christoforo

PhD

https://orcid.org/0000-0002-4066-080X • alchristoforo@ufscar.br

Contribution: Conceptualization; Project administration; Supervision; Writing – review & editing

7 Francisco Antonio Rocco Lahr

PhD

https://orcid.org/0000-0002-3510-8498 • frocco@sc.usp.br

Contribution: Conceptualization; Project administration; Supervision

How to quote this article

ARROYO, F. N.; FRAGA, I. F.; RUTHES, H. C.; SOARES, L. S. Z. R.; AQUINO, V. B. M.; CHRISTOFORO, A. L.; LAHR, F. A. R. Influence of moisture content on physical and mechanical properties of *Calophyllum* sp wood. **Ciência Florestal**, Santa Maria, v. 33, n. 3, e70446, p. 1-23, 2023. DOI 10.5902/1980509870446. Available from: https://doi.org/10.5902/1980509870446. Accessed in: day month abbr. year.