Current Journal of Applied Science and Technology

26(1): 1-8, 2018; Article no.CJAST.39531
Previously known as British Journal of Applied Science & Technology
ISSN: 2231-0843, NLM ID: 101664541

Estimation of Modulus of Elasticity in Static Bending of Wood in Structural Dimensions as a Function of Longitudinal Vibration and Density

Raquel Schmitt Cavalheiro[1], Diego Henrique de Almeida[2*], Tiago Hendrigo de Almeida[1], André Luis Christoforo[2] and Francisco Antonio Rocco Lahr[3]

[1]Department of Science and Materials Engineering, University of São Paulo, Av. Trabalhador São-Carlense 400, São Carlos - SP, 13566-590, Brazil.
[2]Department of Civil Engineering, Federal University of São Carlos, Rodovia Washington Luís, km 235 - SP310, São Carlos - SP, 13565-905, Brazil.
[3]Department of Structures, University of São Paulo, Av. Trabalhador São-Carlense 400, São Carlos - SP, 13566-590, Brazil.

Authors' contributions

This work was carried out in collaboration between all authors. Authors RSC and FARL designed the study, wrote the protocol and managed the analyses of the study. Author ALC wrote the protocol and statistical analysis. Authors DHA and THA managed the analyses of the study, wrote the first draft of the manuscript and managed the literature searches. All authors read and approved the final manuscript

Article Information

DOI: 10.9734/CJAST/2018/39531
Editor(s):
(1) Elena Lanchares Sancho, Professor, Department of Mechanical Engineering, University of Zaragoza, Zaragoza, Spain.
Reviewers:
(1) Miloslav Milichovsky, University of Pardubice, Czech Republic.
(2) Charles Chinwuba Ike, Enugu State University of Science and Technology, Nigeria.
(3) Halil Görgün, Dicle University, Turkey.
(4) Leo Baldenegro, Mexico.
Complete Peer review History: http://www.sciencedomain.org/review-history/23234

Original Research Article

Received 20th November 2017
Accepted 12th February 2018
Published 17th February 2018

ABSTRACT

In order to use wood in a sustainable and rational way, it is necessary to estimate its characteristics, and in the case of civil construction, the physical and mechanical properties are the most interesting. The aim of this research was to estimate the modulus of elasticity of structural pieces of

---

**Corresponding author: E-mail: diegoestruturas@gmail.com;*

Schizolobium amazonicum Herb. wood through static bending (MOE_{sb}) and longitudinal vibration (MOE_{lv}) methods, in addition, to generate regression models to estimate the modulus of elasticity of static bending. Tests for MOE_{sb} and MOE_{lv} estimation were carried out according to ABNT NBR 7190:1997 and FAKOPP Enterprise, respectively. Linear and quadratic regression models were used to estimate MOE_{sb} as a function of MOE_{lv}. A multivariate regression model was also generated considering the wood density. According to the discussion of the obtained results, MOE_{lv} and MOE_{sb} average values estimated for the studied batch of *Schizolobium amazonicum* Herb. wood were 9.70 and 9.07 GPa, and average density 381.21 kg/m³. Regression models proposed for estimation of MOE_{sb} presented the coefficient of determination close to 60%.

Keywords: Mechanical properties; modulus of elasticity; wood; wood structures.

1. INTRODUCTION

Wood is one of the main raw materials used throughout the world, from different types of tools used in agriculture and animal husbandry practices [1], to artifacts with greater added value [2] reaching advanced technological and constructive aspects [3].

This diversity of wood uses is due to the ease of obtaining and processing of this material [4,5]. Brazil is one of the main countries in the world in relation to the forest sector, since it has a certified forest area equal to 6,378,006 ha [6], in its different biomes, each with specific characteristics of the flora [7,8], among they are the Amazon Forest.

There is no consensus among the exact number of tree species that are in the Amazon Forest [9], recent research estimates that 16,000 species [10], many of them not yet cataloged, without knowledge of their properties and technological potential. However, the scientific community has been developing research to determine the properties of natural resistance to the xylophagous organisms attack [11], physical and mechanical [12,13] and chemical properties [14]. Besides, due to the extension of the Amazon Forest region, edaphoclimatic factors [15] should be considered for determination of wood properties [16,17].

Among the species of trees coming from the Amazon Forest, the *Schizolobium amazonicum* Herb. (common name: Paricá) stands out, due to its rapid growth [18], physical and mechanical properties that allow its use in civil construction, either as a structural element [19] or in glulam manufacturing [20].

In order to use wood in construction, it is necessary to determine its physical and mechanical properties [21,22] according to specific Standard Codes, such as Brazilian [23] and European [24]. However, when it is impossible to produce specimens [25] or pieces present structural dimensions [26], non-destructive tests are performed by different techniques, including transverse vibration [27,28], acoustic tomography [29] and ultrasound [30]. In addition, it is also possible to estimate wood properties as a function of other known properties using regression models [31-34].

This research aims to estimate the modulus of elasticity of structural pieces of *Schizolobium amazonicum* Herb. wood through static bending and longitudinal vibration methods, in addition, to generate regression models to estimate the modulus of elasticity in static bending.

2. MATERIALS AND METHODS

Experimental procedures were performed at the Wood and Timber Structures Laboratory (LaMEM), at the School of Engineering of São Carlos (EESC), University of São Paulo (USP), in the city of Sao Carlos, São Paulo, Brazil.

2.1 Selection and Preparation of Test Specimens

Pieces presenting structural dimensions (boards) of a batch of *Schizolobium amazonicum* Herb. wood from a certified area in the northern region of Brazil (Fig. 1). Firstly, visual classification of all the boards was done, to select 60 boards free of defects (knots or cracks). The moisture content of boards at the time of the tests was close 12%, according to ABNT NBR 7190:1997 [23]. The 60 boards were weighed and measured using caliper (in the cross-section) and tape (length - axial direction to the grain).

Fig. 1. Batch of *Schizolobium amazonicum* Herb

2.2 Modulus of Elasticity in Static Bending

For wood modulus of elasticity determination by three points static bending (MOE_{sb}), the rupture (F_{rup}) of a specimen was estimated. After that, were determined at 10% ($F_{10\%}$) and 50% ($F_{50\%}$) of the rupture the respective deflections ($v_{10\%}$; $v_{50\%}$) for all 60 boards (Fig. 2). These percentages were selected according to ABNT NBR 7190:1997 [23] because it ensures that the elastic regime of wood has not been exceeded. For the calculation of MOE_{sb}, Equation (1) was used, where L is the length between supports, and b and h are the cross-section width and thickness, respectively.

$$MOE_{sb} = \frac{(F_{50\%} - F_{10\%}) \cdot L^3}{(v_{50\%} - v_{10\%}) \cdot 4 \cdot b \cdot h^3} \quad (1)$$

2.3 Modulus of Elasticity in Longitudinal Vibration

Modulus of elasticity in longitudinal vibration (MOE_{lv}) was determined by the Equation (2), where ρ_{ap} is the wood density, *l* is the board length and *f* is the longitudinal vibration frequency.

$$MOE_{lv} = \rho_{ap} \cdot (2 \cdot l \cdot f)^2 \quad (2)$$

Boards were placed on two supports, on one side was placed a microphone to capture the longitudinal vibration frequency and the other free (Fig. 3), for impact with hammer, according to the methodology proposed by Fakopp Enterprise [35], which also provides the software for determination of vibration frequency based on the Fast Fourier Vibration Analyzer.

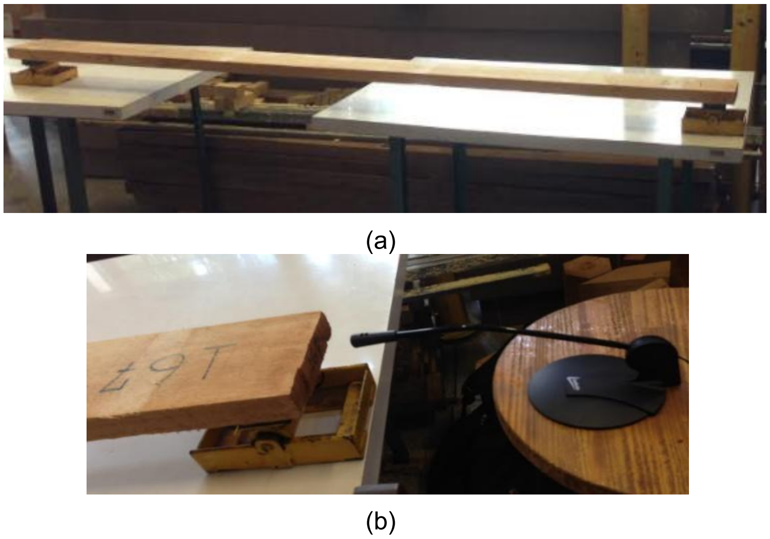
2.4 Density

Wood density (ρ_{ap}) was determined according to ABNT NBR 7190:1997 [23] through the Equation (3), where m and V are weight and volume of the specimen, respectively.

$$\rho_{ap} = \frac{m}{V} \quad (3)$$

(a) (b)

Fig. 2. Static bending test: (a) board in test; (b) instrumenting details.


(a)

(b)

Fig. 3. Longitudinal vibration test: (a) board in test; (b) microphone close to the board.

2.5 Statistical Analysis and Regression Models

Statistical analysis and the proposed regression models were performed using the software R version 3.4.2 [36]. Polynomial univariate regression models of degrees 1 and 2 were tested with the aid of analysis of variance (ANOVA), with MOE_{lv} being the independent variable, and MOEsb the dependent variable, of the functions adjusted by the least squares method.

Also, through ANOVA, a multivariate regression model was tested with the purpose of using the densities of the wood pieces (together with the modulus of elasticity determined by sound), considering the influence of density on the mechanical properties of wood [37] as an explanatory variable, adjusted by least squares method.

For the regression model's ANOVA, also evaluated at the 5% significance level, the stipulated null hypothesis consisted in the non-representativeness of the tested models (H_0: $\sigma=0$), and representativeness as an alternative hypothesis (H_1: $\sigma\neq0$). P-value higher than the level of significance considered implies accepting H_0, refuting it otherwise.

In addition to ANOVA, which allows to accept the representativeness of tested models, the adjusted coefficient of determination (R^2) values were obtained as a way of evaluating the capacity of the variations of the independent variable X to explain the predictive variable Y, among the models, considered significant, the one of best fit by tested relation.

3. RESULTS AND DISCUSSIONS

3.1 Properties of Schizolobium Amazonicum Herb. Wood

Table 1 shows the average (x_m), maximum (Max) and minimum (Min) of modulus of elasticity values obtained by the methods of longitudinal vibration and static bending and the density of the *Schizolobium amazonicum* Herb. boards. Besides, the coefficient of variation (CV) determined for each property studied are also presented. The average value of MOE_{lv} is higher than the average value of MOE_{sb}, both values were higher than those determined by Cavalheiro et al. [38].

Table 1. Modulus of elasticity and density of *Schizolobium amazonicum* Herb.

Properties	x_m	CV (%)	Min	Max
MOE_{sb} (GPa)	9.07	20.52	5.51	12.86
MOE_{lv} (GPa)	9.70	19.72	5.39	12.7
ρ_{ap} (kg/m³)	381.21	13.13	238.33	474.21

Almeida et al. [39] found the modulus of elasticity average value of *Schizolobium amazonicum* Herb. by transverse vibration technique equal to 7.75 GPa, lower than the average values determined in this research.

Almeida et al. [40] studied the complete characterization of *Schizolobium amazonicum* Herb. wood in structural dimensions pieces and found a modulus of elasticity in static bending average value equal to 8.90 GPa, lower than that determined for the batch of this research.

The studied batch of *Schizolobium amazonicum* Herb. presented density equal 381.21 kg/m³, lower than that determined by Terezo and Szücs [20], which reached an average density equal to 490 kg/m³.

Differences between average values found for modulus of elasticity and density are explained by the fact that wood is a material of natural origin and it is influenced by several factors, including anatomical and biotic ones [41,42].

3.2 Regression Models

Figures 3 and 4 present the graphs of linear and quadratic regression models for estimation of MOE_{sb} as a function of MOE_{lv}, respectively. Linear and quadratic regression models presented coefficients of determination equal to 61.80 and 62.65% (Fig. 4 and Fig. 5), respectively. Multivariate linear regression model for MOE_{sb} estimation as a function of MOE_{lv} and density (Equation 4) showed a coefficient of determination equal to 61.27%. The coefficient of determination values found for correlations proposed in this study was satisfactory for estimation of MOE_{sb}.

$$MOE_{sb} = 1.211403 + 0.723266\, MOE_{lv} + 0.002212 \cdot \rho_{ap} \quad (4)$$

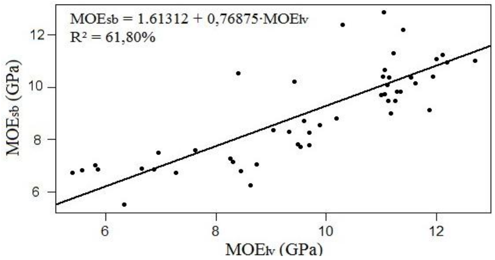


Fig. 4. Linear regression model for MOE_{sb} as a function of MOE_{lv}.

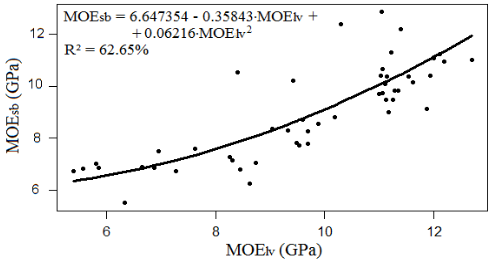


Fig. 5. Quadratic regression model for MOE_{sb} as a function of MOE_{lv}.

Tables 2, 3 and 4 present the statistics DF (Degree freedom), SS (Sum Square), MS (Multiple Square), F-value and P-value for the factors used for liner, quadratic and multivariate linear regression models, respectively. The influence of density on the multivariate linear regression model was not significant (P-value = 0.652), as well as the quadratic parcel of the quadratic model (P-value = 0.134).

Table 2. Linear regression model statistics

Source	DF	SS	MS	F-value	P-value
MOE_{lv}	1	127.80	127.80	96.46	0.000
Residuals	58	76.84	1.33	-	-
Total	59	204.65	-	-	-

Table 3. Quadratic regression model statistics

Source	DF	SS	MS	F-value	P-value
MOE_{lv}	1	127.80	127.80	98.65	0.000
MOE_{lv}^2	1	3.00	3.00	2.31	0.134
Residuals	57	73.85	1.30	-	-
Total	59	204.65	132.10	-	-

Table 4. Multivariate linear regression model statistics

Source	DF	SS	MS	F-value	P-value
MOE_{lv}	1	127.80	127.80	95.14	0.00
ρ_{ap}	1	0.28	0.28	0.21	0.652
Residuals	57	76.57	1.34	-	-
Total	59	204.65	129.42	-	-

Chen and Guo [43] performed a linear correlation for MOE in static bending as a function of MOE in stress wave technique to *Abies fabri* (Mast.) Craib wood, finding coefficient of determination value equal to 63.50%.

Martins et al. [44] conducted research using *Pinus pinaster* (Ait.) poles. A linear regression model was adopted for estimation of mechanical MOE as a function of modulus of elasticity by the longitudinal vibration technique. The coefficient of determination, in this case, was equal to 31%.

Chen and Guo [45] estimated the modulus of elasticity of *Cunninghamia lanceolata* Lamb. Hook and *Ulmus rubra* wood by the techniques of static bending and stress wave. Coefficients of determination of linear regression models proposed for estimation of MOE in static bending as a function of stress wave MOE were equal to 50.20% and 63.30% for *Cunninghamia lanceolata* Lamb. Hook and *Ulmus rubra* wood, respectively.

Oberhofnerová et al. [46] carried out tests to estimate the modulus of elasticity in static bending and longitudinal vibration for *Picea abies* and *Quercus robur* wood and the coefficient of determination values for linear correlations were 50.58% and 47.33%, respectively.

4. CONCLUSIONS

According to the discussion of the obtained results, the values of modulus of elasticity in longitudinal vibration and in static bending estimated for the batch of *Schizolobium amazonicum* Herb. studied in this research presented average values of 9.70 and 9.07 GPa, and density equal to 381.21 kg/m³. Regression models proposed for estimation of MOE_{sb} presented coefficient of determination values close to 60%.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Ahmed N, et al. Diversified traditional wooden implements used in agriculture and animal husbandry practices in Ladakh. British Journal of Applied Science and Technology, 2017;21(5):1-7. DOI:10.9734/BJAST/2017/33907
2. Vieira RS, et al. Small wooden objects using Eucalypts sawmill wood waste. Bio Resources. 2010;5(3):1463-1472.
3. Amorim STA, et al. A madeira laminada cruzada: aspectos tecnológicos, construtivos e de dimensionamento. Revista Matéria, 22(suplemento 1), e-11937, Portuguese; 2017. DOI: 10.1590/S1517-707620170005.0273
4. Almeida DH, et al. Analysis of solid waste generation in a wood processing machine. International Journal of Agriculture and Forestry. 2017;7(3):76-79. DOI:10.5923/j.ijaf.20170703.03
5. Gonçalves MTT. Processamento da madeira. Bauru: Center Xerox, Portuguese; 2000.
6. Forest Stewardship Council (FSC). FSC Facts & Figures. Available:<https://br.fsc.org/pt-br/fsc-brasil/fatos-e-nmeros>. (Accessed: 19 January 2018).
7. Nascimento MF, et al. Physical and mechanical properties of Sabiá wood (*Mimosa caeselpiniaefolia* Bentham.). Current Journal of Applied Science and Technology. 2017;25(4):1-5. DOI: 10.9734/CJAST/2017/38747
8. Silva ES, et al. Colorimetria da madeira de oito espécies nativas do estado do Rio Grande do Sul, Brasil. Ciência da Madeira. Portuguese. 2015;6(1):31-37. DOI:10.12953/2177-6830/rcm.v6n1p31-37
9. Cardoso D, et al. Amazon plant diversity revealed by a taxonomically verified species list. Proceedings of the National Academy of Sciences of the United States of America. 114(40):10695-10700. DOI:10.1073/pnas.1706756114
10. Steege H, et al. The discovery of the Amazonian tree flora with an update checklist of all known tree taxa. Scientific Reports, 2016;6(29549):1-15. DOI:10.1038/srep29549
11. Reis ARS, et al. Natural resistance of four Amazon woods submitted to xylophagous fungal infection under laboratory conditions. Maderas y Bosques. 2017;23(2):155-162. DOI:10.21829/myb.2017.232968
12. Christoforo AL, et al. Physico-mechanical characterization of the *Anadenanthera colubrina* wood specie. Journal of the Brazilian Association of Agricultural. 2017;37(2):376-384. DOI:10.1590/1809-4430-Eng.Agric.v37n2p376-384/2017
13. Logsdon NB, et al. Caracterização físico-mecânica da madeira de Peroba-Mica, *Aspidosperma populifolium* A. DC. (Apocynaceae). Floresta, Portuguese. 2008;38(1):11-21.
14. Castro JP, et al. Uso de espécies amazônicas para envelhecimento de bebidas destiladas: análise física e química da madeira. Cerne, Portuguese. 2015;21(2):319-327. DOI: 10.1590/01047760201521021567
15. Vázquez-Cuecuecha OG, et al. Densidad básica de la madera de los pinos y su relación con propiedades edáficas. Madera y Bosques. Spanish. 2015;21(1): 129-138.
16. Lahr FAR, et al. 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, Portuguese. 2016;40(1):147-154.
DOI: 10.1590/0100-67622016000100016

17. Tuisima-Coral LL, et al. Variation in wood physical properties within stems of *Guazuma crinita*, a timber tree species in the Peruvian Amazon. Maderas y Bosques. 2017;23(1):53-61.
DOI: 10.21829/myb.2017.2311534
18. Carvalho PER. Paricá: *Schizolobium amazonicum*. Colombo: Embrapa, Portuguese; 2007.
19. Almeida DH, et al. Full characterization of strength properties of (*Schizolobium amazonicum* wood for timber structures. International Journal of Engineering & Technology. 2013;13(6):97-100.
20. Terezo RF, Szücs CA. Análise de desempenho de vigas em madeira laminada colada de paricá (*Schizolobium Amazonicum* Huber ex. Ducke). Scientia Forestalis, Portuguese. 2010;38(87):471-480,
21. Lahr FAR, et al. Full characterization of *Erisma uncinatum* Warm wood specie. International Journal of Materials Engineering. 2016;6(5):147-150.
DOI:10.5923/j.ijme.20160605.01
22. Osuji SO; Nwankwo E. Investigation into the physical and mechanical properties of structural wood commonly used in Nigeria: a case study of Benin City. Journal of Civil Engineering Research. 2017;7(5):131-136.
DOI: 10.5923/j.jce.20170705.01
23. Associação Brasileira de Normas Técnicas (ABNT). NBR 7190: Projeto de estruturas de madeira. Rio de Janeiro, Portuguese; 2007.
24. European Commitee for Standardzation (EUROCODE). EUROCODE 5: Design of Timber Structures – Part 1-1: general rules and rules for buildings Structures. Brussels; 2004.
25. Ferro FS, et al. Nondestructive evaluation of timber columns of a Capela Bridge in the state of São Paulo, Brazil. Advanced Materials Research, 2013;778:258-264,
DOI:10.4028/www.scientific.net/AMR.778.258
26. Coimbra PRS, et al. Stress distribution in Tauari wood beam. International Journal of Materials Engineering. 2018;8(1):5-11,
DOI: 10.5923/j.ijme.20180801.02
27. Calil Junior C; Miná AJS. Vibração transversal: um método eficiente para classificação de peças estruturais de madeira. Revista Brasileira de Engenharia Agrícola e Ambiental, Portuguese. 2003;7(2):335-338,
28. Almeida DH. Determinação da rigidez de *Pinus elliottii* em diferentes teores de umidade por meio de ensaios mecânicos não destrutivos. *Scientia Forestalis*, Portuguese. 2016;44(110):303-309,
DOI: 10.18671/scifor.v44n110.03
29. Carrasco EVM, et al. Determinação do módulo de elasticidade da madeira em função da inclinação das fibras utilizando tomógrafo acústico. Revista Matéria, 22(suplemento 1), e-11935, Portuguese; 2017.
DOI: 10.1590/S1517-707620170005.0271
30. Güntekin E; Aydin TY. Prediction of bending properties for some softwood species grown in Turkey using ultrasound. Wood Research. 2016;61(6):993-1002.
31. Almeida TH, et al. Density as estimator of dimensional stability quantities of Brazilian tropical woods. BioResources. 2017;12(3):6579-6590,
DOI:10.15376/biores.12.3.6579-6590
32. Cavalheiro RS, et al. Density as estimator of shrinkage for some Brazilian wood species. International Journal of Materials Engineering. 2016;6(3):107-112.
DOI:10.5923/j.ijme.20160603.08
33. Hodousek M, et al. Comparison of non-destructive methods based on natural frequency for determining the modulus of elasticity of *Cupressus lusitanica* and *Populus x canadensis*. BioResources. 2017;12(1):270-282,
DOI:10.15376/biores.12.1.270-282.
34. Moreira AP, et al. Toughness and impact strength in dynamic bending of wood as a function of the modulus of elasticity and the strength in compression to the grain. International Journal of Materials Engineering. 2017;7(4):61-67.
DOI:10.5923/j.ijme.20170704.01
35. Fakopp Enterprise. Determination of the modulus of elasticity of prismatic bars by longitudinal vibration.
Available: < http://fakopp.com>.
(Accessed: 12 September 2017).
36. R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria; 2017.
Available:<https://www.r-project.org/>.
(Accessed: 19 November 2017).
37. Dias FM; Lahr FAR. Estimativa de propriedades de resistência e rigidez da madeira através da densidade aparente.

Scientia Forestalis. Portuguese. 2004;65:102-113,

38. Cavalheiro RS, et al. Mechanical properties of Paricá wood using structural members and clear specimens. International Journal of Materials Engineering. 2016;6(2):56-59. DOI: 10.5923/j.ijme.20160602.06
39. Almeida DH, et al. Modulus of elasticity of *Schizolobium amazonicum* wood evaluated by transversal vibration technique. Advanced Materials Research. 2014;912-914:247-250, DOI: 10.4028/www.scientific.net/AMR.912-914.247
40. Almeida DH, et al. Caracterização completa da madeira da espécie amazônica Paricá (*Schizolobium amazonicum* HERB) em peças de dimensões estruturais. Revista Árvore, Portuguese. 2013;37(6):1175-1181. DOI: 10.1590/S0100-67622013000600019
41. Toong W, et al. The prediction of wood properties from anatomical characteristics: the case of common comercial Malaysian timbers. Bio Resources. 2014;9(3):5184-5197,
42. Dimou V, et al. Influence of biotic factors on the mechanical properties of wood, taking into account the time of harvesting. Wood Material Science & Engineering. 2015;12(3):140-148. DOI:10.1080/17480272.2015.1063004
43. Chen Y, Guo W. Nondestructive evaluation and reliability analysis for determining the mechanical properties of old wood of ancient timber structure. BioResources. 2017;12(2):2310-2325. DOI: 10.15376/biores.12.2.2310-2325
44. Martins CEJ, et al. Nondestructive methodologies for assessment of the mechanical properties of new utility poles. BioResources. 2017;12(2):2269-2283. DOI:10.15376/biores.12.2.2269-2283
45. Chen Y, Guo W. Mechanical properties evaluation of two wood species of ancient timber structure with nondestructive testing methods. BioResources. 2016;11(3):6600-6612. DOI: 10.15376/biores.11.3.6600-6612
46. Oberhofnerová E, et al. Determination of correlation between destructive and nondestructive test methods applied on modified wood exposed to natural weathering. BioResources. 2016;11(2): 5155-5168. DOI:10.15376/biores.11.2.5155-5168

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sciencedomain.org/review-history/23234