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Ultrasonic method for estimation of modulus of elasticity of *Eucalyptus grandis* wood

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ABSTRACT

This study aimed to verify the relation between the modulus of elasticity of *Eucalyptus grandis* W. Hill ex Maiden wood obtained from destructive testing of static bending and from non-destructive testing by ultrasound, both after thermal rectification. A total of 85 samples, with dimensions of 2.5 x 2.5 x 41.0 cm (thickness, width and length), were made from eucalyptus planks. These samples, as well as those without thermal rectification (control), were subjected to two heat treatments, called Combination and Kiln, and then evaluated. In the combination treatment, the wood was subjected to thermal treatment in an autoclave at 130 ± 3 °C and a pressure of 0.2 MPa for 3 h and, after a conditioning period, to heat in a kiln at 160 ± 1 °C for the same length of time, whereas the other treatment consisted of only thermal rectification in a kiln. The main results showed a moderate relation between destructive and non-destructive methods, with the best results recorded in the samples without thermal rectification. With the continuous improvement of the non-destructive techniques, the ultrasound is confirmed as a viable method to obtain values of the modulus of elasticity as a function of the dynamic modulus of elasticity.

Key words: non-destructive method, thermal rectification, ultrasound

Método ultrassonoro para estimativa do módulo de elasticidade de madeiras de Eucalyptus grandis

RESUMO

Este trabalho teve por objetivo verificar a correlação entre o módulo de elasticidade da madeira de Eucalyptus grandis W. Hill ex Maiden, obtido por ensaios destrutivo de flexão estática e não destrutivos com ultrassom, após tratamento térmico. Foram confeccionadas 85 amostras das pranchas de eucalipto com dimensões de 2,5 x 2,5 x 41,0 cm (espessura, largura e comprimento). Avaliaram-se amostras submetidas a dois tratamentos térmicos denominados Combinação e Estufa, além daqueles sem tratamento térmico (Controle). No tratamento combinado as madeiras foram submetidas à termorretificação em autoclave a 130 ± 3 °C e pressão de 0,2 MPa por 3 h e, após um período de condicionamento, submetidas ao calor em estufa a 160 ± 1 °C, pelo mesmo período; já o outro tratamento consistiu apenas na termorretificação em estufa. Com base no estudo realizado foram encontrados resultados com relação moderada entre os métodos destrutivo e não destrutivo, sendo os melhores deles registrados nas amostras que não sofreram tratamentos térmicos. Com o aperfeiçoamento constante das técnicas não destrutiva o ultrassom é um método viável para obtenção de valores de módulo de elasticidade estático em função do módulo de elasticidade dinâmico.

Palavras-chave: método não destrutivo, termorretificação, ultrassom

Introduction

The tests of a destructive nature, in general, are the main methods used to understand the technological properties of wood. The results obtained with this methodology are sometimes cumbersome, because of the time wasted on the production of samples and the money spent on equipment. Moreover, the results obtained are only estimates, because the tests are done on samples, and not from the real piece in use (Stangerlin et al., 2008).

Wang et al. (2007) reported that significant efforts have been made towards the development of a consistent technology for non-destructive assays, which would be able to predict the intrinsic properties of the wood effectively, helping both the quality control and the classification of products in forestry production lines. Among the non-destructive technologies, the use of an apparatus which emits ultrasound waves can be mentioned. According to Gonçalez et al. (2001), ultrasound waves are the acoustic waves which have a frequency exceeding 20 kHz. The ultrasound method is based on the examination of the propagation and its connection with the ultrasonic response and the elastic constants of wood.

Calegari (2006) described the use of the ultrasound for the emission of electric pulses by an electronic circuit. These electrical pulses are conducted by coaxial cables and converted into elastic waves by the piezoelectric crystal situated in the transducers. The mechanical vibrations travel through the material, which mitigates the signal emitted by the generator. The retarded signal is recovered by another piezoelectric crystal and is then amplified and converted into electric pulses again, in order to measure the propagation time. With that, the velocity of the wave can be obtained from the distance and the time of its travel.

As to wood, according to Bucur & Bönhke (1994), the factors which influence the propagation of ultrasonic waves are the anatomical, physical (basic and apparent density) and morphological (types of wood and grain angle) properties; presence of imperfections (knots and splits), the geometry of the specimen, environmental conditions (temperature and relative humidity) and the procedure used to measure it (frequency and type of transducer).

The use of non-destructive methods to evaluate the quality of wood needs further studies since these methods consider the material to be analyzed as homogenous, continuous and isotropic. However, wood is a heterogeneous and anisotropic material, which can sometimes show defects like knots, imperfections in fibers, tracheids and other anatomical elements, thus reducing the accuracy of the results.

Even so, many studies have been conducted in order to obtain the modulus of elasticity with the use of non-destructive methods, and they have found good determinations with the results obtained with the destructive methods (Baradit et al., 1998; Machado, 2000; Ross et al., 2000; Bartholomeu, 2001; Oliveira, 2001; Nogueira, 2003; Wang et al., 2007).

The use of wood in places and situations with some restrictions requires the study of improvements in its quality. Heat treatments are done in woods, mainly, in order to reduce the water absorption (Kartal et al., 2007), induce color changes (Esteves et al., 2008), reduce the wettability (Huang et al., 2012) and improve dimensional stability (Esteves et al., 2007). Considering the many advantages that heat treatment brings to the properties of wood, it is a method already used on an industrial scale in many European countries (Rodrigues, 2009).

Therefore, according to what has been mentioned, the purpose of this study was to relate the modulus of elasticity of *Eucalyptus grandis* W. Hill ex Maiden heat-treated wood obtained from destructive testing of static bending and by non-destructive testing by ultrasound.

Material and Methods

Characterization of material and preparation of samples

The trees of *Eucalyptus grandis* were obtained from a homogeneous population of the State Foundation of Agricultural Research (Fundação Estadual de Pesquisa Agropecuária – FEPAGRO FLORESTAS), situated in Boca do Monte, a district of Santa Maria, in Rio Grande do Sul State, Brazil.

Three trees of approximately 25 years old were randomly selected and the first two logs (2 m length), were cut. Two planks with dimensions of 7.0 x 20.0 cm (thickness x width), diametrically opposed (Figure 1), were cut from the logs by tangential sawing method, using a vertical band saw.

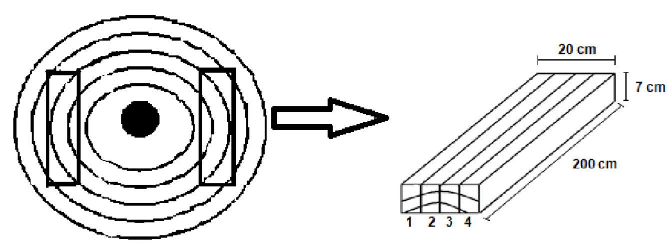

Figure 1. Diagram of extraction of the planks from the log and withdrawal of the samples

In the preparation of the samples for the assays, these were carefully identified with the numbering of the planks, which was given after the sawing of planks and in the sequence of the sampling, so as to distribute the adjoining samples between the treatments, avoiding the effect of the diametrical and longitudinal positions in the planks on the results.

A total of 85 samples, with dimensions of 2.5 x 2.5 x 41.0 cm (thickness, width and length), were made from the eucalyptus planks, according to the American Society for Testing and Materials – ASTM D143 (2000). After this stage, the samples remained in a climate chamber at 20 °C and 65%, of relative humidity until they reached an equilibrium moisture content at 12%. This moisture content was considered the starting point for the beginning of the thermal rectification treatments, whereas the reference pieces remained in the climate chamber.

Heat treatments

The samples were subjected to two thermal rectification treatments: Combination (wood previously treated in an autoclave and, after a period of conditioning, subjected to kiln treatment, with 29 samples); and Kiln (wood treated only in the kiln, with 29 samples).

Moreover, the reference (wood without treatment), with 27 samples, was also taken into account, totaling three treatments. The temperature and the length of the thermal rectification treatments can be seen in Figure 2. The length of the treatments begun to be considered after the needed temperature was reached.

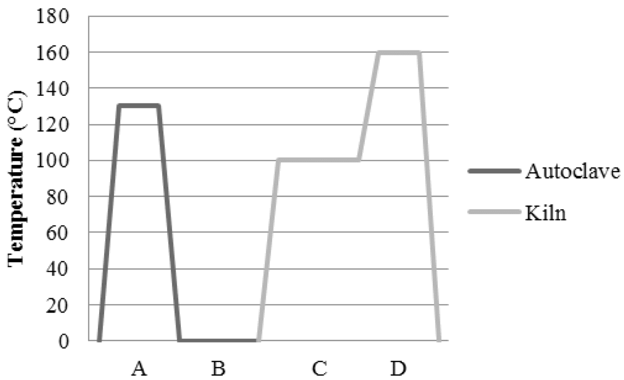

Figure 2. Stages of the Combination (autoclave + kiln) and Kiln treatments. Thermal rectification treatment in an autoclave at 130 ± 3 °C and a pressure of 0.2 MPa for 3 h (A); Period of conditioning in a climate chamber at 20 °C 65% UR to constant weight (B); Previous drying in a kiln at 100 ± 1°C for 24 h (C); Thermal rectification treatment in kiln at 160 ± 1 °C for 3 h (D)

For the thermal rectification of the material, a laboratory autoclave with an internal size of approximately 79 x 85 x 125 cm (capacity of 225 L) and a kiln with air circulation and digital temperature control were used.

After the thermal rectification, the samples were taken back for conditioning in a climate chamber and remained there until they reached a new hygroscopic equilibrium, after which the destructive and non-destructive assays started.

Non-destructive and destructive assays

In order to perform the non-destructive tests, an ultrasound equipment with dry point contact transducers of frequency of 54 kHz was used. These transducers measured the wave propagation time directly, in microseconds (μs).

The determination of the propagation time of the ultrasonic waves was done in the center of the samples, considering the longitudinal direction of the wood. The wave propagation time was measured twice and from the proportion between the mean time and the covered distance (real length of the specimen), the wave propagation speed was calculated. The dynamic modulus of elasticity (Ed) was calculated on the basis of the product between the propagation speed and the density of the wood (Eq. 1).

$$E_d = V_{som}{}^2 \cdot ME \cdot 10^{-6}$$

in which: E_d= Dynamic modulus of elasticity (MPa); V= wave propagation speed ($m.s^{-1}$); ME= wood density at 12% moisture content ($kg.m^{-3}$).

In order to evaluate the accuracy and the sensitivity of the ultrasonic method, the samples were subjected to destructive tests of static bending, and then the modulus of elasticity (Ec0) was obtained with the use of a universal testing machine, according to the American Society for Testing and Materials – ASTM D143 (2000).

Statistical analysis

The results were interpreted through of tests of mean comparison (Fisher's Least Significant Difference test, $p > 0.05$) and regression analysis, in which the independent variable was the dynamic modulus of elasticity, obtained from ultrasound testing and the dependent variable was the modulus of elasticity, obtained from a conventional testing of static bending. The quality of fit of models was evaluated by the coefficient of determination (R^2) and the mean absolute error (MAE) of waste.

Results and Discussion

In Table 1, the maximum, minimum and mean values of the apparent specific density at 12% (ME12%), the ultrasonic speed (V_{som}) and the dynamic modulus elasticity (Ed) are shown.

According to the results obtained in the test of means, the ME 12% had a decrease in its value after both the Combination (Autoclave + Kiln) and the Kiln treatments. This decrease is due to the decay of the hemicellulose as well as due to the evaporation of volatile extractives (Esteves & Pereira, 2009).

The ultrasonic wave propagation speed (V_{som}) had an opposite effect to the ME 12%, in which the minimum value appeared in the samples which were not treated (control samples). The reason for this is because after the thermal rectification, the voids in the wood were reduced, increasing the surface hardness. This way, the ultrasonic speed increases according to the decrease of the voids in the wood (Shimoyama, 2005), changing the values of the dynamic modulus of elasticity

Table 1. Maximum, minimum and mean values of the apparent density at 12%, ultrasonic wave propagation speed and dynamic modulus of elasticity from the samples of *Eucalyptus grandis* subjected to the different treatments

Property	Treatment	Maximum	Minimum	Average	CV(%)	F	p-value
ME 12% ($g\ cm^{-3}$)	Combination	0.53	0.39	0.46 a	8.16	3.13	0.04
	Kiln	0.55	0.40	0.48 ab	8.53		
	Control	0.54	0.42	0.49 b	6.65		
V_{som} ($m\ s^{-1}$)	Combination	4230.00	3910.00	4081.11 a	2.11	3.41	0.04
	Kiln	4250.00	3850.00	4041.92 ab	2.75		
	Control	4290.00	3830.00	4000 b	3.58		
Ed (MPa)	Combination	8843.83	6344.77	7708.23 a	9.74	0.10	0.90
	Kiln	9542.71	6113.85	7894.47 a	12.55		
	Control	9133.0	6243.59	7813.17 a	10.83		

ME 12% = apparent density at 12%; Vsom = ultrasonic speed, Ed = dynamic modulus of elasticity and F = F statistic. Among the properties, the means followed by the same letter in the column, for each variable, do not show a significant statistical difference at a 95% confidence level, according to Fisher LSD test of the wood. Also, there was not a significant difference between the Combination and Kiln treatments, since the mean values of both treatments were similar. The values of the Ed did not show statistical differences according to the mean test (Table 1).

The average values of the wave propagation speed in the samples along the length were similar to the values related by other researchers, such as Ballarin & Nogueira (2005), Calegari et al. (2007) and Stangerlin et al. (2008), ranging from 4.000 to 6.000 m s^{-1}.

The dynamic modulus of elasticity did not change as the specific density and the ultrasonic speed (although these are directly related). This is because the magnitudes of specific density and ultrasonic speed differ.

As for the Ec0 shown in Table 2, note that according to the mean test the samples which did not undergo a thermal rectification showed higher actual values. Thus, the thermal rectifications reduce the wood mechanical properties (Poncsak et al., 2006; Jones & Hill 2007). However, among the treatments, significant statistical differences were not verified.

Table 2. Maximum, minimum and mean values of the modulus of elasticity of Eucalyptus grandis samples subjected to the different treatments

	Ec0 (MPa)			F	p-value
	Combination	Kiln	Control		
Maximum	9870.76	11110.70	11273.1	0,08	0,92
Minimum	7919.70	5987.58	6423.70		
Average	8822.64 a	8894.27 a	9103.09 a		
CV(%)	6.04	15.07	14.87		

Ec0 = modulus of elasticity obtained from static bending testing; F = F statistic. Among the properties, the means followed by the same letter in the line do not show a significant statistical difference at a 95% confidence level, according to Fisher LSD test.

In the analyses of the results (Table 3), it can be seen that there was a significant difference between the values of the Ec0 in the three treatments. As Ouis (2002) asserted, because of the viscoelastic nature of wood, the greater the excitation frequency of the source, the higher the value implied to the Ed.

Table 3. Maximum, minimum and mean values of the modulus of elasticity and the dynamic modulus of elasticity of the *Eucalyptus grandis* samples subjected to different treatments

Treatment	Property (Mpa)	Maximum	Minimum	Average	CV (%)
Combination	Ec0	9870.76	7919.7	8894.27 a	6,04
	Ed	8843.83	6344.77	7708.23 b	9,74
Kiln	Ec0	11110.7	5987.58	8822.64 a	14,76
	Ed	9542.71	6113.85	7894.47 b	12,55
Control	Ec0	11273.1	6423.7	9103.09 a	14,86
	Ed	9133	6243.59	7813.17 b	10,83

Ec0 = modulus of elasticity obtained from static bending tests and Ed = dynamic modulus of elasticity. Among the properties, the means which are followed by the same letter in the column do not show a significant statistical difference, at a 95% confidence level according to Fisher LSD test

According to studies conducted by Bartholomeu (2001), Nogueira & Ballarin (2002) and Puccini (2002), the relations between Ed/E_{c0} vary from 1.06 to 1.38. However, it can be seen in Table 3 that the mean values of the Ed were not higher than those of the Ec0. The reason for that may be related to the kind of wave generated, most likely a surface one, which has a low propagation speed and, consequently, low value of Ed. Nesvijski (2003) observed that some transducers of exponential kind may not generate directed waves, which provides a longer propagation time when compared to the waves generated by transducers of flat faces.

The analysis of the Figure 3A, 3B and 3C show that the statistical models presented significant values, with an error probability of 1%. Besides, the reference treatment, when compared to the heat treatments, presented the best adjustment of model (higher R^2 and equal p-value.). A possible reason for that is the heterogeneity that the thermal rectification can produce on the samples.

The angular coefficient is positive in all the mathematical models, indicating a positive inclination of the line. This fact confirms the hypothesis proposed by NDT (2012) that, if the

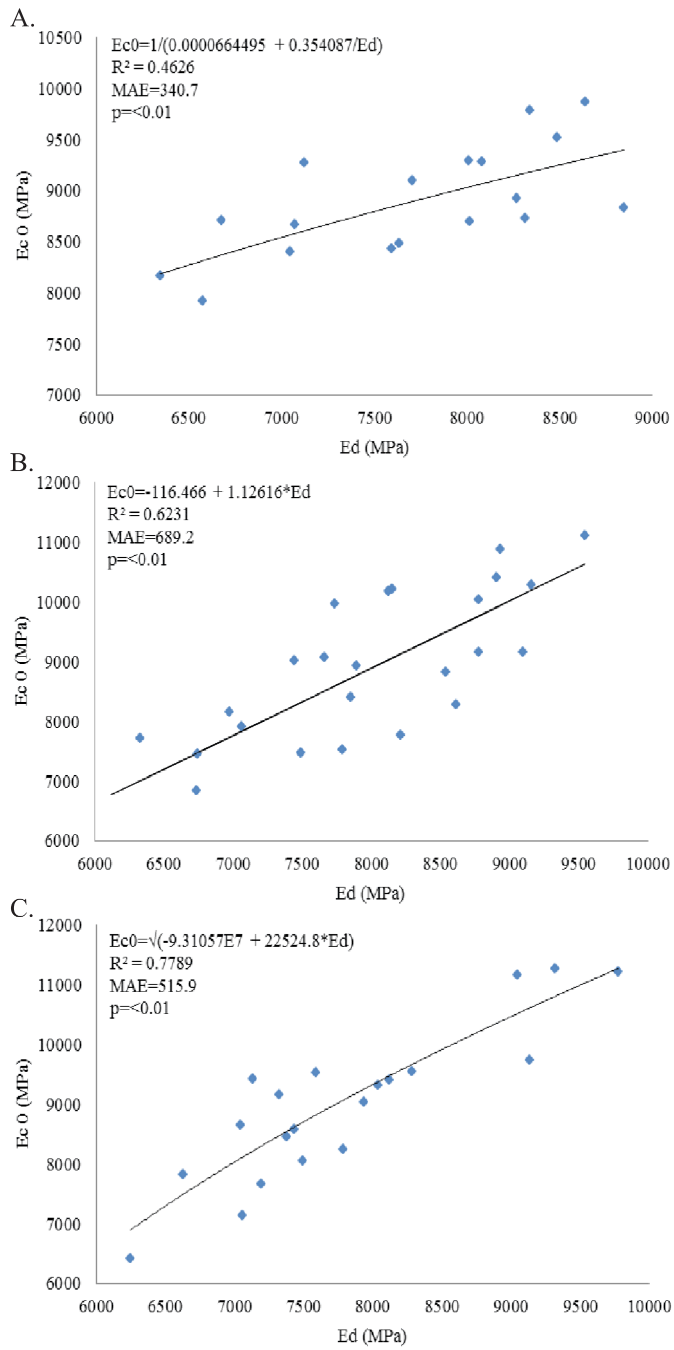

Figure 3. Variation of the modulus of elasticity (Ec0) as a function of the dynamic modulus of elasticity (Ed) in the different thermal rectifications. A = Combination; B = Kiln; C = Control; point = observed; line = calculated; R² = coefficient of determination; MAE = mean absolute error

elastic property is individually analysed, materials with high elastic properties have high stiffness and also high proximity between its molecules. So, a great interaction between the molecules is generated and, consequently, the sound velocity is increased.

Conclusions

There were no significant differences in the dynamic modulus of elasticity (Ed) as to the heat and reference treatments.

There were significant differences between the modulus of elasticity (Ec0) and the dynamic modulus of elasticity (Ed) in all treatments.

The samples which were not subjected to thermal rectification had a better adjustment of models to the estimate of the modulus of elasticity (Ec0) as a function of the dynamic modulus of elasticity (Ed).

With the continuous improvement of the non-destructive techniques, the ultrasound is, indeed, a viable method to obtain the values of modulus of elasticity (Ec0) as a function of the dynamic modulus of elasticity (Ed).

Literature Cited

American Society for Testing and Materials. ASTM – D 143: Standard methods of testing small clear specimens of timber. West Conshohocken: Annual Book of ASTM Standards, 2000. 31p.

Ballarin, A.W.; Nogueira, M. Determinação do módulo de elasticidade da madeira juvenil e adulta de *Pinus taeda* por ultra-som. Engenharia Agrícola, v.25, n.1, p.19-28, 2005. <http://dx.doi.org/10.1590/S0100-69162005000100003>

Baradit, E.; Rozas, C.; Vargas, G. Aplicación de ultrasonido en la evaluación de madera de *Pinus radiata*. Maderas. Ciencia y Tecnologia, v. 1, n.1, p. 27-33, 1998.

Bartholomeu, A. Classificação de peças estruturais de madeira através do ultra-som. Campinas: Universidade de Campinas, 2001. 105p. Tese Doutorado.

Bucur, V.; Böhnke, I. Factors affecting ultrasonic measurements in solid wood. Ultrasonics, v.32, n.5, p.385-390, 1994. <http://dx.doi.org/10.1016/0041-624X(94)90109-0>

Calegari, L. Uso da onda ultra-sônica como meio de controle do processo de secagem da madeira. Santa Maria: Universidade Federal de Santa Maria, 2006. 91p. Dissertação Mestrado.

Calegari, L.; Stangerlin, D.M.; Santini, E.J.; Haselein, C.R.; Longhi, S.J.; Carmo, P.I.O.; Silva Filho, L.C.P.; Gatto, D.A. Monitoramento do teor de umidade de madeiras de *Pinus elliottii* Engelm. e *Eucalyptus grandis* Hill ex Maiden, sob diferentes temperaturas de secagem, através do ultra-som. Ciência Florestal, v. 17, n.4, p. 399-408, 2007. <http://cascavel.ufsm.br/revistas/ojs-2.2.2/index.php/cienciaflorestal/article/view/1971>. 12 Set. 2012.

Esteves, B.; Marques, A.V.; Domingos, I.; Pereira, H. Heat-induced colour changes of pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) wood. Wood Science and Technology, v. 42, n. 5, p. 369-384, 2008. <http://dx.doi.org/10.1007/s00226-007-0157-2>

Esteves, B.; Marques, A.V.; Domingos, I.; Pereira, H. Influence of steam heating on the properties of pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) wood. Wood Science and Technology, v. 41, n.3, p. 193-207, 2007. <http://dx.doi.org/10.1007/s00226-006-0099-0>

Esteves, B.M.; Pereira, H.M. Wood modification by heat treatment: a review. BioResources, v. 4, n. 1, p. 370-404, 2009. <http://www.ncsu.edu/bioresources/BioRes_04/BioRes_04_1_0370_Esteves_P_Wood_Mod_Heat_Treatment_Rev_367.pdf>. 12 Sep. 2012.

Gonçalez, J.C.; Valle, A.T.; Costa, A.F. Estimativas das constantes elásticas da madeira por meio de ondas ultra-sonoras (ultra-som). Cerne, v. 7, n. 2, p. 81-92, 2001. <http://www.dcf.ufla.br/cerne/artigos/13-02-20097707v7_n2_artigo%2008.pdf>. 12 Set. 2012.

Huang, X.; Kocaefe, D.; Boluk, Y.; Kocaefe, Y.; Pichette, A. Effect of surface preparation on the wettability of heat-treated jack pine wood surface by different liquids. European Journal of Wood and Wood Products, v. 70, n.5, p. 711-717, 2012. <http://dx.doi.org/10.1007/s00107-012-0605-z>

Jones, D.; Hill, C.A.S. Wood modification – a brief overview of the technology. In: Šernek (Ed.). Bonding of modified wood: Proceedings of the 5th COST E34 International Workshop. Ljubljana: Biotechnical Faculty; Department of Wood Science and Technology, 2007. CD Rom.

Kartal, S.N.; Hwang, W.; Imamura Y. Water absorption of boron-treated and heat-modified wood. Journal of Wood Science, v. 53, n.5, p. 454-457, 2007. <http://dx.doi.org/10.1007/s10086-007-0877-9>

Machado, J.M.R.S.S. Avaliação da variação das propriedades mecânicas de pinho bravo (*Pinus pinaster* Ait.) por meio de ultra-som. Lisboa: Universidade Técnica de Lisboa, 2000. 265p. Tese Doutorado.

Nesvijski, E.G. Dry point contact transducers: design for new applications. The e-Journal of Nondestructive Testing, v.9, n.9, 2003. <http://www.ndt.net/article/v08n09/nesvi/nevsi.htm>. 04 Jul. 2012.

Nogueira, M. Determinação de módulos de elasticidade à compressão da madeira de *Pinus taeda* L. com o uso de ultra-som. Botucatu: Universidade Estadual Paulista Júlio de Mesquita Filho, 2003. Dissertação Mestrado.

Nogueira, M.; Ballarin, A.W. Correlação entre módulos de elasticidade estático (flexão) e dinâmico (ultra-som) para algumas espécies de eucalipto. In: Congresso Ibero-Americano de Pesquisa e Desenvolvimento de Produtos Florestais, 2., 2002, Curitiba. Anais... Curitiba: UFPR/FUPEF, 2002. CD Rom.

Oliveira, F.G.R. Estudo de propriedades mecânicas de dicotiledôneas por meio de ensaios não destrutivos utilizando equipamento de ultra-som. São Carlos: Universidade de São Paulo, 2001. 55p. Tese Doutorado.

Ouis, D. Dispersion of wood as a consequence of its viscoelasticity. In: International Symposium on Nondestructive Testing of Wood, 13., 2002, Berkeley. Proceedings... Berkeley: University of California, 2002. p.8.

Poncsák, S.; Kocaefe, D.; Bouazara, M.; Pichette, A. Effect of high temperature treatment on the mechanical properties of birch (*Betula papyrifera*). Wood Science and Technology, v.40, n.8, p.647–663, 2006. <http://dx.doi.org/10.1007/s00226-006-0082-9>

Puccini, C.T. Avaliação de aspectos de qualidade da madeira utilizando o ultra-som. Campinas: Universidade Estadual de Campinas, 2002. 139p. Tese Doutorado.

Rodrigues, T. O. Efeitos da torrefação no condicionamento de biomassa para fins energéticos. Brasília: Universidade de Brasília, 2009. 82p. Dissertação Mestrado.

Ross, R.J.; Wang, X.; Mattson, J.A.; Erickson, J.R.; Forsman, J.W.; Geske, E.A.; Wehr, M.A. Comparison of several nondestructive evaluation techniques for assessing stiffness and MOE of small diameter logs. In: International Symposium on Nondestructive Testing of Wood, 12., 2000, Sopron-Hungary. Proceedings... Sopron: University of Western Hungary, 2000. p. 155-163.

Shimoyama, V.R. S. Estimativas de propriedades da madeira de *Pinus taeda* através do método não-destrutivo emissão de ondas de tensão, visando à geração de produtos de alto valor agregado. Curitiba: Universidade Federal do Paraná, 2005. 151p. Tese Doutorado.

Stangerlin, D.M.; Calegari, L.; Santini, E.J.; Domingues, J.M.X.; Gatto, D.A.; Melo, R.R. Determinação do módulo de elasticidade em madeiras por meio de métodos destrutivo e não-destrutivo. Revista Brasileira de Ciências Agrárias, v.3, n.2, p.145-150, 2008. <http://dx.doi.org/10.5039/agraria.v3i2a284>

Nondestructive Testing Resource Center (NDT). Sound. The speed of sound in other materials. <http://www.ndt-ed.org/EducationResources/HighSchool/Sound/hs_sound_index.htm>. 12 Sep. 2012.

Wang, X.; Carter, P.; Ross, R.J.; Brashaw, B.K. Acoustic assessment of wood quality of raw forest materials – a path to increased profitability. Forest Products Journal, v.57, n.5, p. 6-14, 2007. <http://www.fpl.fs.fed.us/documnts/pdf2007/fpl_2007_wang003.pdf>. 12 Sep. 2012.