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Evaluation of modulus of elasticity in static bending of particleboards manufactured with *Eucalyptus grandis* wood and oat hulls

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ABSTRACT. The aim of this study was to determine the modulus of elasticity (MOE) in static bending using two different calculation methods, a simple one based on Brazilian standard ABNT NBR 14810 (ABNT, 2006), and an alternative one, based on the Least Squares Method, and evaluate whether there is statistical equivalence between these MOE calculation methods. The alternative method employed results obtained from static bending tests at three-points, with three dial gauges, non-destructively, by imposing limits on two displacements ($L\ 300^{-1}$ and $L\ 200^{-1}$), where L is the specimen length. Results of confidence intervals indicated statistical equivalence between MOE values obtained by means of both methods, thus corroborating the simple mathematical model proposed by ABNT NBR14810 (ABNT, 2006). Panels produced with up to 15% oat hulls (Treatments 1 to 6) showed the highest average MOE values. The methods employed to obtain MOE in static bending were statistically equivalent. However, in addition to being non-destructive, the alternative method proposed here in provided more reliable results, just by taking into account more measures along the specimens.

Keywords: particleboards, least squares method, recovery of waste, lignocellulosic particles.

Avaliação do módulo de elasticidade na flexão estática de aglomerados manufaturados com madeira de *Eucalyptus grandis* e cascas de aveia

RESUMO. O objetivo deste trabalho foi avaliar o módulo de elasticidade na flexão estática (MOE), usando dois diferentes métodos de cálculo (um simples, decorrente de norma ABNT NBR 14810 (ABNT, 2006), e um alternativo, baseado no Método dos Mínimos Quadrados) e avaliar se há equivalência estatística entre os métodos de cálculo do MOE. Na metodologia alternativa foram utilizados resultados de três pontos nos testes de flexão estática, com três relógios indicadores, não destrutivamente, impondo limites em dois deslocamentos ($L\ 300^{-1}$ e $L\ 200^{-1}$), onde L é o comprimento do corpo de prova (mm). Resultados dos intervalos de confiança revelaram equivalência estatística entre MOE obtidos a partir de ambas as abordagens, demonstrando a boa aproximação fornecida pelo modelo matemático simplificado proposto pela ABNT NBR 14810 (ABNT, 2006). Painéis produzidos com até 15% de partículas de cascas de aveia (tratamentos 1-6) apresentaram os maiores valores médios de módulo de elasticidade. Os métodos de obtenção do módulo de elasticidade em flexão estática foram estatisticamente equivalentes. No entanto, o método alternativo proposto aqui tem resultados mais confiáveis, considerando mais medidas ao longo das amostras, além de ser um método não destrutivo.

Palavras-chave: painéis de partículas, método dos mínimos quadrados, aproveitamento de resíduos, partículas lignocelulósicas.

Introduction

Wood-based panels have been widely used around the world in various segments of the timber industry. Thus, alternative raw materials have been systematically investigated in order to reduce the demand for wood particleboard production (ASHORI; NOURBAKHSH, 2008; GIRODS et al., 2009; GULER et al., 2008; FIORELLI et al., 2011; FIORELLI et al., 2012a). In the segment of wood products, special attention should be given to wood-based panels, because they constitute an essential raw material for a range of industrial applications. Indeed, Mendes et al. (2012) claim that furniture and construction industries are the main driving forces for technological development of the particleboard industry.

The most commonly employed tests to evaluate mechanical properties of particleboards are of the destructive kind. However, new non-destructive methods are being devised to evaluate properties of wood and its byproducts. Among them are methods that employ stress wave, electrical properties, ultrasound, deflection, gamma radiation, near infrared spectroscopy, and X-ray (MENDES et al., 2012).

The traditional method for determining the modulus of elasticity (hardness) in bending in wood and its derivatives is still widely used. Researchers obtain the elastic modulus in static bending of the material under investigation and compare the value obtained to that recommended in national and international standards.

Fiorelli et al. (2011) evaluated hardness and strength of particleboards produced from sugarcane bagasse. This study employed a conventional three-point bending test, in which specimens were placed on two supports of the universal testing machine, as prescribed by ABNT NBR 14810 (ABNT, 2006). The hardness of the panels did not meet the 2750 MPa requirement in ANSI A208.1 (ANSI, 1993).

Iwakiri et al. (2012) determined the modulus of elasticity in bending of particleboards at three points. Tests were performed according to EN 310 (EN, 1995) and all treatments met the requirements of the standard employed.

Guimarães Júnior et al. (2011) determined the hardness in bending at three points of particleboards made of various *Eucalyptus* species. Their obtained results did not meet CS 236-66 (CS, 1968), which requires minimum values of 1050 MPa for low-density panels and 2450 MPa for medium density particleboards.

The quality of wood-based panels is given by their physical and mechanical properties, determined in tests such as static bending (modulus of elasticity and rupture or MOE and MOR, respectively), internal adhesion, pullout screw strength, density, water absorption, thickness swelling, among others (IWAKIRI, 2005; MOSLEMI, 1974). MOE is very important in that it indicates the particleboard application, so it is necessary to devise alternative tests conducive to more reliable results.

Christoforo et al. (2012) devised an alternative method to determine the modulus of elasticity (E_{otm}) in structural timber beams (Equation 1), based on the least squares method, conducted on 18 Jatobá (*Hymenaea* sp.) wood beams with dimensions 5 × 5 × 140 cm, using the four-point static bending test and three dial gauges (Figure 1). In Equation 1, δ_1, δ_2 and δ_3 correspond to displacements measured at a point to the left of the midpoint, at midpoint, and at a point to the right of the midpoint, respectively, F is the applied load, L the distance between supports, and b and h the cross section width and height, respectively. It should be emphasized that the displacement (δ_2) at midpoint (L) in this study was limited to L 200^{-1}, a measure of small displacements employed to check the limit state by Brazilian standard ABNT NBR 7190 (ABNT, 1997), ensuring physical and geometrical linearity for the structural elements tested, through non-destructive tests. Their results indicated statistical equivalence between MOE values obtained through both calculation methods. However, the authors favored the use of the alternative method because it was more accurate as compared to the adapted Brazilian standard method. The alternative method developed by Christoforo et al. (2012) is express by equation 1.

$$E_{otm} = \frac{443 \cdot F \cdot L^3}{36 \cdot (20 \cdot \gamma + 23 \cdot \delta_2) \cdot b \cdot h^3}, \ \gamma = \delta_1 + \delta_3 \quad (1)$$

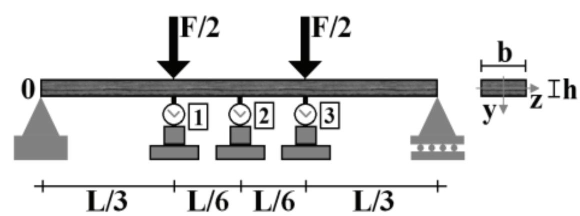


Figure 1. Proposed model for determining the alternative modulus of elasticity (E_{alt}). Source: Christoforo et al. (2012).

In addition to the Brazilian standard ABNT NBR 14810 (ABNT, 2006), other normative documents can be employed to characterize these panels, such as ASTM D3043 (ASTM, 1995), ASTM D47611 (ASTM, 1996), ASTM D5456 (ASTM, 2006), EN (1995) among others. However, the method for obtaining the modulus of elasticity of materials is based on direct concepts of materials mechanics, devoid of optimization criteria.

Thus, this study aimed to evaluate the hardness of panels manufactured with *Eucalyptus grandis* wood particles and oat hulls by an alternative means, based on the least squares method and mechanics of materials, similar to what was done by Christoforo et al. (2012), and compare the MOE results thus obtained with those obtained through the method found in Brazilian standard ABNT NBR 14810 (ABNT, 2006), adapted to non-destructive testing.

Material and methods

Panels manufacturing

Panels were manufactured with *Eucalyptus grandis* wood particles (apparent density of 640 kg m^{-3}) and oat hulls (*Avena sativa*) with apparent density of 290 kg m^{-3}. These particles were generated in a Willey-type knives mill, Marconi MA 680 model, using 2.8 mm sieve opening. *Eucalyptus grandis* wood was obtained from suppliers in the city and region of São Carlos, São Paulo State, Brazil, whereas oat hulls were obtained from companies in this sector.

Particleboards with one layer (homogeneous panels) of high density were manufactured. Mass of particles, bonded with castor oil-based polyurethane resin (PU), was established for each set of panels as function of compaction ratio and panel density. This process employed PU resin, bi-component, 1:1 prepolymer/polyol ratio, and 100% solids content. The PU resin amounts used were 10, 12, and 14% relative to dry mass of particles.

Panels manufactured in this study had nominal densities ranging from 800 to 1068 kg m^{-3}, thus attaining the condition of high density panels, according to Brazilian standard ABNT NBR 14810 (ABNT, 2006). The press cycle parameters were: 4MPa press pressure, 10 min. press time, and 100ºC press temperature, as in other studies also carried out at the Laboratory of Wood and Structural Timber (BERTOLINI et al., 2013; ROCCO LAHR, 2008). Figure 2 shows the panels being manufactured.

Particles of both materials were weighed and mixed with resin for approximately five minutes. The glue machine used, Lieme, BP-12 SL model, is shown in Figure 2b. Then, the particles with resin were subjected to pre-pressing (about 0.013 MPa) performed by mechanical press of own manufacturing (Figure 2c). Subsequently, panels were pressed by means of Marconi semi-automatic press, model MA 098/50 (Figure 2d). Lastly, after curing for 72 hours (time required for the resin to fully polymerize and in order to achieve moisture equilibrium with the environment), panels were properly squared, i.e., 20 mm were removed from each edge, as shown in Figure 2f.

Panels were then divided into groups according to different amounts of *Eucalyptus grandis* particles and oat hulls (Table 1).

Table 1. Experimental factors and levels.

T	Amounts of constituents
1	10% adhesive
2	100% *Eucalyptus grandis* 12% adhesive
3	14% adhesive
4	10% adhesive
5	(85% *Eucalyptus grandis* - 15% Oat hulls) 12% adhesive
6	14% adhesive
7	10% adhesive
8	(70% *Eucalyptus grandis* - 30% Oat hulls) 12% adhesive
9	14% adhesive
10	10% adhesive
11	100% Oat hulls 12% adhesive
12	14% adhesive

For each treatment (T), six panels were manufactured (totaling 72 panels), with nominal dimensions 10 × 280 × 280 mm. One 50 × 250 mm specimen was extracted from each panel (as recommended by ABNT NBR 14810 (ABNT, 2006)) to determine the modulus of elasticity in static bending.

Method used to determine MOE

Figure 3 shows two MOE calculation methods in static bending: conventional method and alternative method.

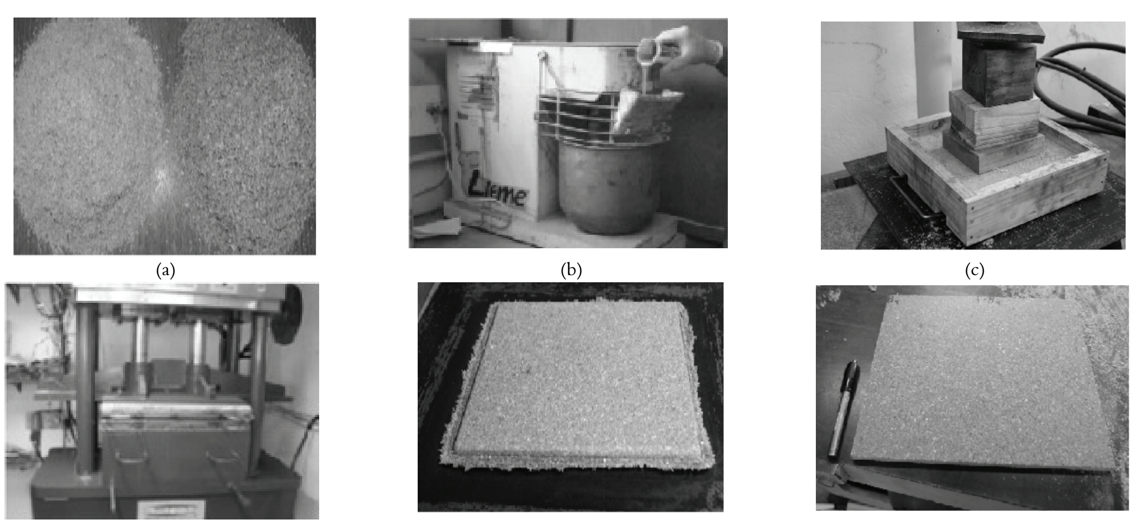
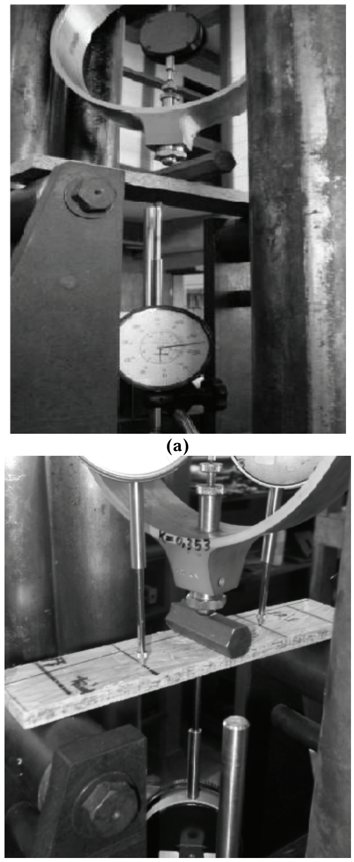


Figure 2. Particles of materials (a), glue machine (b), pre-press (c), hydraulic press (d), panel after pressing (e) and panel after squaring (f).



(a)

(b)

Figure 3. Conventional (a) and alternative (b) static bending tests.

In the conventional test, E_m was obtained in accordance with Brazilian standard ABNT NBR 14810 (ABNT, 2006).

In this study, E_m was also calculated using average values obtained from an alternative method based on the Least Squares Method. In this case, it is necessary to know three displacement values, as shown in Figure 4. Non-destructive bending tests were conducted in linear phase with loads corresponding to L 300^{-1} and L 200^{-1} (small displacements).

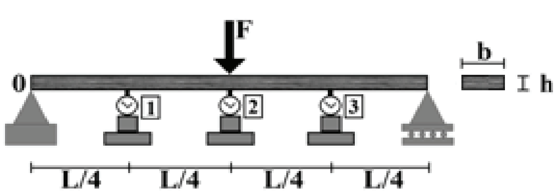


Figure 4. Static bending tests with three deflectometers.

From Virtual Forces Method, displacements (V_i) in dial gauges 1, 2, and 3 (Figure 3b) are expressed by Equations 2 and 3. I_Z is the moment of inertia of the cross section.

$$V(L/2) = V_2 = \frac{F \cdot L^3}{48 \cdot E_m \cdot I_z} \quad (2)$$

$$V_1 = V_3 = \frac{11 \cdot F \cdot L^3}{768 \cdot E_m \cdot I_z} \quad (3)$$

The modulus of elasticity calculated with information from test model presented in Figure 4 is based on the Least Squares Method (Equation 4), aimed at determining the value of E_o so that the residue generated between the analytical (V) and experimental (δ) displacement values is minimized.

$$f(E_o) = \frac{1}{2} \cdot \sum_{i=1}^{n} (V_i - \delta_i)^2 \quad (4)$$

When the first derivative of Equation 4 leads to zero, we obtain the E_o value that minimizes the residue between the displacement values (Equation 5). The second derivative confirms that E_o is a global minimum point.

$$E_o = \frac{249 \cdot F \cdot L^3}{32 \cdot \gamma \cdot b \cdot h^3}, \ \gamma = 11 \cdot (\delta_1 + \delta_3) + 16 \cdot \delta_2 \quad (5)$$

Statistic method used

Note that the load used in calculating the elastic modulus by averages of the simplified method (E_m) was defined as the difference between $F_{L\,200}{}^{-1}$ and $F_{L\,300}{}^{-1}$, obtained by the limitations of L 200^{-1} and L 300^{-1} displacements, respectively. These displacement limits were employed individually to calculate the alternative modulus of elasticity (E_o), i.e., $E_{o,L\,200}{}^{-1}$ and $E_{o,L\,300}{}^{-1}$, respectively.

In order to evaluate the differences between MOE values, i.e., through Brazilian standard ABNT NBR 14810 (ABNT, 2006) (simplified - E_m) and Equation 5 (alternative - E_o), the confidence interval between averages was used at 5% significance level (α), expressed by Equation 6.

$$\bar{x}_m - t_{\alpha/2,n-1} \cdot S_m / \sqrt{n} \le \mu \le \bar{x}_m + t_{\alpha/2,n-1} \cdot S_m / \sqrt{n} \quad (6)$$

where:

μ : average of population of differences;

$\bar{x}_m$: sample average of differences;

n : number of samples;

S_m: sample standard deviation of differences;

$t_{\alpha/2,n-1}$: t (Student) for $n-1$ degrees of freedom at α significance level.

Results and discussion

Average MOE values in static bending $E_{o,L\,200}{}^{-1}$, $E_{o,L\,300}{}^{-1}$, and E_m corresponding to the six specimens for each one of the twelve treatments (T) are presented in Table 2.

According to Table 2, the panels manufactured with up to 15% oat hulls (treatments 1 to 6) provided the highest average MOE values. This can be attributed to a difficulty in binding particles of both materials when more than 15% oat hulls were added. Therefore, the better the interface between the particles is, the higher the modulus of elasticity will be.

Table 2. Average MOE values in static bending.

T	$E_{o,L/200}$ (MPa)	$E_{o,L/300}$ (MPa)	E_m (MPa)	Density (kg m^{-3})
1	2516 (8)	2486 (11)	2349 (14)	951 (5)
2	2432 (9)	2377 (7)	2581 (13)	957 (5)
3	3026 (11)	3019 (8)	2982 (10)	929 (6)
4	2503 (7)	2458 (8)	2366 (18)	941 (7)
5	2426 (9)	2453 (4)	2364 (9)	939 (7)
6	2661 (9)	2683 (10)	2915 (11)	927 (9)
7	2239 (13)	2282 (7)	2342 (9)	946 (7)
8	2421 (6)	2497 (9)	2389 (9)	913 (9)
9	2161 (8)	2201 (7)	2560 (17)	940 (8)
10	1882 (8)	2029 (9)	1942 (13)	1016 (3)
11	1863 (12)	1866 (6)	2079 (9)	968 (6)
12	1875 (7)	1918 (11)	2171 (4)	1008 (5)

Note: in parenthesis are coefficients of variation in percentage (%).

Iwakiri et al. (2012) manufactured panels with sawmill waste of nine tropical wood species from the Amazon region and obtained similar results to ours, with average modulus of elasticity (MOE) ranging from 2185 MPa for Castanha-de-paca (*Scleronema* sp.) panels to 3232 MPa for Louro (*Ocotea* sp.) panels.

Results obtained in this study were higher than those reported by Naumann et al. (2008) for *Eucalyptus urophylla* and *Schizolobium amazonicum* panels with average MOE values of 734 MPa and 1873 MPa, respectively. On the other hand, results obtained in this study are similar to those found by Fiorelli et al. (2011), who manufactured bagasse panels with castor oil-based polyurethane resin. The average modulus of elasticity (MOE) of panels manufactured by Fiorelli et al. (2011) was 2432 MPa.

Figure 5 shows probability plot results for modulus of elasticity. Points evenly distributed along the line meet the conditions of normality and independence of random variables, thereby validating the use of the confidence interval between averages.

Table 3 present the results obtained from the confidence interval between MOE averages. The existence of 0 in the confidence intervals, is found the statistical equivalence between the values of the modulus of elasticity, implying not significant the methodology of calculation used and the values of the displacement imposed (limits).

Table 3. Results from the confidence interval between MOE averages.

Tests of hipothesis		Standard Deviation	Average (MPa)	Confidence interval
T-Test:	E_m	401	2420	(-220,0765; 47,5276)
	$E_{o,L\,200}^{-1}$	412	2334	
T-Test:	E_m	401	2420	(-196,1765; 67,8096)
	$E_{o,L\,300}^{-1}$	401	2356	
T-Test:	$E_{o,L\,200}^{-1}$	412	2334	(-111,7375; 155,9194)
	$E_{o,L\,300}^{-1}$	401	2356	

Figure 6 displays the sample MOE interval. It can be observed that the average value E_m is slightly higher and that there is no significant difference between $E_{o,L\,200}^{-1}$ and $E_{o,L\,300}^{-1}$ sample bands.

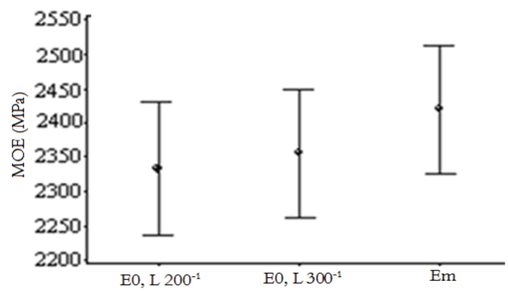


Figure 6. Sample interval of modulus of elasticity: $E_{o,L\,200}^{-1}$, $E_{o,L\,300}^{-1}$, and E_m.

The MOE average value obtained in this study is similar that of other studies, e.g., Fiorelli et al. (2012b), who obtained average MOE values ranging from 1400 to 2040 MPa, with high density particleboards manufactured with coconut fiber and castor oil-based polyurethane resin (PU). Bertolini et al. (2013) obtained average MOE values ranging from 2300 to 2900 MPa, with high density particleboards manufactured with *Pinus sp*. particles treated with CCB and PU resin.

The methods for obtaining the modulus of elasticity in static bending were statistically equivalent. However, the alternative method proposed by this study provides more reliable results by taking into

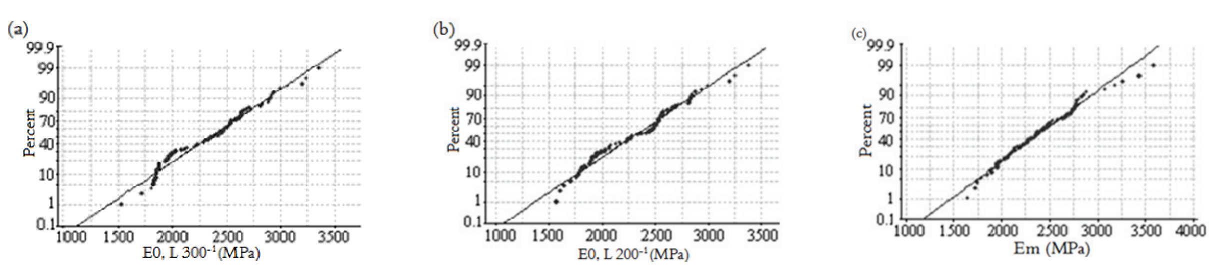


Figure 5. Probability plots for $E_{o,L\,300}^{-1}$ (a), $E_{o,L\,200}^{-1}$ (b), and E_m (c).

account more measures along specimens, in addition to being a non-destructive method.

Conclusion

The alternative approach provides more reliable values, as it is based on the Least Squares Method, and also by requirements data, i.e., more detailed information about displacements in tested specimens. However, statistical analysis showed equivalence among $E_{o,L\ 200}^{-1}$, $E_{o,L\ 300}^{-1}$, and E_m, for all treatments under investigation;

Panels produced with up to 15% oat hulls (treatments 1 to 6) had the highest average MOE values;

It´s important to note that results obtained in this study should not be extrapolated for similar or different materials compositions, the non-homogeneity obtained in panel manufacture (i.e., significant variations in density) may be conducive to different results (i.e., non-equivalence between MOE values), thereby corroborating the need for alternative calculation approaches for each research developed.

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