Prediction of the Modulus of Elasticity of *Eucalyptus grandis* Through Two Nondestructive Techniques

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ABSTRACT

The present study aimed to estimate the modulus of elasticity (MOE) at static bending of Rose gum (*Eucalyptus grandis)* heartwood and sapwood through two nondestructive techniques: ultrasound and stress wave. Sixty samples of heartwood and sapwood were prepared. Nondestructive tests were performed using ultrasound and stress wave timer equipment, while destructive tests were carried out in a universal machine through static bending tests. The main results showed that the heartwood presented better behavior than the sapwood in the non-destructive tests. However, the best model was obtained considering both wood types through the ultrasonic technique. Therefore, stress wave and ultrasonic techniques could be employed to estimate the modulus of elasticity of Rose gum wood.

Keywords: ultrasound, stress wave, wood technology.

Predição do Módulo de Elasticidade de *Eucalyptus grandis* Por Meio de Duas Técnicas Não Destrutivas

RESUMO

O presente estudo objetivou estimar o módulo de elasticidade à flexão estática da madeira de cerne e alburno de *Eucalyptus grandis*, por meio de duas técnicas não destrutivas: ultrassom e ondas de tensão. Para tal, 60 amostras de cerne e alburno foram preparadas. Os testes não destrutivos foram realizados por meio de um equipamento de ultrassom e um de ondas de tensão, enquanto que os testes destrutivos de flexão estática foram realizados em uma máquina universal de ensaios. Os principais resultados mostraram que a madeira de cerne apresentou melhor comportamento nos ensaios não destrutivos, quando comparada à madeira de alburno. No entanto, o melhor modelo matemático foi obtido considerando-se cerne e alburno, quando estes foram analisados por meio da técnica ultrassônica. Dessa maneira, concluiu-se, no presente estudo, que as técnicas de ondas de tensão e ultrassom podem ser empregadas com o intuito de estimar o módulo de elasticidade da madeira de *Eucalyptus grandis*.

Palavras-chave: ultrassom, ondas de tensão, tecnologia da madeira.

1. INTRODUCTION

Nondestructive materials evaluation is the science of identifying physico-mechanical properties of a piece of material without modifying its characteristics and final application, using this information to make decisions regarding its applications (Ross et al., 1998). The area of nondestructive evaluation (NDE) is in constant evolution, especially in the wood sector (Brashaw et al., 2009); however, wood is an anisotropic and heterogeneous material that hinders evaluation and characterization compared to other materials (Feeney et al., 1998).

The most commonly used NDE techniques are transverse vibration, stress wave, ultrasound (acoustic emission and acoustic ultrasonic emission) (Ross & Pellerin, 1994); electrical resistance, colorimetry, dielectric properties, and X-rays (Pellerin & Ross, 2002).

Stress wave propagation in wood is a dynamic process that is directly related to physico-mechanical properties. Generally, stress wave presents better propagation on wood with high sonorous quality than on decayed wood. This technique is employed in order to analyse wood pieces, besides evaluating the internal conditions of trees by measuring the propagation time in radial direction (Wang et al., 2004).

The ultrasonic technique is employed mainly for determination of the elastic constant, which is used to predict the biological modifications in wood structure and evaluate the process of sawing. According to Targa et al. (2005), techniques that employ resonance frequency, ultrasonic velocity and acoustic emission can evaluate structural and functional integrity of many wood products.

Many studies using ultrasonic techniques reported basic information of properties of anisotropic materials. These results present a wide application range, especially in the definition of material properties, which could be used in software simulations to examine the impact of silvicultural practices on wood quality (Brashaw et al., 2009).

Stress wave and ultrasonic techniques are simpler and less expensive than image techniques. Wave propagation is a mechanical phenomenon used to detect internal flaws in wood (Ross & Pellerin, 1994). Likewise, non-destructive techniques are used mainly to verify how these occurrences affect the physical and mechanical properties of wood (Gonçalez et al., 2001).

Nondestructive techniques have been frequently used to predict the mechanical properties of wood, such as the modulus of elasticity (MOE) (Oliveira et al., 2002; Carrasco & Azevedo, 2003; Stangerlin et al., 2008; Del Menezzi et al., 2010; Missio et al., 2013a, b).

Nondestructive techniques have many advantages, such as velocity of analyses, low cost, versatility, utilization in live trees, and easy transportation of equipment compared with destructive techniques. The material analyzed is not affected by the phenomenon of propagation; the samples could be tested many times without deformation and could be evaluated in service (Oliveira et al., 2002). These techniques also enable wood maintenance through mapping of decayed areas without the need to remove parts of the structure. In this context, the present study aimed to predict the modulus of elasticity at static bending through ultrasound and stress wave techniques.

2. MATERIAL AND METHODS

2.1. Raw material

Rose gum (*Eucalyptus grandis*) trees (17 years old) from a homogeneous population located in the north coast of Rio Grande do Sul state, Southern of Brazil (30° 14' 09.73" S, 50° 19' 55.07" O) were harvested, all of them with cylindrical trunk and diameter over 25 cm at diameter breast height (DBH, 1.30 m height).

The first log (3.15 m length) of each tree was cut. Then, sixty samples of heartwood and sapwood (30 per treatment) measuring 10 × 10 × 200 mm (radial × tangential × longitudinal) were prepared, all of them with straight grain and absence of knots. The heartwood and sapwood samples were cut from the region between pith and bark and its distinction was realized by visual analysis of color.

The samples were then placed in climatic chamber at 20 °C and 65% relative humidity for stabilization

of moisture content so that nondestructive and destructive tests could be carried out.

2.2. Nondestructive tests

The ultrasonic tests were performed in an ultrasound equipment (Proceq, model TICO) using dry-point transducers (frequency of 54 Hz). The time and velocity of wave propagation were measured by direct method. Thus, the elastic constant in ultrasonic tests (ED_{us}) was measured through Equation 1.

$$ED_{us} = \left(V^2 \cdot \rho_{12\%}\right) \cdot 10^{-6} \tag{1}$$

where: ED_{us} = elastic constant in ultrasonic tests (MPa); V = velocity of wave propagation (m s^{-1}); $\rho_{12\%}$ = specific gravity at 12% moisture content (kg m^{-3}).

The stress wave tests were performed in stress wave timer equipment (Metriguard, model 239A). The heartwood and sapwood samples were placed between two sensors with a span length of 140 mm. The timer of the equipment was reset and the pendulum was liberated in order to obtain the time of wave propagation (μs). Thus, the velocity of wave propagation (m s^{-1}) and, consequently, the elastic constant in stress wave tests (ED_{swt}) were measured (Equation 2).

$$ED_{swt} = \frac{V^2 \cdot \rho_{12\%}}{A} \tag{2}$$

where: ED_{swt} = elastic constant in stress wave tests (MPa); V = velocity of wave propagation (m s^{-1}); $\rho_{12\%}$ = specific gravity at 12% moisture content (kg m^{-3}); A = gravitational acceleration (9.80 m s^{-2}).

2.3. Destructive tests

Destructive evaluation was carried out in a universal testing machine (EMIC, model DL-30000) with capacity of 300 kN. The static bending tests were performed in a three-point bending apparatus with a span length of 140 mm according to ASTM D143-94 (ASTM, 1997).

2.4. Statistical analysis

The data were assessed by analysis of variance (p<0.05) and regression analysis. In the analysis of variance, when the null hypothesis was rejected, the mean values were compared by the Tukey test at 5% significance level. The regression models were adjusted as a function of coefficient of determination (R^2), F-statistic, and mean absolute error (MAE). Moreover, a *p*-value of 0.05 (corresponding to 5% probability of error) was considered.

3. RESULTS AND DISCUSSION

Mean values of $\rho_{12\%}$ of heartwood and sapwood were statistically different (Table 1). $\rho_{12\%}$ of sapwood was 14.4% higher than $\rho_{12\%}$ of heartwood.

Table 1. Mean values of physico-mechanical properties of *Eucalyptus grandis* wood.
Tabela 1. Valores médios das propriedades físico-mecânicas da madeira de *Eucalyptus grandis*.

Property	Wood type	Mean	CV (%)
$\rho_{12\%}$ (kg m^{-3})	Heartwood	494 **a**	10.15
	Sapwood	578 **b**	6.76
MOE (MPa)	Heartwood	11169.6 **a**	14.36
	Sapwood	13021.6 **b**	17.79
V_{us} (m s^{-1})	Heartwood	5905.09 **a**	6.26
	Sapwood	5844.48 **a**	6.36
ED_{us} (MPa)	Heartwood	17384.6 **a**	19.54
	Sapwood	20170.0 **b**	18.50
V_{swt} (m s^{-1})	Heartwood	3903.90 **a**	5.10
	Sapwood	3958.44 **a**	5.68
ED_{swt} (MPa)	Heartwood	7722.4 **b**	15.39
	Sapwood	9397.4 **a**	17.04

$\rho_{12\%}$ = specific gravity at 12% moisture content; MOE = modulus of elasticity in static bending tests; V_{us} = ultrasonic velocity; ED_{us} = elastic constant in ultrasonic tests; V_{swt} = stress wave velocity; ED_{swt} = elastic constant in stress wave tests; CV = coefficient of variation. Mean values in the same column for each property followed by the same letter are not statistically different at level of 5% probability of error by the Tukey test.

Poubel et al. (2011) reported values of specific gravity of heartwood lower than sapwood in *Eucalyptus pellita*. Specific gravity could vary as a function of anatomical characteristics, such as vessel proportion, thickness of fiber wall, and length, width and diameter of lumen (Panshin & De Zeeuw, 1970).

The results of mechanical properties were statistically higher in sapwood than in heartwood.

The mean values of MOE, ED_{us} and ED_{swt} of sapwood were 14.22, 13.80 and 17.82% higher than those of heartwood.

The mean value of ED_{us} in heartwood was 17384 MPa, which is similar to that found by Stangerlin et al. (2008) for the same species. On the other hand, the mean value of ED_{swt} in heartwood was 7722.4 MPa. Garcia et al. (2012), using the stress
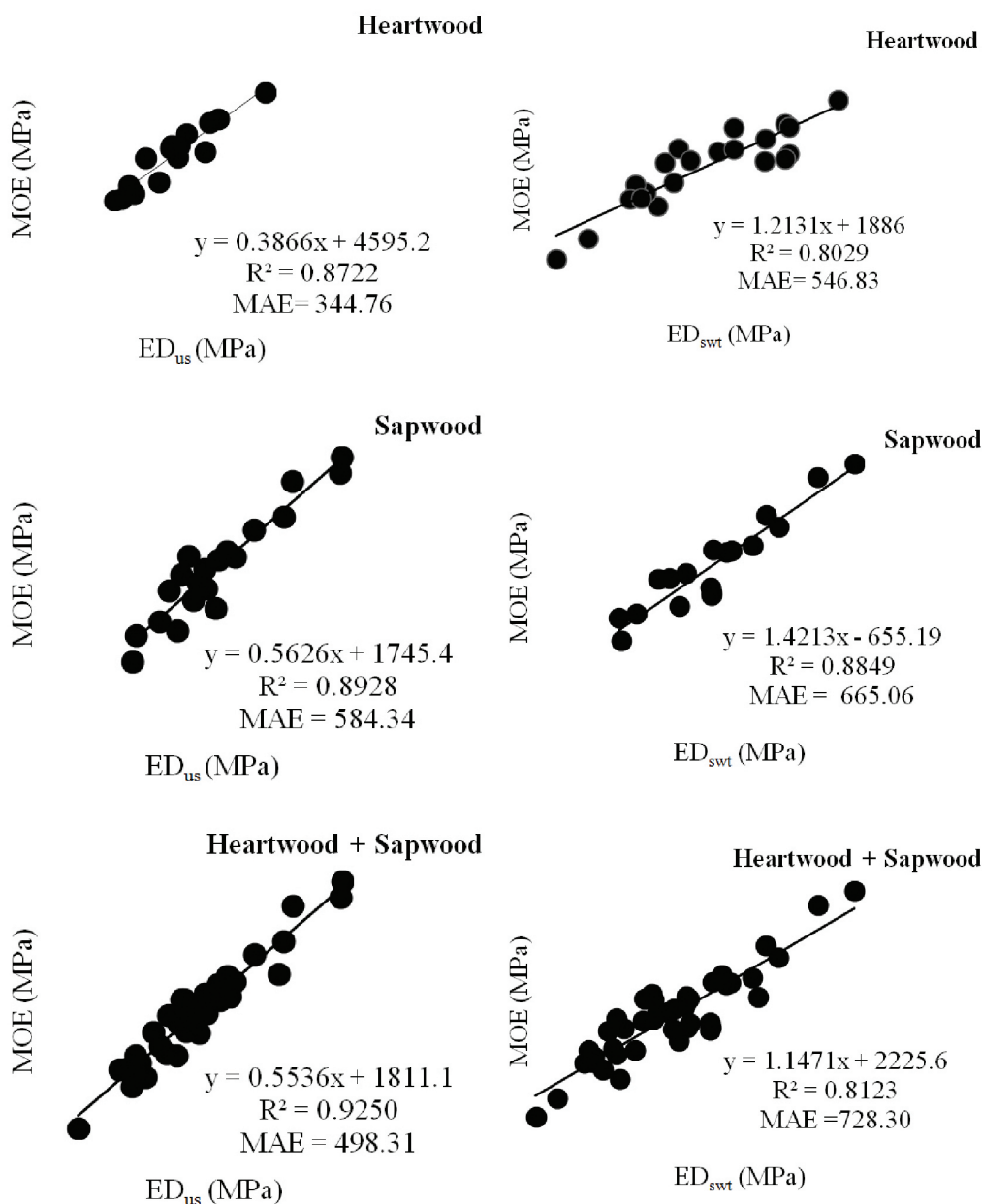

Heartwood

MOE (MPa) vs ED_{us} (MPa)

$y = 0.3866x + 4595.2$
$R^2 = 0.8722$
$MAE = 344.76$

Heartwood

MOE (MPa) vs ED_{swt} (MPa)

$y = 1.2131x + 1886$
$R^2 = 0.8029$
$MAE = 546.83$

Sapwood

MOE (MPa) vs ED_{us} (MPa)

$y = 0.5626x + 1745.4$
$R^2 = 0.8928$
$MAE = 584.34$

Sapwood

MOE (MPa) vs ED_{swt} (MPa)

$y = 1.4213x - 655.19$
$R^2 = 0.8849$
$MAE = 665.06$

Heartwood + Sapwood

MOE (MPa) vs ED_{us} (MPa)

$y = 0.5536x + 1811.1$
$R^2 = 0.9250$
$MAE = 498.31$

Heartwood + Sapwood

MOE (MPa) vs ED_{swt} (MPa)

$y = 1.1471x + 2225.6$
$R^2 = 0.8123$
$MAE = 728.30$

Figure 1. Mathematical models adjusted to MOE as a function of ED_{us} and ED_{swt} of *Eucalyptus grandis* wood.
Figura 1. Modelos matemáticos ajustados para o MOE em função do ED_{us} e ED_{swt} da madeira de *Eucalyptus grandis*.

wave technique, found ED_{swt} between 11166 and 12735 MPa. Considering that, V_{us} and V_{swt} did not present significant difference; it is possible to affirm that $\rho_{12\%}$ had great influence on the nondestructive properties (see Equation 1). Oliveira & Sales (2006) found a significant tendency between species for the increase of ultrasonic velocity as a function of specific gravity. However, analyses of the anatomical structure of wood are important to visualize changes in nondestructive properties, such as tracheid length and fiber length (Oliveira & Sales, 2000).

Moreover, the mean values of ultrasonic tests overestimated MOE, while the mean values of stress wave tests underestimated MOE. ED_{us} was 35.5 and 35.7% higher than in MOE for heartwood and sapwood, respectively. On the other hand, ED_{swt} was 30.9 and 27.8% lower than MOE. Cunha & Matos (2010) also observed an underestimation of MOE after tests with stress wave timer (~50%) in glulam beam of *Pinus taeda*. Regarding overestimation of MOE by ultrasound tests, Miná et al. (2004), in *Eucalyptus citriodora* wood poles, and Stangerlin et al. (2010), in *Peltophorum dubium* wood, also verified this behavior.

This difference between mean values of modulus of elasticity obtained through nondestructive and destructive techniques was also observed in other studies using transversal vibration (Targa et al., 2005; Teles et al., 2011), ultrasound (Oliveira et al., 2002; Stangerlin et al., 2008; Vivian et al., 2012), resonance analysis (Leite et al., 2012), and stress wave (Ishiguri et al., 2008; Del Menezzi et al., 2010; Teles et al., 2011;).

The mathematical models adjusted for Rose gum heartwood and sapwood are shown in Figure 1.

Figure 1 shows that all models were significant at level of 5% probability of error. All the models presented values of coefficient of determination between 0.80 and 0.93, proving that more than 80% variation of MOE can be explained by the variation of ED_{us} or ED_{swt}. The models created for heartwood showed R^2 slightly lower than the models created for sapwood for both nondestructive techniques.

Other studies (Del Menezzi et al., 2010) investigated the relationship between MOE and ED_{swt} in six species, and found a coefficient of determination of 0.91. According to the authors,

the models showed low predictability for the same species when the variability was small. However, these reports differ from the present study, in which models with $R^2 > 0.80$ were observed for the same species. Likewise, Oliveira et al. (2002) reported coefficients of determination of 0.63 and 0.59 in the relationship MOE versus ED_{us} for *Goupia glabra* and *Hymenaea* sp. wood, respectively.

All the mathematical models presented positive angular coefficients, which indicate a positive inclination of the tendency line. This fact confirms the hypothesis proposed by The Speed Sound (NDT, 2013). The authors affirmed that, if the elastic property is individually analyzed, materials with high elastic properties present high stiffness and proximity between molecules.

4. CONCLUSIONS

The use of nondestructive techniques for prediction of modulus of elasticity showed better behavior in heartwood compared with sapwood of Rose gum. However, the best model was obtained considering both wood types when analyzed through the ultrasonic technique.

The results obtained in the present study showed that stress wave and ultrasound techniques can be employed to predict the modulus of elasticity of *Eucalyptus grandis* wood.

SUBMISSION STATUS

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