APPLICATION OF STRESS WAVES TO ESTIMATE MOISTURE CONTENT IN *Eucalyptus* WOOD

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ABSTRACT: Accurate monitoring of moisture content in *Eucalyptus* wood during the drying process is critical to improving product quality. And as electric meters lose accuracy in some moisture ranges, in this work a Stress Wave Timer was used to try and assess the possibility of estimating wood moisture based on variation in the propagation velocity of stress waves in two *Eucalyptus* species. Effects of knot area and board basic density on the propagation of stress waves were also analyzed, using analysis of variance and observing mean values for these characteristics. Equations were fitted and wood moisture content could be estimated by the stress wave propagation method using nonlinear models or a multiple linear model, with wave propagation velocity, basic density and knot area being used as independent variables. Best fits were obtained for boards showing no visible defects (knots, cracks etc.). The propagation velocity of stress waves through the wood was found to vary as a function of the knot area, wood density and anatomical orientation (visual analysis) of the boards. Knots had a stronger influence on wave transmission when they were present in radially cut boards.

Key words: Wood moisture content, basic density, knots, stress wave timer.

APLICAÇÃO DE ONDAS DE TENSÃO PARA A ESTIMATIVA DA UMIDADE EM MADEIRA DE *Eucalyptus*

RESUMO: *O acompanhamento preciso da umidade da madeira de Eucalyptus durante o processo de secagem é fundamental para melhorar a qualidade dos produtos. Considerando-se que os medidores elétricos perdem precisão em algumas faixas de umidade, utilizou-se neste trabalho um temporizador de ondas de tensão (Stress Wave Timer) com o objetivo de verificar a possibilidade de estimativa da umidade da madeira a partir da variação da velocidade de propagação de ondas de tensão em duas espécies de Eucalyptus. Também foi analisada a influência da área de nós, assim como da densidade básica das tábuas na propagação das ondas de tensão por meio das análises de variância e das médias dessas características. Foram feitos ajustes de equações e a umidade das madeiras pode ser estimada pelo método de propagação das ondas de tensão por meio de modelos não-lineares ou ainda por um modelo linear múltiplo, utilizando a velocidade de propagação das ondas, a densidade básica e a área de nós como variáveis independentes. Os melhores ajustes foram obtidos para tábuas livres de defeitos visíveis (nós, rachaduras etc.). A velocidade de propagação das ondas de tensão na madeira variou em função da área de nós nas tábuas, da densidade da madeira e da orientação anatômica das tábuas (análise visual). Os nós exerceram maior influência no deslocamento das ondas quando presentes em tábuas cortadas no sentido radial.*

Palavras-chave: Umidade da madeira, densidade básica, nós, temporizador de ondas de tensão.

1 INTRODUCTION

The determination of wood moisture content during the drying process is of great importance to ensure efficient process control. Skaar (1972) describes several methods for determination of moisture content in wood, including the gravimetric method and the electric resistance method.

In the gravimetric method, moisture content is given by the ratio of water mass removed to the oven dry mass of a sample. This method is considered to be the most accurate (SKAAR 1972).

Electric resistance methods offer some advantage in comparison with the gravimetric method in that they enable immediate readings of moisture content and are non-destructive. In a study estimating moisture content in reforestation species and native hardwoods by using electric meters, Galina (1997) found that moisture can be accurately estimated up to a maximum value in the range of 19% to 40%, depending on the fiber saturation point of

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each wood. Beyond this point, which is variable among species, the low electric resistance in the wood will impair reading accuracy. Likewise, the minimum moisture content for which electric meters offer good accuracy is in the range of 5% to 7% (SANTINI 1996). With values below this range, the high electric resistance in the wood will also impair reading accuracy.

In a study monitoring the drying process of pinewood, eucalyptus and imbuia using ultrasound equipment, Gonçalves & Costa (2002) developed equations to explain moisture content as a function of the velocity of wave propagation. The equation fits and the graphically depicted tendencies both suggest that this method offers greater precision than the electric meter method beyond the fiber saturation point, since the latter lacks accuracy.

The method used by Gonçalves & Costa (2002) relies on ultrasound equipment, one of the characteristics of which is the possibility of controlling the frequency applied. The timer used in this work, on the other hand, emits waves in the natural frequency of vibration of woods, is cost-effective, and yet, judging by the characteristics of stress waves, it is highly sensitive to wood moisture, enabling more accurate equations to estimate moisture, even in ranges where electric meters are inefficient.

With the above considerations in mind, the objective of this work is to fit equations to explain the behavior of wood moisture as a function of the propagation velocity of stress waves, and also the effect of knot area and basic density on such determinations.

2 MATERIAL AND METHODS

2.1 Sampling

For the experiment, trees of *Eucalyptus urophylla* and *Eucalyptus cloeziana* were obtained from eucalyptus plantations owned by V & M Florestal and located in Paraobeba region, Minas Gerais state. Five trees of each species were collected, all 16 years old. A log was removed from each of the 10 trees comprising the 6.5m to 8m high segment of the trunk, and four boards 1.5m long were obtained from each log, two each side of the pith.

The sample boards were all cut to a standard size, 1.10 m long x 12 cm wide x 1.2 cm thick. Top sides were waxed to prevent excess moisture loss. The boards were then stacked inside a temperature controlled environmental chamber at 20°C and 65% RH, in order to homogenize ambient conditions during the drying process and allow samples to achieve a moisture balance.

2.2 Determination of the propagation time of stress waves in board samples

The propagation time of stress waves was determined by a 239A Metriguard Stress Wave Timer.

To apply waves, equipment clamps were attached to each sample specimen opposite each other in parallel alignment with the axial axis of the board. A stress wave was applied by swinging a pendulum against one of the clamps, axially passing through the board before reaching the other clamp. The time interval is recorded by transducers attached to the clamps, in microseconds.

Readings were taken by attaching the clamps to five different points which were systematically marked along the width of each board. Three readings were taken at each of the five points of the time required for a wave to travel from one transducer to the other. Thus each board had 15 readings, taken every 48 hours, until the moisture content of the boards was in balance with the moisture content of the surrounding environment. The boards were then weighed using a 3000 grams maximum weight digital scale, accurate to 0.01g.

2.3 Determination of moisture content

After measurements were taken, the boards were placed in a forced air circulation oven at 103 ± 2°C for determination of oven dry mass. Based on the dry and fresh mass of each sample, as measured at different reading dates, the moisture content of each board was then determined.

2.4 Determination of basic density

To determine the basic density of the boards, samples measuring 10 cm were taken from the top of each board. The volume of such samples was determined by water immersion, according to Archimedes, after which time they were oven dried (103 ± 2°C) to constant mass. Basic density determination was based on the ratio of dry mass to fresh volume of the sample (ABNT 2003).

2.5 Knot area

The knot area was determined by drawing a rectangle around each knot of each board, following the width and length orientation of the board, so that each knot had its area individually measured in cm^2.

2.6 Statistical analyses

All data were tabulated on an electronic spreadsheet and subjected to statistical analyses using softwares Statgraphics and R (Project for Statistical Computing).

Analyses of variance were performed to examine the propagation velocity of stress waves between the two *Eucalyptus* species and between boards. Mean values and coefficients of variation were computed for the obtained data.

Using data of basic density, knot area and propagation velocity of stress waves, multiple linear equations were fitted to estimate the moisture content of each species separately.

Nonlinear equations were fitted to estimate the moisture content of each species, using propagation velocity of stress waves only.

3 RESULTS AND DISCUSSION

3.1 Initial moisture content

At the start of the experiment, the initial moisture content of *E. urophylla* and *E. cloesiana* boards ranged from 33% to 81% (Table 1).

3.2 Knot area and basic density

Mean values and coefficients of variation of knot area and basic density for the two *Eucalyptus* species are presented in Table 2.

E. urophylla had smaller knot area than *E. cloeziana* (Table 2). The coefficients of variation were high, particularly on account of knot quantity being found to vary considerably between boards of the same genetic material.

When the mean knot area is expressed as area per square meter, the value is 75.75 cm^2/m^2, lower than the result obtained by Chies (2005) studying pinewood, 142.35 cm^2/m^2 on average.

A visual analysis of the boards used in this experiment reveals that, where boards are cut closer to the pith, larger knot areas are found. This is so because knots develop outwardly from the pith to the bark, and so boards closer to the pith tend to be radial pieces, which means that the knots are intersected longitudinally in them, while in tangential pieces the knots are intersected transversely, reducing their area of influence.

E. cloeziana had a higher basic density value, while *E. urophylla* had a higher CV value. Brito & Barrichelo (1980) obtained density values of 0.594 g/cm^3 for *E. urophylla* and 0.508 g/cm^3 for *E. cloeziana*, all four years old. It is known, however, that as far as genus *Eucalyptus* is concerned, older trees within a species tend to have higher densities, partially explaining result variations between this work and the work of Brito & Barrichelo (1980) for the same species. The higher density of *E. cloesiana* in relation to *E. urophylla* can also be partially explained by the former species having a larger knot area.

Table 1 – Maximum, minimum and mean values of moisture content in two *Eucalyptus* species.

Tabela 1 *– Valores médios, mínimos e máximos da umidade das tábuas para as duas espécies de Eucalyptus.*

Species	Board moisture content (%)		
	Minimum	Mean	Maximum
E. urophylla	45.1	62.6	80.6
E. cloeziana	33.3	41.2	47.9

Table 2 – Mean value and coefficient of variation of knot area and basic density in boards of two *Eucalyptus* species.

Tabela 2 *– Média geral e coeficientes de variação da área de nós e da densidade básica das tábuas de duas espécies de Eucalyptus.*

Genetic material	Knot area		Basic density	
	Mean (cm^2)	CV (%)	Mean (g/cm^3)	CV (%)
E. urophylla	5.0	105.5	0.615	8.3
E. cloeziana	14.9	95.1	0.772	4.2

3.3 Application of stress waves

The velocity of wave propagation ranged between 3162 m.s^{-1} and 4761 m.s^{-1} (Table 3), a wider range than the result found by Oliveira et al. (2006a) using ultrasound equipment – between 3296 m.s^{-1} and 4360 m.s^{-1} for *E. grandis* and between 4048 m.s^{-1} and 4777 m.s^{-1} for *E. citriodora*. Given that the anatomy of eucalyptus wood is very similar among species and that wave velocities generated by SWT and ultrasound are equivalent, this range difference probably occurred because of differences in sample sizes, this being one of the factors that potentially causes variations in propagation velocity (OLIVEIRA et al. 2005, 2006b). Also, Nogueira & Ballarin (2006) argued that larger samples tend to present more defects, whether manifested externally or internally and barely perceptible. The boards used in this work for application of stress waves were not rated as to the presence of defects.

Figure 1 depicts scatter plots of moisture content variation as a function of the propagation velocity of stress waves, in each *Eucalyptus* species.

Figure 1 shows a higher wave velocity in *E. cloeziana*. From the scatter plot, a tendency can be noted in both species toward some distinct point clustering. These clusters were analyzed and the boards corresponding to such points in species *Eucalyptus urophylla* were characterized by having higher basic densities than the others. In species *Eucalyptus cloeziana*, the cluster points corresponded to boards carrying more and larger knots, usually extending radially across the piece.

Figure 2 shows the individual behavior pattern of a board. This pattern is followed by all boards being analyzed in that with decreasing moisture content an increase follows in the propagation velocity of stress waves, as was observed by Costa & Gonçalves (2006) and Oliveira et al. (2006a) with some softwoods and hardwoods.

3.4 Variation in stress wave propagation between genetic materials and boards

The analysis of variance considering data of all genetic materials together is illustrated in Table 4.

Table 3 – Propagation velocity of stress waves in *Eucalyptus* wood.

Tabela 3 *– Velocidade de propagação das ondas de tensão aplicadas na madeira de Eucalyptus.*

Genetic material	Stress wave propagation velocity (m.s^{-1})		
	Minimum	Mean	Maximum
E. urophylla	3542	4216	4761
E. cloeziana	3162	3843	4451

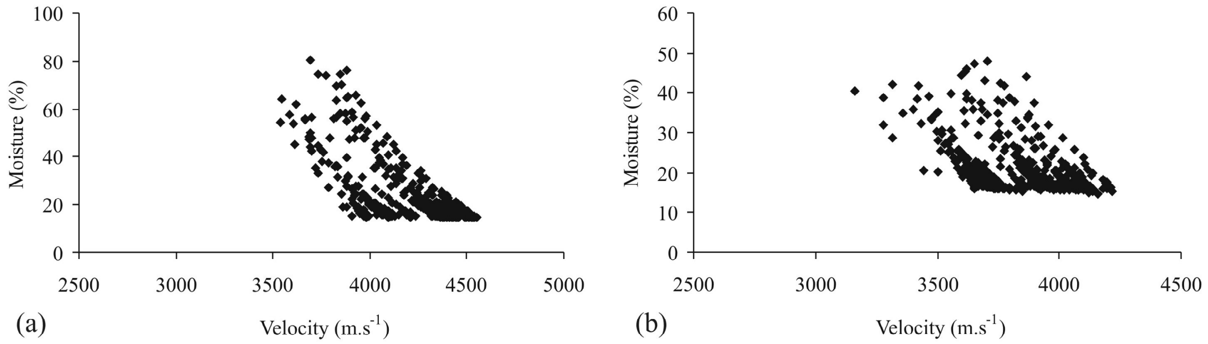

Figure 1 – Moisture content variation in wood of *Eucalyptus urophylla* (a) and *Eucalyptus cloeziana* (b) respectively, as a function of the propagation velocity of stress waves.

Figura 1 *– Variação da umidade da madeira de Eucalyptus urophylla (a) e Eucalyptus cloeziana (b), respectivamente, em função da velocidade de propagação das ondas de tensão.*

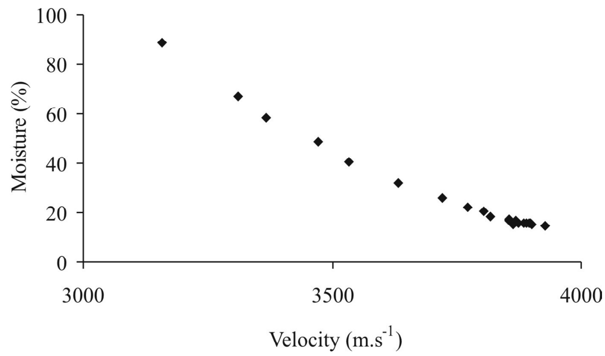

Figure 2 – Moisture content behavior in *Eucalyptus* wood as a function of the propagation velocity of stress waves through a board.

Figura 2 *– Comportamento da umidade da madeira de Eucalyptus em função da velocidade de propagação de ondas de tensão em uma tábua.*

Table 4 – Analysis of variance of stress wave velocity as a function of genetic material and board in *E. urophylla* and *E. cloeziana* woods.

Tabela 4 – *Análise de variância da velocidade da onda de tensão em função de material genético e tábua para as madeiras de E. urophylla e E. cloeziana.*

All genetic materials together		
Source	DF	MS
Genetic material	1	33417000**
Board	3	284251**
Reading	23	814470**
Residual	932	

** Significant at the 1 % level

This analysis has statistical significance at the 1% level for genetic material, board and reading, showing that genetic materials differ from each other in the velocity of stress waves. Also, at also least one board differs from the others in this characteristic. The reading significance shows a variation in the propagation velocity of stress waves over time.

Table 5 illustrates analysis of variance results for *Eucalyptus* genetic material separately.

As regards board, only *E. urophylla* was statistically significant at the 1% probability level, showing that a variation exists in the propagation velocity of stress wave among *E. urophylla* boards. This difference could be explained by variation in the size of anatomical structures and wood properties, radially in the log, considering the presence of juvenile wood in fast-growing timber, as is the case with *Eucalyptus.*

Both species showed statistical significance for readings, confirming variation in the wave propagation velocity over time, as observed visually in the scatter plots of moisture as a function of velocity (Figure 1).

3.5 Moisture content as a function of the propagation velocity of stress waves

To select the best regression models, linear and nonlinear equations were tested in an attempt to use the propagation velocity of stress waves for estimation of moisture content in wood.

To start with, the estimation of moisture content with wave velocity data was possible using a multiple linear equation for knot area and basic density data. However, by eliminating boards presenting differentiated scatter plot patterns within a species, a nonlinear equation was obtained in which moisture content is estimated by wave propagation velocity alone. With linear fits, two equations were obtained, one for each species.

Table 6 illustrates multiple linear equations to explain moisture content as a function of propagation velocity of stress waves, basic density and knot area in *E. urophylla* and *E. cloeziana* wood.

All variables in the fit model were statistically significant at the 5% level.

Although the boards of *E. urophylla* wood showed considerable variation in basic density (Table 2), this species gave the best fit in comparison to the other species, with a coefficient of determination of 85.82% and a standard error of estimate of 5.10%, significant at the 1% probability level.

As regards *E. cloeziana*, the equation constant was significant at the 5% probability level while the other variables were significant at the 1% probability level. The equation fit revealed lower values, 49.01% for coefficient of determination and 4.89% for standard error of estimate, significant at the 1% probability level. These values could be explained by the low initial moisture content in the boards of this genetic material, therefore the equation fit was based on a lower moisture content range (between 15% and 50%).

Scatter plots with fit residuals for the two species are illustrated in Figure 3.

Due to the visual nonlinearity of scatter plot data, nonlinear fits were performed using models with three coefficients, in software R.

The nonlinear equation explaining moisture content variation in *E. urophylla* as a function of the propagation velocity of stress waves is illustrated in Equation 1.

$$M = \frac{245.861125}{1 + EXP\left[\left(\frac{3449.08831293 - V}{370.293818}\right)\right]} \quad (1)$$

Where:
M = Estimated moisture content (%).
V = Propagation velocity of stress waves through wood ($m.s^{-1}$)

The nonlinear equation explaining moisture content in *E. cloeziana* as a function of the propagation velocity of stress waves is illustrated in Equation 2.

$$M = \frac{94.524889}{1 + EXP\left[\left(\frac{3448.93880242 - V}{390.159762}\right)\right]} \quad (2)$$

Scatter plots with the relevant fit residuals are illustrated in Figure 4.

Table 5 – Analysis of variance of the stress wave velocity as a function of the board for *Eucalyptus urophylla* and *Eucalyptus cloeziana*.

Tabela 5 *– Análise de variância da velocidade da onda de tensão em função da tábua para os Eucalyptus urophylla e Eucalyptus cloeziana.*

	E. urophylla	
Source	DF	MS
Board	3	340899**
Reading	23	600453**
Residual	453	29182
	E. cloeziana	
Source	DF	MS
Board	3	58255.3
Reading	23	256657**
Residual	453	29551.1

** Significant at the 1 % level

Table 6 – Results of the multiple linear model fit describing the relationship between moisture content and propagation velocity of stress waves, basic density and knot area in *E. urophylla* and *E. cloesiana* wood.

Tabela 6 *– Resultados do ajuste do modelo linear múltiplo que descreve a relação entre a umidade da madeira e a velocidade de propagação das ondas de tensão, densidade básica e área de nós da madeira de E. urophylla e E. cloesiana.*

E. urophylla		*E. cloeziana*	
Variables	Estimated coefficients	Variables	Estimated coefficients
Constant	1865.42**	Constant	-846.535*
V^2	-0.000076355**	V^2	0.000546461**
$1 / V^3$	-29309900000000**	V^3	-0.000000123956**
KA	-2.2053**	$1 / V^3$	-45614000000000**
Bd	6426.88**	Bd	21576**
KA^2	0.0487298**	V*Bd	-11.6315**
Bd^2*KA	4.5069**	V^2*Bd	0.00155685**
V*Bd	-3.63927**	V^2*Bd^2	-0.00000000022303**
V^2*Bd	0.000492849**		
R^2 – 85.82%	S_{yx} –5.09%**	R^2 – 49.01%	S_{yx} – 4.88%**

V = velocity propagation of stress waves; KA = knot area; Bd = basic density
** - Significant at the 1 % level; * - Significant at the 5 % level

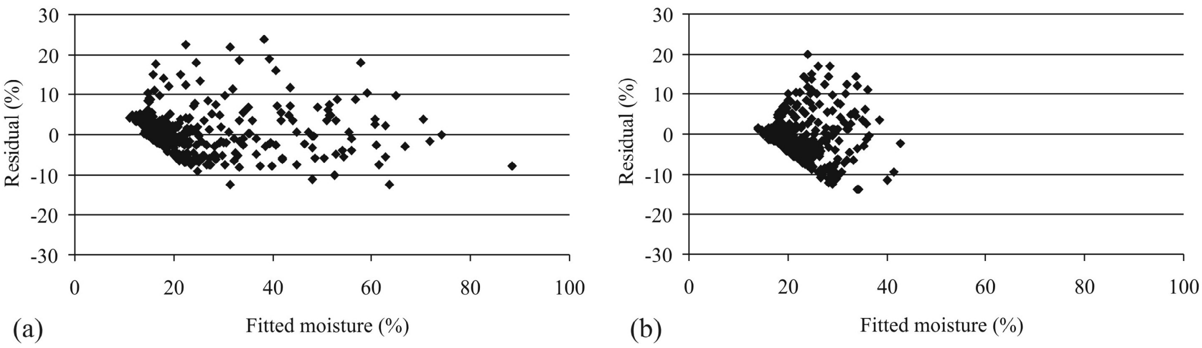

Figure 3 – Scatter plot of fit residuals of the equation estimating moisture content based on stress wave propagation, basic density and knot area in *E. urophylla* (a) and *E. cloeziana* (b) wood.

Figura 3 *– Dispersão dos resíduos do ajuste da equação que estima a umidade da madeira a partir da propagação das ondas de tensão, densidade básica e área de nós da madeira de E. urophylla (a) e E. cloeziana (b).*

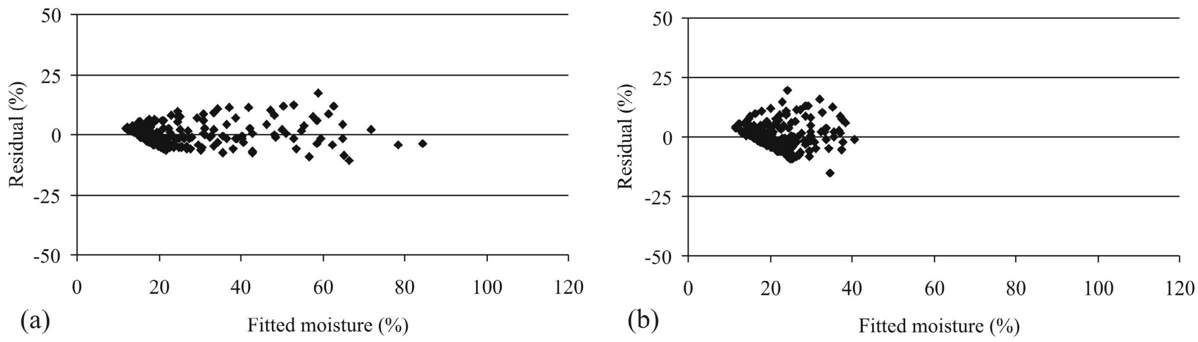

Figure 4 – Scatter plot of fit residuals of the nonlinear equation estimating moisture content based on stress wave propagation in wood of *Eucalyptus urophylla* (a) and *E. cloeziana* (b).

***Figura 4** – Dispersão dos resíduos do ajuste não-linear da equação que estima a umidade da madeira a partir da propagação das ondas de tensão na madeira de Eucalyptus urophylla (a) e E. cloeziana (b).*

4 CONCLUSIONS

Considering the above results, it can be said that:

- Moisture content in wood can be estimated through propagation of stress waves, using nonlinear models or using multiple linear models that include other variables.
- The propagation velocity of stress waves can vary as a function of the knot area and basic density of boards, considerably reducing the accuracy of moisture content estimations.
- Knots exert stronger influence on the propagation of stress waves if present in radially cut boards.

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