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Evaluate of use of ultrasonic waves for determination of moisture content in wood drying of *Eucalyptus saligna*

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ABSTRACT

Background: This study aimed to evaluate the use of ultrasonic waves as a method of control conventional drying of *Eucalyptus saligna*, through correlation with the velocity of propagation of ultrasonic waves in wood, thus being able to estimate the moisture content of the wood. **Methodology:** For preparation of samples, tangencies boards with 25 x 110 x 2100 mm, were selected and resized to 25 x 110 x 660 mm (thickness x width x length), resulting in 66 boards. On each board was removed two samples from the edges to determine the initial moisture content of the boards. The monitoring of moisture content was performed using Stress Wave Timer (SWT) in the control samples, and the data analysis performed on the basis of the specific gravity of the woods. **Results:** The results show that the class of less than 0.60 $g.cm^{-3}$ of specific gravity there is heterogeneity in the velocity of wave propagation in moist wood, the same is not observed in dried wood, whereas the specific gravity class of 0.60 to 0.79 $g.cm^{-3}$, there is a uniformity in the velocity of the ultrasonic wave with higher correlation coefficients thus concluding that moisture influences the transition of ultrasonic waves, which is characterized by a reduction in wave velocity and a significant reduction in the moisture content of *Eucalyptus saligna*.

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INTRODUCTION

The monitoring of moisture content during the drying process of wood is of fundamental importance since it is widely used for the execution of the drying program, as well as to determine the final moisture of the process, and quality of the final product beyond industrial costs involved in drying steps. Several researchers (Santini; Tomaselli, 1997; Santini, 2000; Calonego *et al*., 2006; Batista *et al*., 2008) has studied new techniques for determining the moisture content of wood, among them using electrical appliances, whose operation is by resistance to the transition of electrical current between the wood fibers.

Some technological alternatives studied for application in control of the drying process are the methods based on the variation of temperature in the wood pile (Santini; Tomaselli, 1997), temperature variation in wood (Santini, 2000), variation of contraction in the load inside the Kiln (Rasev; Petropavlosvskij, 1969), infrared stimulation, the temperature coefficient of the wood/wet bulb temperature, and methods based on acoustic emissions, with emphasis on the use of ultrasonic waves (Calegari, *et al*., 2011).

The use of ultrasound for detecting defects in wood, which have cracks and discontinuities are not significant features when it comes to its constitution, ultrasound tests are generally used to determine physical and mechanical parameters in the wood since the moisture of wood influences the propagation of ultrasonic wave Calegari *et al*. (2007, 2008, 2011). Studies by Simpson (1998), Simpson; Wang (2001), Gonçalves; Costa

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(2002), Brashaw *et al*. (2004), Dyk; Rice (2005) and Calegari *et al*. (2011) correlated the ultrasonic velocity of moisture, highlighting this point to monitor the moisture content of wood during the drying process.

The observation of the speed of propagation of ultrasonic waves as a method of indirect determination of moisture content in wood is innovative, being in the research phase, and showing very promising (Cruz *et al*., 2009; Calegari *et al*., 2011).

As studies and techniques to determine the moisture content of wood with ultrasonic waves, are new in Brazil and little research has been conducted so far, when related to the drying of the wood, only involving processes in determining the quality and strength of wood.

Thus, the present study aimed to use the ultrasound waves as a method of control of conventional drying of *Eucalyptus saligna*, and thus correlate the speed of propagation of waves with the moisture content of the wood.

MATERIALS AND METHODS

Preparation of material:

The studied specie was *Eucalyptus saligna* provided by the company MADEMAPE - Lumber Industry Ltda. located in the region of Campina Grande do Sul, Paraná State. So the tangential boards were selected with dimensions of 25 x 110 x 2100 mm (width x length x thickness) with presence of heartwood and sapwood, due to its plant health, from newly unfolded logs.

For preparation of samples for drying, the boards were resized to 25 x 110 x 660 mm (thickness x width x length), getting 66 boards. For each board intended for drying were removed two samples with dimensions of 50 x 25 x 110 mm (length x width x thickness) on both ends for determining the initial moisture content of each board according Simpson (1996), following recommendations regulating of Brazilian Standard - NBR 7190 (1997), from Brazilian Association of Technical Standards - ABNT.

Stacking and Drying Program of Woods:

The stacking of the boards was carried out in the central region of the conventional drying chamber and in the tangential direction to the air flow inside the Kiln. Was Separated the layers of the stack with partitions with dimensions of 25 x 20 x 1100 mm (thickness x width x length) which allow free air circulation through the stack. The method of stacking the wood was according Klitzke (2002).

The drying program (Table 1) was developed from a literature review on the characteristics of the wood anatomy of species, assessing the rate of drying, physical properties, and difficulty of drying of refractory hardwoods such as Eucalyptus.

Table 1: Drying program of *Eucalyptus saligna*

Wood Moisture (%)	Temperature (^oC)		R.M (%)	E.M (%)	Time (h)	Drying Potential
	Dryed Bulb	Wet Bulb				
Heating	40	40	100	-	3	-
45	40	38	88	18	-	2,5
35	44	41	84	16	-	2,2
31	46	42	78	14	-	2,2
28	50	45	77	14	-	2,0
25	54	48	71	12	-	2,1
20	58	49	64	10	-	2,0
17	60	49	55	8	-	2,1
15	62	49	48	7	-	2,1
12	66	51	46	6	-	2,0
10	66	47	35	5	-	2,0
Conditioning	62	56	73	12	8	-
Cooling	44	35	55	9	4	-

Note: RM: relative moisture. E.M Equilibrium moisture

Monitoring of Drying By Ultrasonic Waves:

First of all were used the gravimetric method for monitoring the moisture as a way to complement monitoring by ultrasonic waves. in order the gravimetric method was used to determine the loss of moisture from the wood during the drying cycle, therefore the masses were measured daily in the timber for 8 hours intervals interleaved over all period of drying using an electromechanical scale with a capacity of 6000 g ± 0.5 g of accuracy.

For monitoring the moisture content by ultrasonic waves was used the Stress Wave Timer (SWT), model 239A from METRIGUARD, equipment that consists of two transducers accelerometers arranged on the material to be measured and a clock register of the wave speed.

The process of measuring of the speed propagation of the waves was the placement of the boards between the two sensors with clearance of 56 cm by clearing up the logger clock and releasing a metal pendulum that clashes with the sensor emitting the wave in the transverse face of the lamella, causing the wave to scroll along the board to the receiver. These measurements were daily being performed interchangeably every 8 hours over the period of wood drying. For taking measurements occurred so as not to impair the drying load, they were carried out only in the woods allocated in the last layer of the stack, totaling six boards for drying load.

Analysis and Evaluation of Results:

For data analysis, monitoring the moisture content of wood due to the propagation speed of the ultrasonic wave, the wood was first grouped in the specific gravity and the experimental results were analyzed using simple and multiple regression. Measures of suitability and selection of regression models were made by analyzing the adjusted coefficient of determination (Raj2), standard error of estimate (Syx) F value and visual analysis of waste.

RESULTS AND DISCUSSION

The Table 2 shows the results for the three loads of drying. Note that the duration in time of the loads were 314.89 for the first load, which corresponds to a time of 13 days while the loads 2 and 3 lasted 239.67 and 287.48 hours, totaling 10 and 12 days respectively. Ciniglio (1998) studying the drying of the wood of *Eucalyptus grandis* and *Eucalyptus urophylla* 25 mm thick met drying cycles 25 and 22 days, respectively. Batista (2009) evaluating the quality of conventional drying for *Eucalyptus saligna*, *E. grandis* and *E. dunnii* found 18;19;20 days of drying cycles respectively. This difference found in the literature for the drying cycle for Eucalyptus wood is related beyond the drying program adopted, but also to factors intrinsic to wood.

Table 2: Drying cycle (hours) Initial and final moisture of *Eucalyptus saligna* wood.

Loads	Duration (hours)	Initial moisture (%)	Final moisture (%)
1	314.89	76.99 a (18.47) (23.99)	9.40 a (2.24) (23.86)
2	239.67	59.86 b (14.57) (24.34)	10.03 a (2.14) (21.37)
3	287.48	73.64 a (18.25) (24.79)	10,06 a (2.10) (20.90)

Note: Valor in parentheses are standard deviation and coefficient of variation, respectively. Means followed by the same letter do not differ statistically from each other (Tukey, $p \geq 0.05$).

Another factor influencing the drying cycle is the initial moisture content of the wood, it is observed that only to the second load, and the initial moisture was lower corresponding to 59.86%, which was statistically different at 5% of probability with the first and third load valuesof initial moisture content of 76.99 and 73.64%, respectively.

However, the final moisture, it is noted that statistically there was no difference at 5% probability for the three loads of drying, however the woods corresponding to second and third loads had higher final moisture corresponding to values close to 10% while woods for the first load finished the drying with 9.40% moisture.

Currently the monitoring of moisture content in conventional drying occurs by assembly of sensor pins posted along the load of wood to be dried, which depending on the load capacity and production volume of the drying kiln causes loss of material for its fixation. As an alternative to this method of moisture control has the speed of passage of the ultrasonic wave in the axial direction of the wood, its speed being inversely proportional to the moisture content of wood.

The Table 3 contains the estimated moisture content of *Eucalyptus saligna* in its wet state as a function of ultrasonic wave for each density class.

Table 3 - Estimation of moisture content of the wet wood as a function of ultrasonic velocity density for different loads drying of *Eucalyptus saligna*.

Specific gravity	Drying Loads	Adjusted Models	Velocity ($m \cdot s^{-1}$)	R_{aj}^2 (%)	S_{yx} (%)	F
0.40< S.g <0.59	1	M= e^(2E-7*vel2-0,0019*vel +9,0026)^	4157.01	24.02	4.83	4.32
	2	M =e^(-8E-7*vel2+0,0064*vel-8,5162)^	3984.54	26.38	3.16	3,33
	3	M= e^(3E-7*vel2 - 0,003*vel + 11,31)^	4099.05	26.00	4.95	5.74
Specific gravity	Drying Loads	Adjusted Models	Velocity ($m \cdot s^{-1}$)	R_{aj}^2 (%)	S_{yx} (%)	F
0.60< S.g <0.79	1	M= e^(-6E-7*vel2+0,0046*vel-3,9047)^	4114.10	71.41	2.80	37.23
	2	M= e^(2E-7*vel2 -0,0014*vel+6,7275)^	4038.30	36.11	1.01	5.80

	3	M= $e^{(-6E-7*vel2+ 0,0044*vel-3,794)}$	4050.02	51.54	2.65	23.87

Note: S.g: specific gravity; M: moisture; vel: ultrasonic wave velocity; R_{aj}^2: adjusted coefficient of determination; S_{yx}: standard error of the estimate; F: the significance factor

In general, there is the classic effect of the influence of wood moisture in the passage of ultrasonic waves, which is characterized by reduced wave velocity due to the increase in moisture content of the wood.

It is noted for the first class of specific gravity (less than 0.60 g.cm-3) the velocity of wave transition was similarly for the three evaluated loads (1, 2 and 3) with a maximum difference of 172.47 m.s^{-1} between loads 1 and 2 as well as what occurred for the translocation velocity of the waves, the correlation coefficient determined for the models were similar between the loads. It is observed that the adjusted correlation coefficient for this class is lower than the specific gravity of all adjusted models, being 24.02; 26.38 and 26.00, respectively, for charges 1, 2 and 3. With the reduction of the specific gravity of the wood, occur more intracellular spaces, in which is contained capillary water with higher specific gravity than the beam wood material per unit volume which the wave will go. Due to this heterogeneity of specific gravity, can be one of the factors of low representation of the correlation coefficient presented, however, observing the standard error of the estimate, its observed that they were low (4.83, 3.16 and 4.95) respectively for loads 1, 2 and 3. These values of correlation coefficient, together with the values of the standard error of the estimate, show the proposed set of mathematical models to determine the velocity of ultrasonic wave for *Eucalyptus saligna* in its wet state.

Evaluating the specific gravity class between 0.60 to 0.79 g.cm^{-3}, it's noted that there is uniformity in velocity of the ultrasonic wave for three loads, however, with higher correlation coefficients, because the amount of wood material per unit volume is greater, which results into the less heterogeneity in the flow of fluid to the transition of the sound wave.

Simpson (1998), Gonçalves; Costa (2002), Oliveira *et al*. (2005) and Costa (2004), Calegari *et al*. (2007) studying different species and sizes of samples, observed a higher correlation for moisture below the fiber saturation point (PSF) and, for high moisture presenting no significant correlations. The great influence of moisture on the static modulus of elasticity in the moisture content corresponding to completely dried wood until its PSF, would be responsible for this significant variation of ultrasonic velocity. Therefore, moisture contents above the PSF provided minor variations of the ultrasonic velocity and hence worse mathematical adjustments.

The table 4 contains the estimated moisture content of *Eucalyptus saligna* as a function of ultrasonic wave to each class of specific gravity

Table 4: Estimation of moisture content of dried wood as a function of ultrasonic velocity specific gravity for different drying loads of Eucalyptus saligna.

Specific gravity	Drying Loads	Adjusted Models	Velocity ($m \cdot s^{-1}$)	R_{aj}^2 (%)	S_{yx} (%)	F
0.40< S.g <0.59	1	M=$e^{(-4E-7*vel2 + 0,0043*vel-9,2325)}$	5182.71	73	1.77	21.40
	2	M = $e^{(-5E-7*vel2 + 0,0041*vel-5,5059)}$	5269.22	48	8.35	2.88
	3	M= $e^{(-9E-7*vel2 + 0,0085*vel-18,805)}$	5160.88	48	4.36	6.46
Specific gravity	Drying Loads	Modelos ajustados	Velocity ($m \cdot s^{-1}$)	R_{aj}^2 (%)	S_{yx} (%)	F
0.60< S.g <0.79	1	M = $e^{(4E-7*vel2 - 0,005*vel + 17,028)}$	5197.41	81	4.08	40.96
	2	M=$e^{(9E-7*vel2 - 0,0087vel +24,205)}$	5134.46	48	2.81	10.25
	3	M= $e^{(3E-7*vel2 - 0,0015*vel +3,0802)}$	5199.21	63	6.13	13.79

Note: S.g: specific gravity; M: moisture; Vel: ultrasonic wave velocity; R_{aj}^2: adjusted coefficient of determination; S_{yx}: standard error of the estimate; F: the significance factor.

We note that for the class of specific gravity less than 0.60 g.cm^{-3}, which according to the classification of Carvalho (1996) falls in the woods with low density to moderately heavy, the average speed of the passage of ultrasonic waves was of 5204.27 m.s^{-1}, being the speed measured for each load similar within, and the difference between the maximum value and the minimum obtained of 108.34 m.s^{-1}.

Observe that the set adjusted models for the determination of wood moisture within this range of specific gravity, the moisture and the propagation velocity of ultrasonic waves showed correlation coefficients of 73% for the first drying load and 48% for the second and third loads. We note that the standard errors of estimate of the models evaluated were low, 1.77% for the first drying load and 8.35 and 4.36% for loads 2 and 3 respectively.

For the class of specific gravity between 0.60 to 0.79 g.cm-3, classified as heavy to very heavy wood in the classification of Carvalho (1996), the average speed of the transition of ultrasonic waves was 5177.03 m.s^{-1} , verifying same trend for the speed of ultrasonic wave to the wood of low specific gravity to moderately heavy, evaluated for each load. Having a difference of 64.75 m.s^{-1}.between the maximum and minimum values obtained.

It is observed that the models adjusted for moisture content determination within this range of specific gravity had adjusted correlation coefficients of 81% for the first charge to be dried and 48 and 63% for loads 2 and 3 respectively. We note that the lowest adjusted coefficient of determination (48%) had the lowest standard error of estimate (2.81%), and the standard error of estimate for the models of the first and third loads of 4.08 and 6.13%, respectively.

The possibility of tweaking the models, as well as obtaining of the low standard error of the estimate, has become possible due to the linearization of the moisture content of the wood, hence the coefficient of variation of the moisture reduced. The heterogeneity of the moisture for the different loads were shown in Table 2, which were within the expected range for the wood drying in a conventional kiln that can be influenced by the location of each piece inside the drying kiln as well as by the type of the wood.

Calegari *et al*. (2007) in similar study, but with distinct methodology presented mathematical models to estimate the moisture content of the wood of *Pinus elliottii* and *Eucalyptus grandis* for the moisture levels from green up to 12%, and from 30% up to 12% of moisture, which in their models presented took into account the specific gravity and temperature of drying.

The drying temperature was considered by the author (Calegari *et al*., 2007), due to the evaluation of models with samples of small size and the drying mechanism occurs in a climatic chamber and kiln with forced air ventilation.

The control of the ultrasonic velocity (ms-1) measured every 8 hours in the woods during drying listed in Figure 1, being shown the monitoring of the first drying load (A) and the second load (B) that was similar to the load 3.

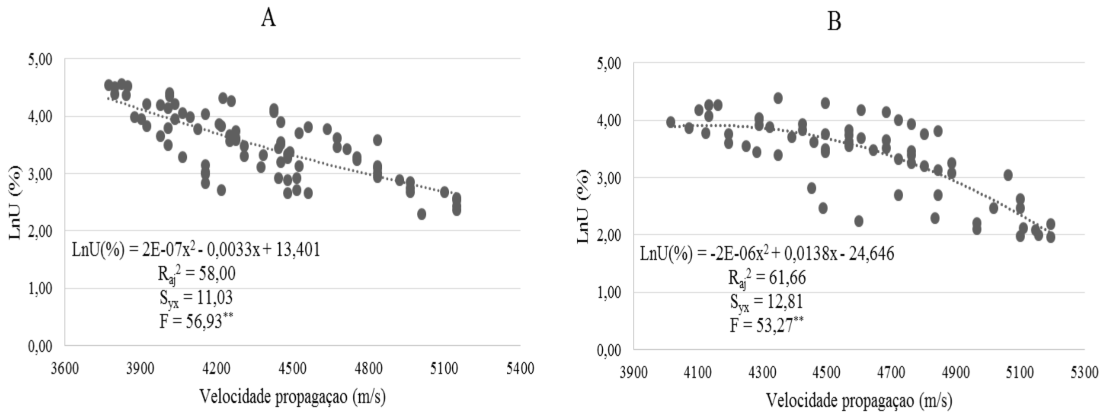

Fig. 1: Velocity of propagation of ultrasonic wave due to the moisture of *Eucalyptus saligna* during the drying load 1 (A) and the second load (B).

It is observed that the reduction of the moisture content of *Eucalyptus saligna*, provided the increase in ultrasonic velocity (Figure 1). The moisture content of the wood is one of the biggest factors influencing the speed of propagation of ultrasonic waves, Simpson (1998); Gonçalves; Costa (2002), Dyk; Rice (2005); Oliveira *et al*. (2005); Brashaw*et al*. (2004) and Costa (2004), exploring this point for monitoring moisture of different species during the drying process, observed a higher correlation for moisture below the PSF, commonly considered between (28-30%), what it is not observed for most technological alternatives tested to date, for the control of the drying process, and above the PSF correlation became no significant.

We note that the coefficient of determination of the adjusted models were high, being significant by the F test, and the standard error of estimate of 11.03 and 12.81%, respectively for the first drying load and the loads 2 and 3. This standard error of the estimate can be related to the influence that the speed of propagation of ultrasonic waves suffer by the discontinuity of the fluid to be traversed (wood). The exemplification of the effect of continuity, would be a place composed of steel balls adjacent to each other in spite of their high specific gravity and uniform moisture, does not guarantee a high propagation speed of the wave, due to the number of points of discontinuity. The wood for their natural trait of presenting high discontinuity, does not contribute to the effective propagation of ultrasonic waves, which is related to the standard error of estimate of the evaluated models as well as for the values of correlation coefficients found in this research.

Calegari *et al*. (2007, 2008) stated that the major influence of moisture on the static modulus of elasticity for wood in its saturated state (above PSF) would be the main cause of significant variation of the ultrasonic velocity. Therefore, moisture contents above the PSF provided higher ultrasonic velocity variations and thus worse mathematical adjustments. Besides the influence of moisture, the speed of propagation of ultrasonic waves is influenced by the anatomical properties (species), physical (density), morphology (type rated wood and angulations of the grain), the presence of defects (knots and cracks) and environment conditions (drying temperature) as Calegari *et al*. (2008). Shimoyama (2005) which also complements that, wood with higher specific gravities have higher proportion of wood material per unit volume, causing larger propagation velocity of the ultrasonic waves.

Bartholomew; Gill (2000) studying wood from *Eucalyptus citriodora* and *Pinus elliottii* observed the increase in velocity of the ultrasonic wave with the increase of the specific gravity. The explanation given by the author is that the transfer of ultrasonic energy is more associated with the cellular structure of the wood than its specific gravity. Wang *et al*. (2003) analyzing the wood of *Taiwania cryptomerioides* observed that in the longitudinal direction, the speed tends to decrease linearly with increasing density, and in radial diretion tended to increase.

Conclusions:

There is variation in the speed of the waves with the variation of moisture characterized by reduced wave velocity due to the increase in moisture content of the wood.

A significant reduction in the moisture content of *Eucalyptus saligna*, provided the increase in ultrasonic velocity.

The regression models to estimate the moisture content of *Eucalyptus saligna* were best fitted to the data for dry wood when compared to the wet wood.

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