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ON THE EFFECT OF THE NUMBER OF ANNUAL GROWTH RINGS, SPECIFIC GRAVITY AND TEMPERATURE ON REDWOOD ELASTIC MODULUS

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ABSTRACT

Due to the natural origin of wood, physical parameters such as specific gravity and the number of growth rings per inch affect its properties. In this study, to evaluate the effect that these physical parameters have on the elastic properties of wood, particularly on elastic modulus, a uniaxial compression test was performed on specimens. These specimens consisted of solid cubes of the Redwood species of wood with a width of 10.16 cm. Three different temperature conditions—ambient temperature (18°C), cold temperature (-28°C) and hot temperature (65°C) were used to carry out the tests. Specific gravity ranged from 0.29 to 0.45, and the number of growth rings per inch varied from 2 to 24 rings per inch. The minimum moisture content in the specimens was 2%, and reached a maximum of 16% according to the temperature conditions. The results from the statistical analysis indicated that the effect that the number of growth rings per inch has on elastic modulus is more significant than the effects of specific gravity or even of temperature. As a consequence, we suggest that the number of growth rings per inch can be used as a predictor for wood elastic modulus.

Keywords: Moisture content; number of annual growth rings per inch; specific gravity; temperature; wood elastic modulus.

RESUMEN

Debido al origen natural de la madera, parámetros físicos como la gravedad específica y el número de anillos de crecimiento afectan sus propiedades. En este estudio para evaluar el efecto que estos parámetros físicos tienen sobre las propiedades elásticas de la madera, particularmente en el módulo de elasticidad, ensayos de compresión uniaxial se realizaron en probetas normalizadas. Estos probetas consistieron en cubos sólidos de la especie de madera Redwood con arista de 10,16 cm. Tres diferentes condiciones de temperatura fueron utilizadas para llevar a cabo las pruebas: ambiente (18 °C), bajo cero (-28 °C) y temperado (65 °C). La gravedad específica osciló entre 0,29 a 0,45 y el número de anillos de crecimiento varió de 2 a 24 anillos por pulgada. El mínimo contenido de humedad en las muestras fue del 2% y alcanzó un máximo del 16% de acuerdo a las condiciones de temperatura. Los resultados del análisis estadístico indicaron que el efecto del número de anillos de crecimiento por pulgada es más importante que los efectos de la gravedad específica o incluso que el de la temperatura sobre el módulo de elasticidad. En consecuencia, se sugiere aquí que el número de anillos de crecimiento por pulgada pueda ser utilizado como predictor del módulo de elasticidad de la madera.

Palabras clave: Contenido de humedad, número de anillos de crecimiento anual por pulgada; gravedad específica; temperatura; módulo de elasticidad de la madera.

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INTRODUCTION

Several pieces of research, including Bodig and Jayne (1982) and Dinwoodie (2000), have analyzed the behavior of wood under a uniaxial stress field to determine the elastic constants of the wood. In these analyses, the influences of physical parameters, such as moisture content and specific gravity, on the modulus of elasticity were considered.

Wood is a heterogeneous material whose properties depend greatly on the species, biological diversity and growth conditions. Indeed, wood properties are affected by many parameters, including temperature, creep, knots, number of growth rings and grain angle.

The literature contains many analyses showing that moisture content significantly affects the elastic constants of wood (Wood Handbook 1987). Similarly, there are several studies, for instance Gerhards (1982) and Lenth and Sargent (2004), showing that an increase in temperature results in a decrease in the elastic constants of wood. Since, changes in temperature imply changes in moisture content, both parameters are, in practice, often interrelated. Some studies, such as Dinwoodie (2000), also demonstrate that there is a high correlation between specific gravity and the elastic constants of wood.

The number of growth rings per inch also affects the modulus of elasticity; this is especially important when comparing the effects of specific gravity and different temperature conditions. This fact is not commonly presented in the literature and, as we will demonstrate in this paper, significantly interferes with the values of the modulus of elasticity obtained.

The specific aim of this paper is to evaluate the influence of specific gravity and the number of annual growth rings on the Young´s modulus of wood. To do this, three different temperature conditions are applied, and the results of a compression test in Redwood specimens are analyzed, focused on the extensive statistical procedure. We also note that the moisture content of the specimens used in the tests varied according to the temperature, clearly altering the values of wood elastic modulus.

As a result of this research, we suggest that the number of growth rings per inch should be considered good predictor of wood material properties.

PARAMETERS THAT INFLUENCE WOOD ELASTIC CONSTANTS

In this study we analyzed parameters that exert any influence on the wood elastic modulus. The literature regarding the influence of moisture content on the wood elastic constants,such as Gerhards (1982) and Hanhijiirvi (2000), states that if this parameter increases, the elastic moduli decrease, whereas the Poisson´s ratios increase. These variations occur until the moisture content reaches the Fiber Saturation Point—around 27% to 30% for most species of wood.

In contrast, Dinwoodie (2000) and the U.S. Dept. of Agriculture's Wood Handbook (1987) show that the elastic constants are increased by increasing specific gravity. In addition, procedures analyzing the effect of the specific gravity on the wood elastic constants show evidence of a high correlation between the specific gravity and the elastic constants for example, Ballarin and Palma (2003). This is due to the fact that specific gravity is a function of the ratio between cell wall thickness and cell diameter. This ratio is related to the stiffness of wood and consequently to the elastic modulus.

Focusing on the influence that temperature exerts wood properties, it has been described in technical literature, for instance Bodig and Jayne (1982), that when temperature increases, the values of elastic parameters of wood decrease. Furthermore, changes in temperature influence changes in moisture

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content. Dinwoodie (2000) highlights that when the moisture content is at 0% (dry condition) and the temperature varied between -20°C and +60°C, the reduction in stiffness is 6%. However, when moisture content reached 20%, the reduction in stiffness was approximately 40%. Lenth and Sargent (2004) obtained similar results studying the tensile stiffness of specimens of radiata pine.

In their study of the parameters that influence redwood crush, Cramer, Hermanson and McMurtry (1996) and Hermanson (1996) note that the number of growth rings per inch may, in some cases, predict the crush behavior more efficiently than the specific gravity. Therefore, by considering the number of rings, it is possible to take into account the actual differences in specimen microstructure of the Redwood species.

Using the finite element method, Ando and Ohta (1999) analyzed the effects that the location of the crack tip in an annual ring and the direction of crack propagation have on the fracture toughness of the TR crack propagation system of coniferous wood. This validated earlier findings regarding the changes in elastic modulus and strength within an annual ring as, for instance, Bodig and Jayne (1982) showed results suggesting a variation in the tensile strength of wood within the location of the growth rings.

In light of these earlier findings, it can be expected that since the elastic modulus and the strength have a strong statistical relationship, the number of growth rings per inch will also have a statistically significant relation to elastic modulus. In the following, the relationship between the previously mentioned parameters and the wood elastic modulus are evaluated.

MATERIAL AND EXPERIMENTAL METHODS

The experimental data used to analyze the modulus of elasticity and the parameters that influence the elastic coefficients were obtained from S.M. Cramer and J.C. Hermanson at the University of Wisconsin-Madison, Hermanson (1996). Here, we present a summary of the experimental procedure.

38 specimens of Redwood species were used from a random sample. The specimens consisted of solid cubes with a width of 10.16 cm, fabricated from 15.24 cm by 15.24 cm lumber, 5.40 m to 6.60 m in length.

The fiber orientations with respect to the applied vertical load varied from 0° to 5°. We used this range so that the fiber directions would have no significant effect on the values of the modulus of elasticity. We observe that many studies, such as Bodig and Jayne (1982), Dinwoodie (2000) or Mascia (2003), the effect of grain angle orientation on the elastic modulus constitutes the fundamental cause of wood anisotropy. It is responsible for the greatest changes in the values of the elastic constant values of wood.

Figure 1 illustrates this mechanical behavior of 101 values of elastic modulus (this sample includes specimens with fiber directions varied from 0° to 90°) obtained by S.M. Cramer and J.C. Hermanson. It can be observed that the pattern of the nonlinear curve follows the constitutive equation for wood and also the previous cited studies provide more specific information.

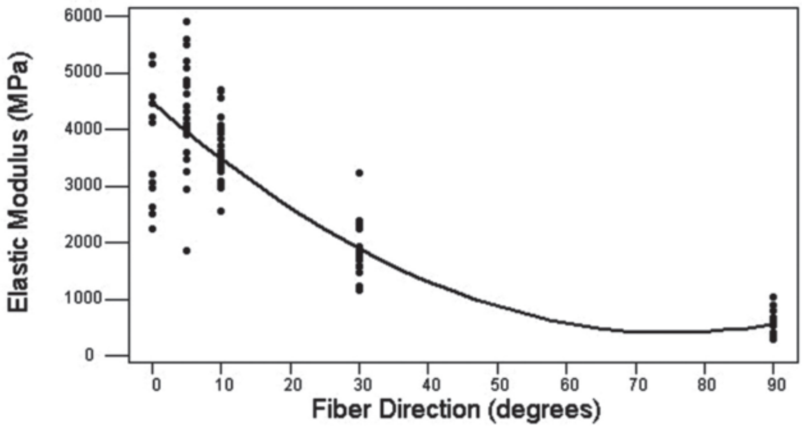

Figure 1. Variation of Elastic modulus with the fiber direction of wood.

The specific gravity varied between 0.29 and 0.41. The number of growth rings per inch were recorded by photocopying the end of the specimen, and ranged from 2 to 24 growth rings per inch (2.54 cm).

Three different temperature conditions were used: an ambient temperature (18°C), a cold temperature (-28°C) and a hot temperature (65°C). In this experimental procedure, all specimens were equilibrated to approximately 13%, but according to the temperature conditions the moisture content varied between 2.3 and 15.7%.

The tests consisted of applying a vertical load to redwood cubes unconfined in an instrumental steel box as it is presented in Figure 2. The displacements were measured at the centroid of the specimens.

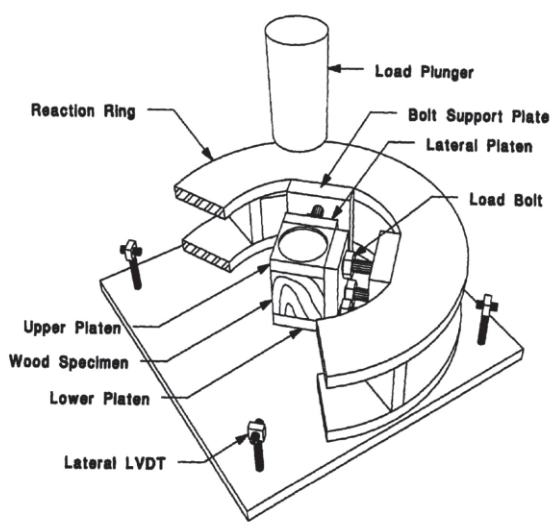

Figure 2. Schematic of triaxial test divice. (S.M. Cramer and J.C. Hermanson at University of Wisconsin-Madison).

Just to exemplify, Table 1 contains the experimental data used in this work.

Table 1. Sample of Experimental data.

Specimen Number	Moisture Content (%)	Specific Gravity	Number of Rings per inch	Temperature (ºC)	Elastic Modulus (MPa)
1	13.6	0.29	2.8	18	2639.66
2	12.7	0.29	2.8	18	2250.59
3	12.6	0.30	2.8	18	3218.56
4	13.6	0.40	20.8	18	4467.82
5	13.8	0.30	2.3	18	2524.87
6	5.4	0.32	2.6	65	2964.61
7	4.0	0.33	11.8	65	4121.10
8	2.3	0.31	7.3	65	4597.90
9	3.3	0.42	20.0	65	5315.38
10	3.7	0.42	16.8	65	4597.83
11	13.5	0.30	2.3	-28	3058.17
12	13.7	0.41	21.5	-28	5164.33
13	12.5	0.35	11.0	-28	4226.29
14	14.0	0.42	17.3	-28	4468.71
15	12.9	0.30	6.5	18	1862.74
16	12.7	0.38	18.5	18	4427.50
17	13.0	0.40	23.8	18	4194.61
18	13.5	0.39	23.8	18	5501.45
19	14.1	0.41	21.0	18	3481.39
20	14.0	0.38	23.8	18	5599.48
21	13.7	0.38	19.3	18	4807.51
22	13.4	0.34	10.5	18	3268.82
23	4.3	0.42	22.5	65	4888.42
24	3.7	0.40	17.0	65	3598.55
25	2.3	0.32	8.5	65	5099.00
26	2.9	0.34	12.5	65	5928.93
27	5.1	0.34	13.0	65	4873.21
28	5.5	0.39	18.0	65	5229.51
29	3.5	0.30	7.3	65	4644.72
30	4.9	0.34	12.0	65	4803.20
31	15.7	0.34	12.0	-28	4018.82
32	14.2	0.41	17.0	-28	4780.20
33	13.9	0.44	20.8	-28	4060.95
34	12.6	0.36	11.5	-28	3960.23
35	14.3	0.41	22.5	-28	3904.99
36	13.1	0.30	7.5	-28	2951.72
37	13.8	0.40	17.0	-28	4322.64
38	12.4	0.35	10.0	-28	4114.19

RESULTS AND DISCUSSIONS

In this analysis we developed five comparisons to evaluate the influence that specific gravity, number of growth rings per inch, and temperature associated to the moisture content have on Young´s modulus. To explore the number of growth rings per inch as a predictor for wood elastic modulus, we developed a relationship between this parameter and specific gravity, a known predictor of the elastic modulus of wood.

To carry out this study, we used a linear regression model, and closely analyzed the variance and the values that affect the adopted model.

Before presenting the statistical procedure, we note that the tested sample constitutes a normal distribution, according to the Anderson-Darling test of normality (see Montgomery and Peck (1992) or Ryan and Joiner (1994)), with mean η = 4156.3 MPa, and standard deviation σ = 974.6 MPa. These results constituted a coefficient of variation (CV) of 0.23, a satisfactory value for experimental tests on wood.

Statistical analysis

Following Montgomery and Peck (1992) and Ryan and Joiner (1994), the linear regression model can generally be written as: $y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_k x_k + \varepsilon$. It is supposed that the errors are normally and independently distributed with mean $\eta = 0$ and variance σ^2.

The regression analysis can be summarized by verifying:

1. The test of the significance of regression follows the hypothesis:.

$$H_0 : \beta_1 = \beta_2 = ... = \beta_k = 0 \ \ versus \ H_1 : \beta_1 \neq \beta_2 \neq ... \beta_k \neq 0$$

The statistic $|t_0| > |t_{\frac{\alpha}{2}, n-(k+1)}|$ is employed, implying that the hypothesis $H_0 : \beta_1 = \beta_2 = ... = \beta_k = 0$ is rejected at a desirable level of significance, generally 5–15%. Thus, it is possible to accept or reject the linear model and we make inferences about β parameters that have practical significance. In this case, the t-values for each coefficient in the model should be calculated.

Here, n is the number of pairs of data, k is the number of β parameters in the model (excluding β_0), α is the level of significance, $t_{\alpha/2, n-(k+1)}$ is the Student's t-distribution and $n-(k+1)$ are the degrees of freedom.

2. The analysis of variance is given by the following statistic:

$$F_0 = \frac{SS_R / k}{SS_E /(n-(k+1)} = \frac{MS_R}{MS_E}$$

, where MS_R is the regression mean square and MS_E is the residual mean square.

To test the hypothesis $H_0 : \beta_1 = \beta_2 = ... = \beta_k = 0$, we compute the statistical test F_0 and reject H_0 if $F_0 > F_{\alpha,(k,n-(k+1))}$, with certain probability p. The test procedure is summarized in Table 2. We can observe that if the observed value of F_0 is large, the parameter β_k is statistically different from zero, with probability p.

Table 2. Analysis of the Variance for Significance of Regression

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	p
Regression	SS_R	k	MS_R	MS_R/MS_E	
Residual	SS_E	n-(k+1)	MS_E		
Total	S_{yy}	n-1			

3. The coefficient of determination must satisfy the following:

$$R^2 = \frac{SS_R}{S_{yy}} = 1 - \frac{SS_E}{S_{yy}}$$

This coefficient of determination represents the proportion of the sum of squares of y values' deviations from their means that can be attributed to the linear relation between y and x_i.

Analysis of the modulus of elasticity versus specific gravity

Using the experiment's data set and statistical regression analysis to establish a relation between modulus of elasticity E_{exp} and specific gravity S_G we obtained the following regression:

$$E_{exp} = 160 + 11086\ SG \quad (1)$$

The coefficient of determination *R-sq* is 28.1%. Table 2 shows the analysis of variance of the linear regression.

From this analysis of the variance we can conclude that the regression is significant. We can thus reject the hypothesis $H_0 : \beta_1 = 0$ with a high level of confidence. Figure 3 shows the regression plot. Analyzing the prediction interval, we can, with 95% confidence and prediction bands, observe that some results of the data did not adequately fit in the model.

Table 3. Analysis of the Variance for Significance of Regression

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	p (%)
Regression	9879363	1	9879363	14.08	0.001
Residual	25264673	36	701796		
Total	35144036	37			

Similar to Bodig and Jayne (1982), we note that the linear regression is not the best fit for this data. Employing a quadratic polynomial model, the results improved in terms of coefficient of determination to *R-Sq* = 44.8% and the statistical test reached F_0 =14.19. However, with the cubic model these statistical parameters reached values of *R-Sq* = 46.5 and F_0 = 9.83.

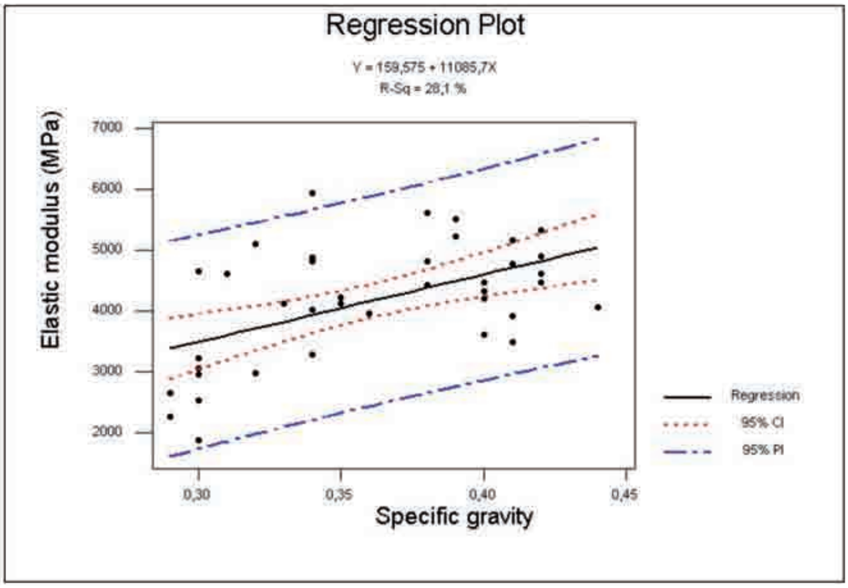

Figure 3. Regression Plot - Modulus of Elasticity and Specific Gravity Analysis of the modulus of elasticity versus number of growth rings per inch.

Using the experimental data set, we analogously established a relation between modulus of elasticity and the number of growth rings per inch per inch, and obtained the following regression:

$$E_{exp} = 2947 + 88.6\ RPI \tag{2}$$

where E_{exp} is the Young´s Modulus considering the three temperature conditions, and *RPI* is the number of growth rings per inch per inch. The coefficient of determination is now *R-sq* = 40.9%.

Table 4 shows the analysis of variance of the linear regression.

Table 4. Analysis of the Variance for Significance of Regresion.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	p (%)
Regression	14375738	1	14375738	24.92	<0.001
Residual	20768297	36	576897		
Total	35144036	37			

Analyzing the variance, we can conclude that the regression is significant, and thus we can reject the hypothesis $H_0 : \beta_1 = 0$ with a high level of confidence.

Figure 4 illustrates the regression plot. Analyzing the prediction interval, we can, with 95% confidence and prediction bands, observe that some results of the data did not adequately fit in the model. Similar to the earlier analysis, the linear regression cannot adequately model this relation, but we have a better adjustment to the adopted model.

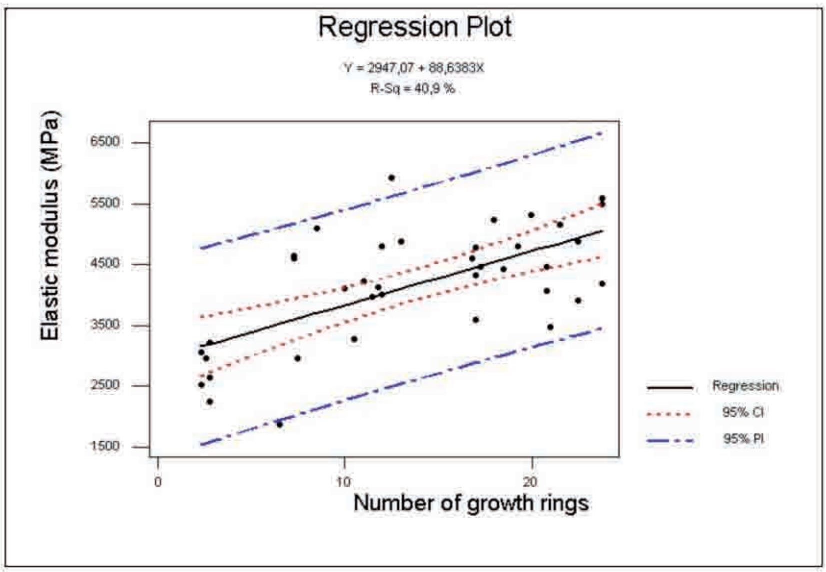

Figure 4. Regression Plot - Modulus of Elasticity and the Number of growth rings per inch.

By adopting a quadratic polynomial model and cubic model, the coefficient of determination in the results improved to *R-Sq* = 48.6% and *R-Sq* = 50.0%, respectively. On the other hand, the statistical test F_0 reached 24.91 for the quadratic model but only F_0 = 11.33 for the cubic model.

Analysis of the Modulus of Elasticity versus Temperature Associated with Moisture Content

The relationship between modulus of elasticity and temperature has been defined. In this study, we also associated the moisture contents of the specimens with three temperature conditions. From the statistical regression analysis we determined the following regression:

$$E_{exp} = 5575 - 3.69\ \ Temp - 124\ MC \qquad (3)$$

where E_{exp} is the Young´s Modulus Temp is the temperature and *MC* the moisture contents. Table 5 shows the analysis of variance of the linear regression.

Table 5. Analysis of the Variance for Significance of Regression

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	p (%)
Regression	5421178	2	2710589	3.19	0.053
Residual	29722858	35	849225		
Total	35144036	37			

In this case, the coefficient of determination *R-sq* is 15.4%, a relatively low value. From this analysis of the variance we can conclude that for p = 0%, the regression is significant.

We can thus reject the hypothesis: with high level of confidence.

$H_0 : \beta_1 = \beta_2 = ... = \beta_k = 0$ *versus* $H_1 : \beta_1 \neq \beta_2 \neq ... = \beta_k \neq 0$ with high level of confidence

In Table 6, note that by using the Student's t-distribution, we can estimate the influence that each parameter has on the Modulus of elasticity.

Table 6. Analysis of the Student´s *t* distribution

Predictor	Coef	Stdev	t-ratio	p (%)
Constant	5675.2	930.5	6.10	<0.001
Temp	-3.688	4.309	-0.86	0.398
Moisture content	-124.41	64.25	-1.94	0.061

From this analysis of the variance we can conclude that, in terms of temperature, the regression is not significant (p is much greater than 15%) Thus, we cannot reject the hypothesis $H_0 : \beta_1 = 0$ with a high level of confidence.

Looking at the influence of moisture content, we can reject the null hypothesis at the 6.1% level of significance, a satisfactory number for wood properties. These results are in accordance with the previous studies as before cited, such as Dinwoodie (2000).

The Modulus of Elasticity versus Specific Gravity, the Number of growth rings per inch and Temperature

In this section, we perform a complete analysis of the influence on Young´s modulus of wood of the following parameters: moisture content, specific gravity, number of growth rings per inch and temperature associated with the moisture content.

We obtained the following regression:

$$E_{exp} = 8455 - 11688\ SG + 167\ RPI - 7.16\ Temp - 185\ MC \quad (4)$$

Table 7 shows the analysis of variance of the linear regression.

Table 7. Analysis of the Variance for Significante of Regression

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	p (%)
Regression	23752306	4	5938077	17.2	<0.001
Residual	11391729	33	345204		
Total	35144036	37			

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The coefficient of determination is *R-sq* = 67.6%, a reasonable result for experimental data.

From this analysis of the variance we can conclude that for p = 0%, the regression is significant.

This means that we can reject the hypothesis: with high level of confidence.

$H_0 : \beta_1 = \beta_2 = ... = \beta_k = 0$ *versus* $H_1 : \beta_1 \neq \beta_2 \neq ... = \beta_k \neq 0$ with high level of confidence

In Table 8, note that by using the Student's t-distribution we can estimate the influence that each parameter has on the Modulus of elasticity.

Table 8. Analysis of the Student´s Distribution

Predictor	Coef	Stdev	t-ratio	p (%)
Constant	8455	1852	4.65	<0.001
Specific gravity	111668	5434	-2.15	0.023
Rings	167.30	35.84	4.67	<0.001
Temp	-7.157	2.999	-2.39	0.023
Moisture content	-185.29	44.05	-4.21	<0.001

From these results, we observe that the effect of the number of growth rings per inch is more significant than the effects of the other parameters. However, the moisture content effect is significant, especially when interrelated with the temperature effects present in the analyzed model. The influences of temperature conditions and specific gravity on this model are negligible in the light of this wood sample and also of this current statistical procedure.

Analysis of Specific Gravity versus Number of growth rings per inch

Finally, we established a relation between specific gravity and the number of growth rings per inch, and adjusted the data through the following regression:

$$SG = 0.278 + 0,00603\ RPI \qquad (5)$$

where *SG* is specific gravity and *RPI* is the number of rings per inch. Table 9 shows the analysis of variance of the linear regression.

Table 9. Analysis of the Variance for Significante of Regression

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	p (%)
Regression	0.066493	1	0.066493	172.46	<0.001
Residual	0.013896	36	0.000386		
Total	0.080389	37			

The coefficient of determination is *R-sq* = 82.7%, an excellent response for wood tests.

From this analysis of the variance we can conclude that the regression is significant. This means that we can reject the hypothesis $H_0 : \beta_1 = 0$ with a high level of confidence.

Figure 5 illustrates the regression plot. Analyzing the prediction interval, we can, with 95% confidence and prediction bands, observe that only a few results did not adequately adjust to the model.

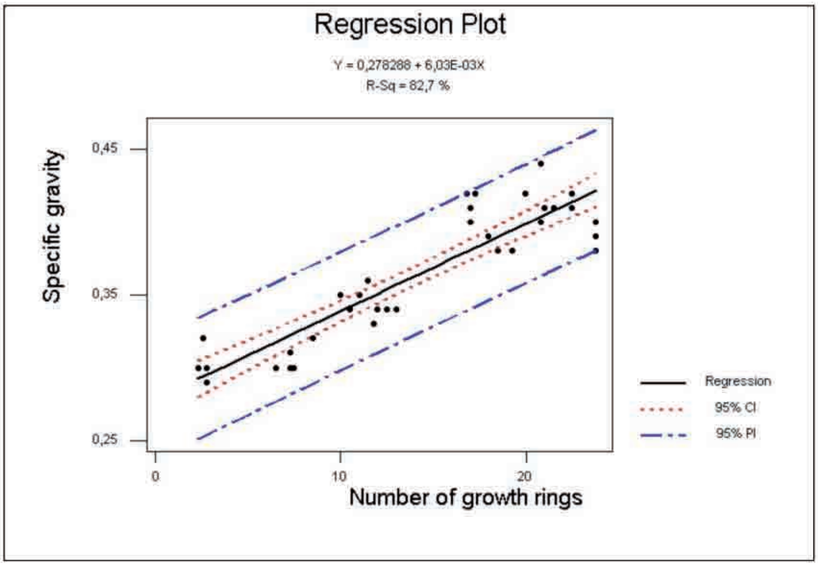

Figure 5. Regression Plot - Specific Gravity and Number of growth rings per inch.

Examining the pertinent literature that contributes to a better understanding the current results, we found, for instance, the study of Cramer *et al.* (2005). They demonstrated that the specific gravity and the position of the ring on the cross section of earlywood and latewood of loblolly pine are strong predictors of elastic modulus. In addition, they emphasized that biological and mechanical responses to the environment are likely causes of variation in elastic modulus of earlywood and latewood.

Two other interesting articles and also consistent with these findings were developed by Ballarin and Palma (2003) and Rall *et al.*(2008), in which average results of elastic modulus of juvenile and mature wood of *pinus taede* L. were evaluated. This piece of research revealed that the overall results of the elastic modulus of juvenile wood were always smaller than that of mature wood, and that the specific gravity and also the number of rings per inch were superior in the latter. A further established issue was that the classification of wood in density classes should be carried out using two different and independent parameters: number of growth rings per inch and the latewood percentage.

These studies and our results evidenced the fact that specific gravity is a predictor of wood properties, and provide arguments to indicate that the number of growth rings per inch may also be used as a predictor of wood properties.

CONCLUSION

In this study, we described the influence that several parameters have on changes in wood mechanical behavior by determining and analyzing the changes in the values of the modulus of elasticity. These parameters included specific gravity and number of growth rings per inch in three different temperature conditions.

Although many results presented in this research are well established, the literature does not present a complete study with a consistent statistical analyses focusing on the influence of the moisture content, the specific gravity, the number of annual growth ring and the temperature on the Young´s modulus of wood.

In this context, the most important conclusions that were drawn can be summarized as follows:

• The effect that the number of growth rings per inch has on the modulus of elasticity is relevant, especially when compared to the effects of specific gravity or temperature. Furthermore, this study proposes that the number of growth rings can serve as a good predictor of elastic modulus of wood.

• The specific gravity is less significant, but we can affirm that if the specific gravity increases, the modulus of elasticity also increases.

• The three different temperature conditions employed in this work changed the moisture content of the specimen, but did not significantly affect the values of the modulus of elasticity.

We noted that the influence of the moisture content on the modulus of elasticity is significant; if the moisture content increases, the modulus of elasticity decreases. However, we should also mention here that the moisture content effect is relative to the temperature effects present in the coupling.

It is important to emphasize that these conclusions are restricted to the current experimental data. To determine whether these results can be generalized, addition tests must be developed that take into account other species of wood, with different moisture content, specific gravity, number of growth rings per inch and temperature conditions.

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