

ELASTIC CONSTANTS OF CHILEAN *Pinus radiata* USING ULTRASOUND

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ABSTRACT

In general, data regarding the mechanical properties of wood is still incomplete, mainly owing to the difficulties involved in preparing well-made standard testing samples, as well as the time-consuming evaluation tests. Therefore, the elastic constants for *Pinus radiata* in this paper were determined using ultrasound technology. In parallel, typical compression mechanical testing was carried out to compare the effectiveness of the nondestructive test using the ultrasound. The longitudinal elastic constant values were similar to the mechanical testing (ultrasound was 12,8 % higher than mechanical testing), showing that ultrasound technique is a reliable and valid tool. The values for radial and tangential moduli obtained by the ultrasound versus mechanical testing showed statistically significant differences. This may be due to the difficulty in obtaining adequate samples for mechanical testing. The symmetry of the shear modulus was revealed by the ultrasound technique ($G_{ij} = G_{ji}$). Poisson's ratios were not comparable using either method; however, values obtained were more consistent with the existing literature for *Pinus* species. Additionally, the elastic anisotropy of the analyzed wood samples was demonstrated through the ultrasound velocity propagation in the material. It was thus possible to obtain the twelve engineering constants that characterize the mechanical behavior of wood employing of the proposed ultrasound technique. The results proved that this technique could be a useful tool for such characterization.

Keywords: Elastic constant, nondestructive evaluation, *Pinus radiata*, Poisson's ratio, shear rate, ultrasound, wave propagation.

INTRODUCTION

Forestry is the second most important economic activity in Chile after copper mining. In 2018, round-wood consumption reached 43 million m³ (solid wood base) as a raw material in the forestry industry (Hernández and Elgueta 2020). The main commercial species are *Pinus radiata* and *Eucalyptus sp.* In sawmills, the use of radiata pine approaches 96 %.

In Chile, however, the use of wood amounts to only 18 % of the materials used in the construction sector (Hernández and Elgueta 2020). This may be due to insecurity regarding wood as an engineering material: wood is a biological resource with poor fungal and fire resistance and may therefore have low outdoor exposure resistance due to its hygroscopic character. Another limiting factor is the lack of information about the variability of the mechanical properties of wood, according to species, age, moisture, treatments, among others

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(Bodig and Jayne 1993). All these aspects have a negative impact on the use of wood in the building sector. Structural design calculation software requires complete information about the mechanical properties of the wood used in order to achieve accurate prediction of its behavior, and said data is often not fully known or available (Kotlínová *et al.* 2010, Gonçalves *et al.* 2011, De Borst *et al.* 2013).

Wood is a heterogeneous and anisotropic material. Its mechanical properties are unique and independent along its three main axes: longitudinal (parallel to wood grain), radial (perpendicular to growing rings) and tangential (perpendicular to grain but tangential to rings). To characterize the elastic properties of wood, nine different elastic constants are required: three elastic moduli (Young's modulus) (E_{LL} , E_{RR} , E_{TT}), three shear moduli ($G_{LR}=G_{RL}$, $G_{LT}=G_{LT}$, $G_{RT}=G_{RT}$), and three Poisson's ratios ($\nu_{LR}=\nu_{RL}$, $\nu_{LT}=\nu_{TL}$, $\nu_{RT}=\nu_{TR}$). These constants are experimentally determined through mechanical testing; however, due to the nature of the wood, said testing is not easily performed. Nondestructive techniques (NDT) have emerged such as ultrasound (Bucur 1983, Baradit and Niemz 2012, Gonçalves *et al.* 2014, Crespo *et al.* 2017, Espinosa *et al.* 2018), X-ray (Perré and Badel 2003), optical digital measurements (Majano-Majano *et al.* 2012), and more sophisticated techniques such as nanoindentation (Gindl *et al.* 2004, Konnerth *et al.* 2010).

The longitudinal elastic modulus (E_{LL}) has been studied more than the other constants, given the difficulty in determining the latter. For example, it is well known that the elastic modulus varies with species, moisture content, temperature, among others. Nevertheless, some relationships have been experimentally determined, such as $E_{LL} : E_{RR} : E_{TT} \approx 20 : 1,6 : 1$ and $G_{LR} : G_{LT} : G_{RT} \approx 10 : 9,4 : 1$ (Bodig and Jayne 1993).

Ultrasonic wave propagation has been reported as a fast and effective method to determine the elastic constants of wood (Bucur 2006, Gonçalves *et al.* 2011). This is relevant considering the destructive nature of mechanical testing and the difficulty of determining the different properties of wood due to its high variability. Other aspects that bear mentioning are the cost of performing a high number of tests as well as the complexity of both the test and the manufacturing of the specimens. This method is particularly important for obtaining information on the shear modulus and Poisson's ratios (Keunecke *et al.* 2007). Different studies have been carried out on native woods and radiata pine using ultrasound, which has provided useful information regarding their elastic constants (Niemz and Aguilera 1995, Sonderegger *et al.* 2010, Baradit and Niemz 2012).

In this study, the elastic moduli, shear modulus, and Poisson's ratios of *Pinus radiata* were determined by ultrasound (US) and mechanical testing. Our goal was to use the fast and convenient ultrasound method to fully characterize this wood's mechanical properties, some of which were heretofore unknown or available only from theoretical analysis.

Theory

The use of US for determining elastic constants is based on the theory of solids and elastic wave propagation. The symmetry of wood is similar to an orthotropic crystal with orthogonal axes corresponding to the main directions of the tree (L-longitudinal, R-radial, and T-tangential). Twelve constants that completely characterize the elastic properties are related to Equation 1.

$$\begin{bmatrix} \gamma_L \\ \gamma_R \\ \gamma_T \\ \gamma_{RT} \\ \gamma_{LT} \\ \gamma_{LR} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_L} & -\frac{\nu_{RL}}{E_R} & -\frac{\nu_{TL}}{E_T} & 0 & 0 & 0 \\ -\frac{\nu_{LR}}{E_L} & \frac{1}{E_R} & -\frac{\nu_{TR}}{E_T} & 0 & 0 & 0 \\ -\frac{\nu_{LT}}{E_L} & -\frac{\nu_{RT}}{E_R} & \frac{1}{E_T} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{RT}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{LT} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{LR} \end{bmatrix} \begin{bmatrix} \sigma_L \\ \sigma_R \\ \sigma_T \\ \sigma_{RT} \\ \sigma_{LT} \\ \sigma_{LR} \end{bmatrix} \quad (1)$$

In Equation 1 the diagonal terms of the compliance matrix are related to elastic and shear moduli for the three main directions; the non-diagonal terms are related to Poisson's ratios. All of these constants can be obtained through transverse and longitudinal polarization waves in the material, using different angles (Royer and Dieulesaint 2000). This is described by Christoffels Equation 2.

$$|\Gamma_{il} - \rho \delta_{il} V^2| = 0 \quad (2)$$

Where $\Gamma_{ij} = C_{ijkl} n_i n_j$ a second tensor, C_{ijkl} -elastic constants (N/m²), n_i -direction cosines, ρ -density (kg/m³), δ_{ij} -Kronecker tensor, V-velocity of wave propagation (m/s). In Equation 2 for each main direction of the tree, there are two velocities of wave propagation with different polarizations.

MATERIALS AND METHODS

Raw material

The samples were obtained from five 20-year-old trees of *Pinus radiata* D. Don, in the Arauco region in Chile. Samples of 130 mm x 130 mm x 1500 mm were taken from the 5th ring of each tree, creating five groups. The samples were conditioned to assure a 12 % moisture content (MC) in a climate-controlled room set at 23 °C ± 1 % and 50 % ± 3 % humidity (INN 1984). Once the desired MC was attained, the wood samples were prepared in order to obtain samples for both US and mechanical testing. Density was calculated according to standard procedure (INN 1988).

Ultrasonic testing

To obtain the non-diagonal terms of Equation 1, cubes of 20 mm ± 1 mm were oriented at different angles following the main direction of the tree. Seventy of these cubes were obtained from each group (10 for each angle: 0°, 15°, 30°, 45°, 105°, 120° and 135°), for a total of 350 samples.

The cubes for the three planes, LR, LT, and RT, are shown in Figure 1. Elastic moduli and shear moduli were determined with the 0° orientation. Density was registered for each cube in Table 1.

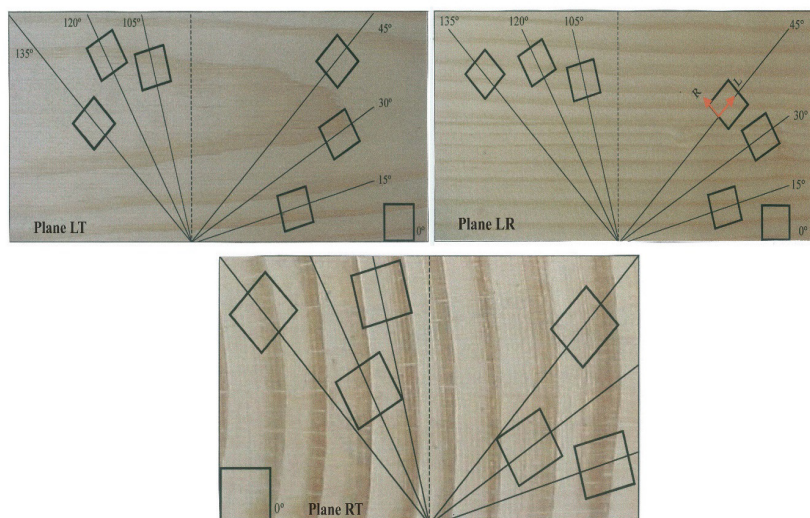


Figure 1: Samples for ultrasonic testing plane LT: longitudinal-tangential, plane LR: longitudinal-radial, plane RT: radial-tangential

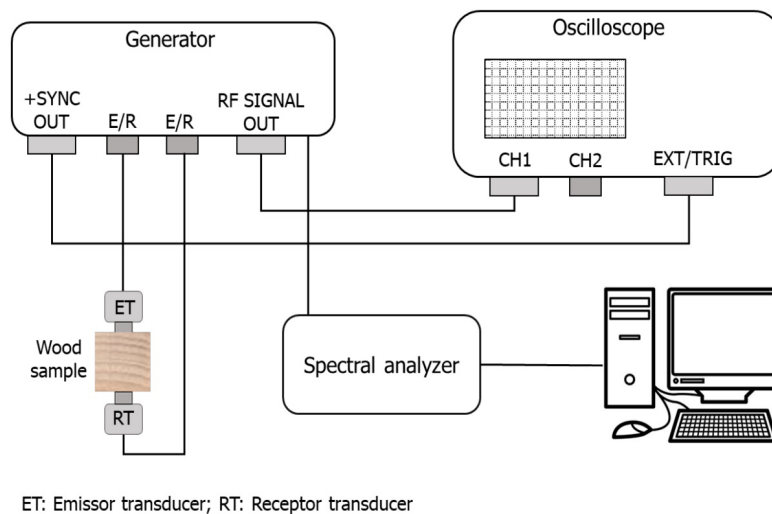
Table 1: Average density at 12 % MC of samples oriented to 0° and oriented off the main axis.

Tree	Density at 0° (kg/m ³)	Density (samples off main axis) (kg/m ³)		
		LR	LT	TR
1	482,0 (2,8)	424,1 (187,1)	480,7 (111,8)	452,9 (129,2)
2	454,5 (13,2)	470,0 (109,4)	418,4 (117,2)	451,0 (131,1)
3	414,6 (56,9)	382,9 (110,7)	457,5 (135,8)	417,3 (126,0)
4	558,2 (21,4)	458,0 (110,8)	523,0 (127,5)	459,4 (130,4)
5	430,0 (43,3)	400,5 (151,9)	400,3 (155,0)	448,0 (130,9)

Plane LT: longitudinal-tangential, plane LR: longitudinal-radial, plane RT: radial-tangential
Standard deviations shown in parentheses

The average density of the samples shows a wide range (415 kg/m³ to 558 kg/m³), mainly due to varying proportions of earlywood or latewood and juvenile and mature wood in the samples, as was expected. This parameter strongly influences ultrasound velocity (Equation 2).

The US measurement was carried out using Panametrics 5800PR transmission equipment and transducers of 1 MHz with longitudinal and transverse polarization, V103 and V153. A pulse is generated and sent to an emission transducer sending the signal through the samples, which is then received by a receptor-transducer. The travel time between the two transducers (delay time) was measured by means of an oscilloscope, and used to calculate the propagation velocity (Figure 2).

**Figure 2:** Ultrasonic system configuration.

A total of 50 samples were used to obtain the average for each velocity V_{ij} . For cubes oriented to 0°, nine characteristic times were obtained corresponding to nine propagation velocities, while for cubes oriented off the main axis, two propagation velocities were obtained: quasi-longitudinal velocity using a longitudinal polarization transducer and a quasi-transversal velocity using a transverse polarization transducer.

Mechanical testing

Three sample groups were made per tree for the compression mechanical testing, corresponding to the longitudinal, radial, and tangential directions. Each group was composed of five samples making a total of 75. The size of the samples was 50 mm x 50 mm x 200 mm (± 1 mm) for parallel-to-grain (longitudinal) and 50 mm x 50 mm x 100 mm (± 1 mm) for perpendicular-to-grain (tangential and radial) directions in accordance with NCh 973/1986 (INN 1986a) and NCh 974/1986 (INN 1986b), respectively.

The load cycle was performed in a Universal Instron machine and the deformations at different loads were acquired with a data logger. To obtain both the elasticity moduli and Poisson ratio, the deformations were mea-

sured by strain gauge KL-10-120-A4 (Kyowa) placed in the wood sample according to the required strains, as shown in Figure 3. When the load was parallel-to-grain, i.e longitudinal direction, three strain gauges were placed in the sample. To obtain the elasticity moduli E_{LL} , one of the said gauges was placed along the longitudinal direction, and for the Poisson's ratio calculations ν_{LR} and ν_{LT} , the other two were placed along the radial and tangential directions, respectively. When the load was along the radial direction, only two strain gauges were placed in the sample. In this case, to obtain the elasticity moduli E_{RR} one strain gauge was placed along the radial direction, and for Poisson's ratio ν_{RT} the other was placed along the tangential direction. When the load was along the tangential direction, only one strain gauge was placed in the sample in this direction to determine the elasticity moduli E_{TT} . Poisson's ratios ν_{TR} and ν_{TL} were determined using symmetry properties.



Figure 3: Wood samples with strain gauges for mechanical testing.

Elastic constant calculations

The six diagonal terms in the Equation 1 were obtained from Christoffel's Equation 2. The elastic constants are expressed by Equation 3:

$$C_{ijkl} = C_{\alpha\beta} = \rho V^2 \quad (3)$$

According to the orthotropic symmetry of wood, four indexes are changed for two in the elastic constants (Royer and Dieulesaint 2000): α - direction of polarization, and β -direction of propagation, ($\alpha, \beta= 1,2,3,4,5,6$). Particularly, the shear moduli were calculated by Equation 4:

$$G_{ij} = G_{ji} = \frac{1}{2} \rho (V_{ij}^2 + V_{ji}^2) \quad (4)$$

For off-diagonal terms in the matrix, an iterative process was developed relating compliance off-terms to the matrix (S_{ij}) with the elastic constants C_{ij} and C_{ii} (Bodig and Jayne 1993).

The iterative process begins by setting the six diagonal coefficients C_{ii} and all combinations between the non-diagonal coefficients C_{ij} . Both C_{ii} and C_{ij} were experimentally obtained by US. After this, the next determinant was calculated by Equation 5:

$$\Delta C = C_{11}C_{22}C_{33} + 2C_{12}C_{13}C_{23} - C_{12}^2C_{33} - C_{23}^2C_{11} - C_{13}^2C_{22} \quad (5)$$

To obtain different coefficients S_{ij} of the Compliance matrix, only combinations with positive determinants ΔC were considered. From this process, a group of solutions for technical constants was obtained. To optimize the results, the elastic constant must satisfy the physical and mechanical properties of

the wood. The E_{LL} , E_{RR} , and E_{TT} values must be positive and fall within the following ranges: 7500 (MPa) $< E_{LL} < 15000$ (MPa); 500 (MPa) $< E_{TT} < 1500$ (MPa); $E_{RR} > 1000$ (MPa); and Poisson's ratios $\nu_{ij} < 1$.

RESULTS AND DISCUSSION

Density

The density values at 12 % moisture content are shown in Table 2.

Table 2: Average density at 12 % moisture content in samples oriented along the three main directions for mechanical testing.

Tree	Average density (kg/m^3) by orientation		
	Parallel	Tangential	Radial
1	458,1 (15,0)	456,4 (21,3)	446,8 (34,8)
2	443,8 (24,8)	426,8 (13,6)	420,2 (20,2)
3	422,0 (20,0)	413,0 (12,0)	416,0 (9,9)
4	412,0 (40,0)	454,0 (87,7)	450,0 (33,1)
5	388,0 (20,0)	462,0 (20,0)	436,0 (18,4)

Standard deviations shown in parentheses

Due to the intrinsic nature of wood, the samples exhibit a wide range of densities. The samples used for mechanical testing show less variability in comparison to those used for ultrasound testing. This is most likely due to smaller specimens containing a higher proportion of latewood or earlywood, which is closely related to greater variability in density (note, for example, the large tangential orientation deviation observed for tree 4).

Shear modulus

The shear modulus obtained by the ultrasound technique using a shear polarization transducer is shown in Table 3. As expected, similar symmetry in propagation velocity was observed. Because of this symmetry, the average values for this modulus were 1230,4 MPa for the LR plane; 887,6 MPa for the LT plane, and 113,2 MPa for the RT plane. The relationship between them (LR:LT:RT) was 11:7,9:1; which is consistent with the literature for wood (Bodig and Jayne 1993).

Table 3: Symmetry of the shear modulus determined by ultrasonic testing.

Tree ID	Propagation velocity (m/s)						Shear modulus (MPa)		
	V_{LR}	V_{RL}	V_{RT}	V_{TR}	V_{LT}	V_{TL}	G_{LR}	G_{LT}	G_{RT}
1	1569	1673	519	541	1422	1371	1265	946	135
2	1585	1619	504	464	1456	1392	1166	921	108
3	1605	1611	456	400	1325	1370	1066	747	79
4	1582	1607	532	524	1299	1338	1409	963	154
5	1640	1657	432	467	1377	1363	1246	861	90
Average	1596,2	1633,4	488,6	479,2	1375,8	1368,8	1230,4	887,6	113,2
SD ^a	27,7	29,7	42,8	55,9	65,3	20,4	127,0	87,6	31,1
CV ^b (%)	1,7	1,8	8,8	11,7	4,7	1,5	10,3	9,9	27,5

^aStandard deviation; ^bCoefficient of variation.

Modulus of elasticity and wood anisotropy

Table 4 shows the elastic moduli obtained by means of mechanical compression tests and ultrasonic measurements for the different directions using longitudinal polarization transducers. As expected, the elastic moduli in the longitudinal direction of the tree for both the mechanical and ultrasonic tests are higher than in the other directions, and in both types of tests, it is observed that $E_{LL} > E_{RR} > E_{TT}$.

The values are consistent with the literature (Bodig and Jayne 1993), except for the elasticity modu-

lus in the radial direction (E_{RR}) obtained in the mechanical test, whose value was significantly higher than that obtained by ultrasound ($t=6,019$; $p\text{-valor}=0,000003<0,01$). For example, during the compression mechanical test in the radial direction, characteristics such as the height and the ring curvature of the wood sample affected the elasticity modulus calculation (Liu and Ross 2005). In the radial direction, earlywood and latewood bands were arranged in series, perpendicular to the applied load. Both bands carried the same load, but latewood deformed much less than earlywood (Kennedy 1968). This phenomenon did not occur when ultrasound propagation waves travelled through the wood sample, and the E_{RR} obtained by ultrasound was closely correlated with the radial modulus described by Liu and Ross (2005).

Table 4: Modulus of elasticity obtained by mechanical and ultrasonic testing.

Tree ID	Mechanical testing			Ultrasonic testing		
	Modulus of elasticity (MPa)			Modulus of elasticity (MPa)		
	Longitudinal E_{LL}	Radial E_{RR}	Tangential E_{TT}	Longitudinal E_{LL}	Radial E_{RR}	Tangential E_{TT}
1	9204	1080	714	13362	2250	840
2	10257	-	678	11370	2062	777
3	10581	946	693	9768	1786	682
4	8896	1071	575	11924	2245	917
5	9145	1132	539	8741	1891	656
Average	9616,6	1057,2	639,8	11033,0	2046,8	774,4
SD	750,4	78,9	77,7	1815,6	208,0	108,6
CV (%)	7,0	6,5	10,9	14,7	9,1	12,5

Table 5 shows the relationship between the elasticity moduli E_{LL} , E_{RR} , and E_{TT} described by other research (Bodig and Jayne 1993, Forest Products Laboratory 2010) and compared to the ultrasound tests. Averages and standard deviations were obtained using the Bootstrap re-sampling estimation method (Efron 1979, Efron and Tibshirani 1993).

Mechanical tests show a 15:1,7:1 ratio for $E_{LL}/E_{TT}:E_{RR}/E_{TT}:E_{TT}/E_{TT}$, whereas for ultrasound said ratio is 14:2,6:1. Therefore, a similar relationship exists between moduli in longitudinal and tangential directions. However, this is not the case for moduli in the radial direction: said value is higher compared with the mechanical test, mainly due to the absence of ring curvature and the highest density. Additionally, the elastic moduli relationships obtained by other authors in pine species are shown in Table 5 (Bodig and Jayne 1993, Forest Products Laboratory 2010).

Table 5: Relationship among moduli of elasticity.

Tree ID	Mechanical testing			Ultrasonic testing		
	Modulus of elasticity (MPa)			Modulus of elasticity (MPa)		
	Longitudinal E_{LL}	Radial E_{RR}	Tangential E_{TT}	Longitudinal E_{LL}	Radial E_{RR}	Tangential E_{TT}
Average ^c	9829	1085	651	10,834	2,017	768
SD	516,0	43,0	26,0	461,0	51,5	26,3
CV (%)	5,3	3,9	4,0	4,3	2,6	3,4
	$E_{LL}/E_{TT}:E_{RR}/E_{TT}:E_{TT}/E_{TT}$			$E_{LL}/E_{TT}:E_{RR}/E_{TT}:E_{TT}/E_{TT}$		
Results	15:1,7:1			14:2,6:1		
Bodig and Jane (1993)	20:1,6:1					
FPL (2010)	12:1,5:1					

^cBootstrap estimation average.

Table 6 summarizes the results for sample anisotropy, measured as the ratio between different propagation

velocities of longitudinal polarization. The differences observed reflect the anatomical structure of wood favoring the mechanical transmission of energy in the longitudinal direction with respect to radial and tangential directions. This is due to the wood's cell arrangements. The values obtained are consistent for the different wood species studied, and they coincide with results by Kollmann (1968) and Bucur (2006) for softwoods. In addition, a greater standard deviation was observed for the modulus of elasticity. This may be because the longitudinal velocity is strongly affected by the grain inclination, and as radiata pine is a rapid growth species, it is not easy to find perfectly aligned fibers.

Table 6: Anisotropy of wood measured by the wave propagation velocity.

Tree ID	Mechanical testing						Ultrasonic testing					
	Poisson's ratio						Poisson's ratio ^d					
	v_{LR}	v_{LT}	v_{RT}	v_{TR}	v_{RL}	v_{TL}	v_{LR}	v_{LT}	v_{RT}	v_{TR}	v_{RL}	v_{TL}
1	0,544	0,401	0,792	0,524	0,064	0,031	0,300	0,210	0,634	0,253	0,047	0,013
2	0,544	0,510	-	-	-	0,034						
3	0,522	0,421	0,826	0,605	0,047	0,028						
4	0,487	0,441	-	-	0,059	0,029						
5	0,549	0,459	0,532	0,253	0,068	0,027						
Average	0,529	0,446	0,430	0,276	0,048	0,030	0,300	0,210	0,634	0,253	0,047	0,013
SD	0,026	0,042	0,161	0,184	0,009	0,003						
CV (%)	4,9	9,4	37,4	66,7	18,8	10,0						

Poisson's ratio

The Poisson's ratios were calculated by means of an iterative process where both coefficients C_{ii} and C_{ij} , calculated experimentally, were used to satisfy the Equation 1 conditions. Poisson's ratio values from mechanical and ultrasound testing are shown in Table 7.

Mechanical tests present a high variability attributed to the difficulty in carrying out the test, particularly the geometry and ring curvature in the wood samples. Nevertheless, the values obtained in both tests are higher than those typically reported in the literature, especially for *Pinus* species, e.g, 0,3 - 0,44 (Bodig and Jayne 1993, Forest Products Laboratory 2010). For the ultrasound test, the Poisson's ratios are lower and are more in line with the literature; v_{LR} , v_{LT} , and v_{RT} of 0,3; 0,2, and 0,634, respectively. Furthermore, the dynamic test using ultrasound showed differences with respect to the static test (mechanical) for v_{LR} , consistent with the results of Gonçalves *et al.* (2011).

Table 7: Poisson's ratio values obtained by mechanical and ultrasound methods.

Tree ID	Propagation velocity (m/s)			
	V_{LL}	V_{RR}	V_{TT}	$V_{LL}:V_{RR}:V_{TT}$
1	5267	2161	1320	1:2,4:4,0
2	4986	2130	1308	1:2,3:3,8
3	4821	2082	1289	1:2,3:3,7
4	4647	2014	1288	1:2,3:3,6
5	4481	2097	1233	1:2,1:3,6
Average	4840	2097	1288	1:2,3:3,8
SD	304,2	55,4	33,4	
CV (%)	6,3	2,6	2,6	

^dAverage values obtained using an iterative process for all trees -Value not obtained.

CONCLUSIONS

The elastic behavior of *Pinus radiata* was studied by means of ultrasound. All elastic constants were determined for three elastic moduli, three shear moduli, and three Poisson's ratios. Mechanical compression testing was carried out to obtain the elastic moduli and Poisson's ratios and compared with those obtained by ultrasound.

The mechanical and ultrasound testing showed more similar values for the elastic moduli (E_{LL}) along the longitudinal direction than along tangential and radial directions. For example, the elastic modulus along the radial direction presented approximately twice the values using ultrasound in comparison to the modulus calculated by the mean of mechanical testing.

This research verified the symmetry of the shear modulus ($G_{ij} = G_{ji}$) by means of US. This was based on the symmetry obtained for the velocities of transversal polarized waves, in agreement with the solid-state theory. Likewise, the values obtained for the shear moduli were in agreement with the literature.

In addition, the values of the Poisson's ratios obtained using ultrasound were similar to the literature for softwoods.

The ratios between velocities of longitudinal polarized waves for the three main directions of *Pinus radiata* shown an anisotropy relationship of 1:2,3:3,8; thus fulfilling the $V_{LL} > V_{RR} > V_{TT}$ relationship.

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