Variation of Perpendicular Compressive Strength Properties Related to Anatomical Structure and Density in *Eucalyptus nitens* Green Specimens

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The objective of this study was to measure compressive strength properties perpendicular to the fiber of green *Eucalyptus nitens* specimens. The data was measured for clear 50 × 50 × 150 mm specimens obtained from 17-year-old trees that were harvested at the Ñuble region in Chile, and the data comprised modulus of elasticity (E_c), compressive strength (f_c), basic density, initial moisture content, and some anatomical characteristics of the wood. The experimental design emphasized the influence of the radial position of the wood within the logs (defined as inner-wood, middle-wood, and outer-wood) on the measurements, and the results showed that the modulus of elasticity, compressive strength, and the basic density all increased from core to bark. The compressive strength of outer-wood showed a strong and positive relation with the basic density. Cell wall thickness and wall cell area showed a significant positive correlation with compressive strength.

Keywords: Basic density; Drying stresses; Compressive strength; Wood collapse

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INTRODUCTION

Eucalyptus nitens species were introduced in Chile in the 1960s, and there are currently 270,000 hectares of plantation corresponding to approximately 12% of the total plantation area (Gysling *et al.* 2019). This species was originally imported to supply pulp and paper for the wood industry, but due to its natural advantages, such as fast growth and resistance to cold weather, there are currently high expectations for finding more commercial applications in the solid wood sector. There are currently scientific and technological efforts in academia and the wood industry in Chile and around the world that focus on the physic-mechanical characterization of this species towards its utilization as solid wood products (Yang and Waugh 1996; Rebolledo *et al.* 2013; Salvo *et al*. 2017).

Measurements of physical-mechanical properties are important to assess whether the characteristics of the wood materials are suitable for structural applications. The basic density is particularly important because it highly affects the manufacturing processes and provides in general a good estimation of the mechanical strength (Prado and Barros 1989). Likewise, some authors affirm that, besides the density, the compressive behavior of wood is strongly dependent on its anatomical characteristics such as cell length, cell wall thickness, fiber diameter, and microfibril angle (MFA) (Alexiou 1994; Evans and Ilic 2001; Müller *et al.* 2003). According to Evans and Ilic (2001), there is a strong relationship between the MFA and the modulus of elasticity (*E*) of *Eucalyptus* wood, and they point out that the MFA is the main factor that affects the *E* of the wood. Evans *et al.* (2000), who measured the MFA in 15-year-old *Eucalyptus nitens*, reported that MFA was between 20° and 30° near the pith and 10° near the bark. This was also reported by McKenzie *et al.* (2003), who obtained that MFA decreased from the pith zone to reach lowest values at the bark. Also, they reported that the MFA showed a moderate negative correlation with *E*, and was a weakly and negatively correlated with cell wall thickness.

Moreover, there are many studies with *E. nitens* in which the basic density is measured in the radial and longitudinal directions with reporting values from 400 to 550 kg/m^3 (Downes *et al.* 1997; Evans *et al.* 2000; Shelbourne *et al.* 2002; Leandro *et al.* 2008). McKimm (1985) studied the variation of properties in 8.5-year-old *E. nitens* and concluded that in general the strength properties are lower than in wood from adult *E. nitens* trees, but the values are comparable with those of *Pinus radiata*, showing the wood materials would be suitable for structural use. This was also confirmed by Yang and Waugh's research (1996), which considered the properties of 15- to 29-year-old plantation trees and the results suggest that wood from that type of plantation with those properties and characteristics can be used for producing sawn lumber for structural applications.

However, one of the problems for producing solid wood from *E. nitens* is the drying process, which is difficult because the wood tends to develop high internal stresses during drying (Pérez *et al.* 2018) and collapse (Ananías *et al.* 2009, 2014). This can greatly reduce the quality of the dried product to a level that has no practical commercial value. In general terms, collapse is an abnormal shrinkage that occurs above the fiber saturation point, and it is caused by capillary forces that arise as the free water is eliminated (Chafe *et al.* 1992). When these forces exceed the compressive strength of the cell walls, the flattening of cell can be produced (Yuniarti *et al.* 2015; Bond and Espinoza 2016). Pérez *et al.* (2018) measured the compression stresses as high as 9 MPa during the drying of *E. nitens* samples, which could explain the tendency to collapse and the development of internal checking. In this line, the stronger wood in compression perpendicular to the fiber would less prone to collapse (Chafe *et al.* 1992).

For this reason, the authors postulated in this study that it is important to know the perpendicular compressive strength variation and correlate with some anatomical characteristics and density, which helps to estimate the effect of these properties on the magnitude of the stresses that would cause cellular compression and collapse during drying.

EXPERIMENTAL

Materials

The testing material was obtained from 17-year-old trees that came from a plantation in Yungay, Region of Ñuble, Chile; and the samples comprised 9 trees from 3 different families of *Eucalyptus nitens.* One disk was cut from each tree at a height of 1.3 m, and each disk was divided into three zones based on the radial distance to the pith (Fig. 1). These areas were defined as inner-wood, referring to wood close to the pith, outer-wood, referring to wood close to the bark, and middle-wood, referring to the area between the other two. Three replicates were cut from each wood zone with 50 mm × 50 mm width and thickness in the disk radial and tangential directions, and 160 mm length in the longitudinal direction. This generated a total of 9 trees by 3 zones by 3 replicates, equal to

81 samples. The disks were kept under controlled environment at -10 °C, for 4 to 6 weeks. Specimens prepared for compression, density, and moisture content tests were kept under water and the tests were performed immediately after saturation.

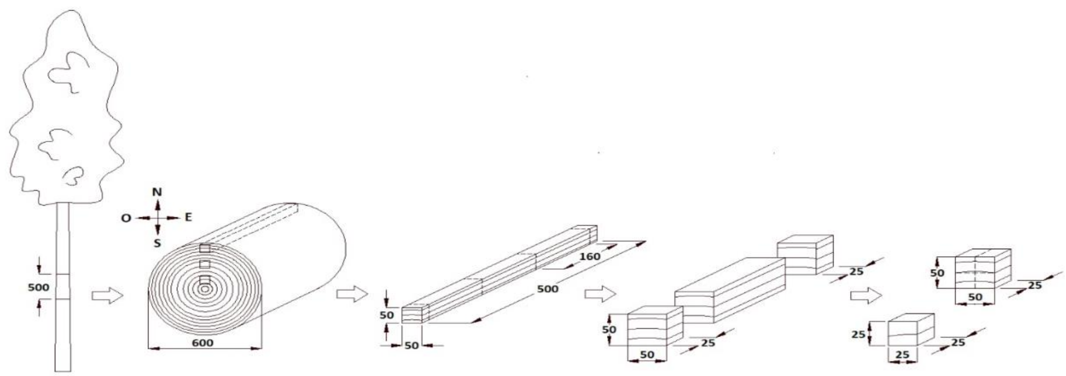


Fig. 1. Extraction of the logs at 1.3 m and specimens on the radial distance to the pith of each disk

Methods

Mechanical test

The compression tests were performed in compliance with the NCh 974 (INN 1986) standard. A universal testing machine (Metrotec 200kN; TechLab Systems S.L., Lezo, Spain) with a head speed of 0.3 mm/min was used. For testing purposes, the probe dimensions were reduced to the standard size of 50 × 50 × 150 mm^3, and the mechanical properties in the direction perpendicular to the sample were calculated as the average between the values measured in the radial and tangential directions. The compressive strength (f_c) and modulus of elasticity (E_c) were calculated based on the load *versus* deformation curve, according to NCh 974 (INN 1986).

Determination of basic density and moisture content

Two 25 × 25 × 25 mm^3 cubes for measuring basic density and moisture content were immediately cut from the opposite extremes of each probe, after measuring the mechanical properties. The basic density was determined in compliance with NCh 176/2 (INN 1988). Similarly, moisture content was determined through the oven-dry method in compliance with the NCh 176/1 standard (INN 1984).

Evaluation of anatomical characteristics

The anatomical characteristics of vessels (diameter and area) and fibers (wall thickness, diameter, and area) were measured as described by Salvo *et al.* (2017), in which two specimens cubes of 25 mm × 25 mm × 25 mm were prepared from each radial position. Ten slices of 20 µm thickness of each anatomical orientation of wood (transversal, radial, and tangential) of each cube were obtained for microscopic observations and image captures. The analysis of images of anatomical characteristics was realized using commercial software Wincell Pro (Regent Instruments Inc., v.2011a, Québec, Canada) and Motic Images Plus 3.0 (Motic Instruments Inc., British Columbia, Canada).

Data analysis

Normality of the data distribution and homogeneity of the variance were tested with the Kolmogorov-Smirnov and Barlett methods, respectively, and the comparison between the data sets was performed through an analysis of variance (ANOVA), and the Tukey test with a 95% confidence level. The relationships between compressive strength and density, as well as some anatomical properties, were investigated by Pearson's correlation analysis. The computer software Statistica (Statsoft Inc., v10.0, Tulsa, OK, USA) was used to perform the statistical analysis.

RESULTS AND DISCUSSION

Table 1 reports the average and standard deviation values measured for basic density, modulus of elasticity, and compressive strength as a function of the type of wood based on the position of the wood in the radial direction. The table also reports the p-values from the ANOVA tests applied to find statistically significant differences between families, trees, and types of wood. The ANOVA test indicated that those three biological factors had statistically significant effects for the wood mechanical properties ($p < 0.05$), with the exception of the compressive strength, which was not significantly affected by the family.

Table 1. Average and Standard Deviation Values of Basic Density, Modulus of Elasticity, and Compressive Strength for *E. nitens* as a Function of the Radial Position

				p-value From ANOVA Test		
Property	Radial Position	Average	Standard Deviation	Family	Tree	Position
Basic density (kg/m^3)	Inner-wood (I)	453.3a	45.0	0.035	< 0.0001	< 0.0001
	Middle-wood (M)	459.1a	47.3			
	Outer-wood (O)	508.8b	34.2			
Moisture content (%)	Inner-wood (I)	157.5a	24.9	0.04	< 0.0001	< 0.0001
	Middle-wood (M)	151.1a	20.8			
	Outer-wood (O)	129.7b	12.4			
E_c (GPa)	Inner-wood (I)	2.1a	0.5	0.033	< 0.0001	0.0008
	Middle-wood (M)	2.3ab	0.3			
	Outer-wood (O)	2.5b	0.3			
f_c (MPa)	Inner-wood (I)	4.1a	0.5	0.139	< 0.0001	0.035
	Middle-wood (M)	4.2ab	0.4			
	Outer-wood (O)	4.4c	0.3			

Averages with a common letter are not statistically different ($p > 0.05$) based on the Tukey test

The average basic density measured for *E. nitens* was 473.7 kg/m^3, with minimum and maximum values of 365.2 kg/m^3 and 599.9 kg/m^3, respectively, and a standard deviation of 48.9. These results are in agreement with data for 8- to 14-year-old *E. nitens* trees reported in the literature (Purnell 1988; Chafe 1990; Chauhan and Walker 2004;

Leandro *et al*. 2008). Furthermore, Kibblewhite *et al*. (2004) reported almost the same basic density of 473 kg/m^3 and also Derikvand *et al*. (2018) reported a close average density of 480 kg/m^3 for 15- and 16-year-old *E. nitens* trees, respectively.

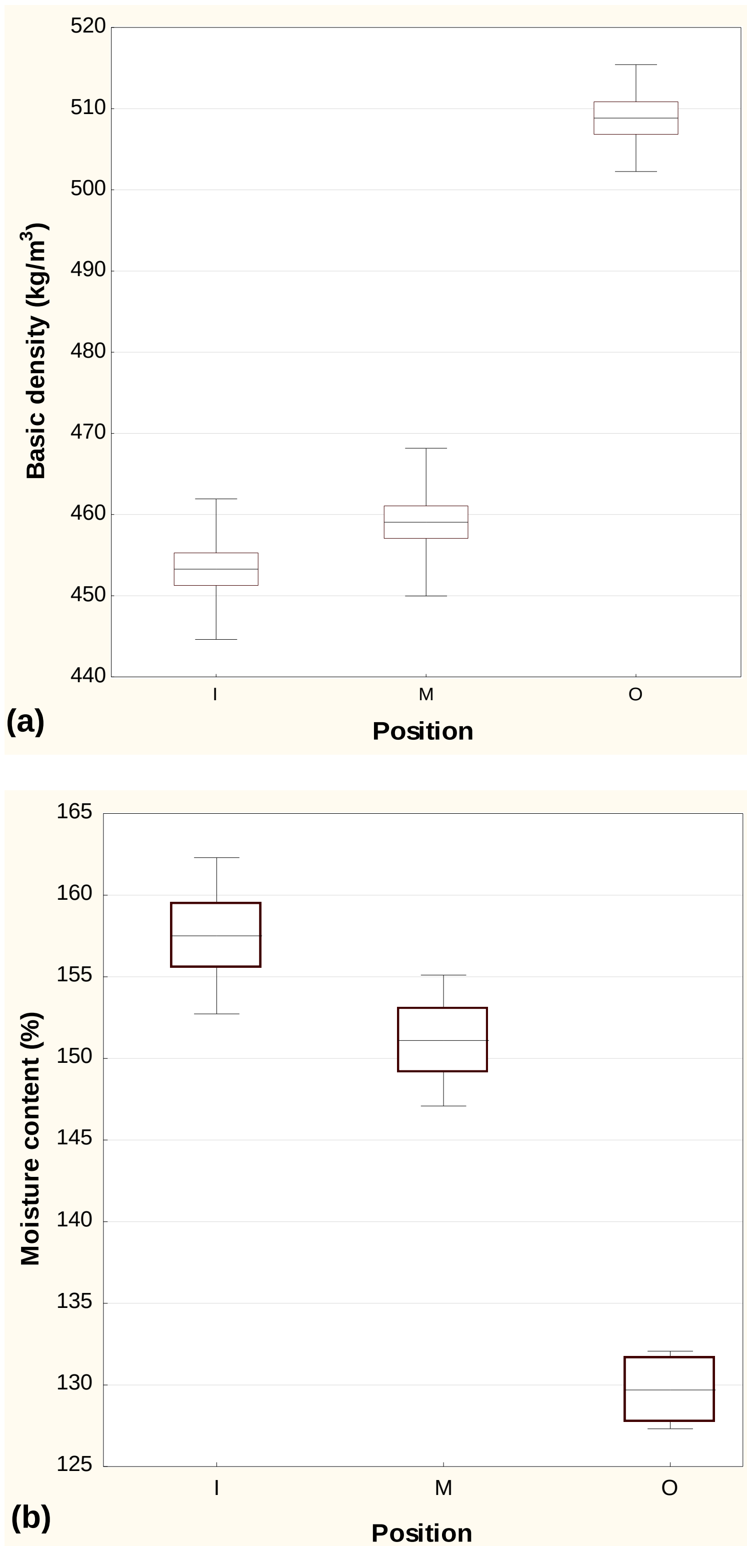


Fig. 2. Variation of (a) basic density and (b) moisture content of *E. nitens* as a function of the radial position

Table 1 indicates that there were no statistically significant differences between inner-wood and middle-wood, but the differences were significant with respect to outer-wood. Figure 2 shows the basic density, moisture content average, and the range of variation as a function of the wood position in the radial direction. It was observed that the basic density tended to increase from pith to bark (Fig. 2a), which is in agreement with other published literature data (Lausberg *et al.* 1995; Downes *et al.* 1997; Evans *et al.* 2000) as well as the common trend typically reported in the literature for the *Eucalyptus* genus (Raymond and Muneri 2001; McKinley *et al.* 2002; Wessels *et al.* 2016).

Similarly, moisture content did not show statistically significant differences between the inner-wood and the middle-wood (Fig. 2b), but only with respect to outer-wood. However, for moisture content, the average moisture content decreased from pith to bark, similarly to what has been reported by Lausberg *et al*. (1995), who measured moisture content values in *E. nitens* varying from 137% to 123% from pith to bark.

The average modulus of elasticity in compression perpendicular to the fiber for the *E. nitens* was 2.3 GPa, with minimum and maximum values of 1.1 and 3.6 GPa, respectively, and a standard deviation of 0.5. These values are much higher than those reported in literature for other older species of the *Eucalyptus* genus (Alexiou 1994; Nogueira *et al*. 2018a,b). Table 1 shows that there were statistically significant differences between inner-wood and outer-wood, but these differences were not significant as the differences between inner-wood and middle-wood, and between middle-wood and outer-wood. Additionally, the general trend was that E_c increased from pith to bark, with values from 2.1 GPa to 2.5 GPa from inner-wood to outer-wood, and which represents an increase of approximately 20%. This can be explained by the fact that the basic density increases in the outer-wood by approximately 12%, compared to the inner-wood.

The measured compressive strength ranged from 2.6 to 5.6 MPa, with an average of 4.2 MPa. These results are comparable with similar values reported in the literature for the same species (McKimm 1985) and for other species of the same *Eucalyptus* genus (Nogueira *et al.* 2018a). On the other hand, the values measured in this study were similar to those reported by Lobão *et al.* (2004) for *Eucalyptus grandis* (4.9 MPa), and the results obtained by Awan *et al.* (2012) for *Eucalyptus camaldulensis* (5.5 MPa). However, these results were obtained in mechanical tests conducted in dry conditions. The trend was that f_c increased from pith to bark, with values from 4.1 MPa to 4.4 MPa from inner-wood to outer-wood. The major value in outer-wood can be explained due to a higher value of density and a lower value of MFA (Evans *et al.* 2000).

One important observation that can be drawn from this study is that the compressive strength perpendicular to the fiber direction of *Eucalyptus nitens* may not be enough to withstand the internal stresses that can induce collapse during drying. That is based on the drying stresses calculated by Pérez *et al.* (2018), who reported values in the range of 8 to 9 MPa. This is important for the processing of *E. nitens* into added value solid wood materials because this species is prone to collapse during drying. Thus, having data about the resistance to perpendicular compressive stress during drying will help researchers to develop drying schedules that can minimize the risk of collapse. Examples of strategies to help reduce the collapse would include by reducing the magnitude of drying stresses by applying lower temperatures, an intermittent drying process, or by using radio-frequency vacuum drying technology (Yang *et al.* 2014; Ananías *et al.* 2018).

Figure 3 shows the modulus of elasticity (Fig. 3a), the compressive strength averages (Fig. 3b), and ranges of values measured for *E. nitens* as a function of the radial position. As with the E_c results, the general trend was also that f_c increased from pith to bark, and the difference between inner-wood and outer-wood was statistically significant at the 0.05 level.

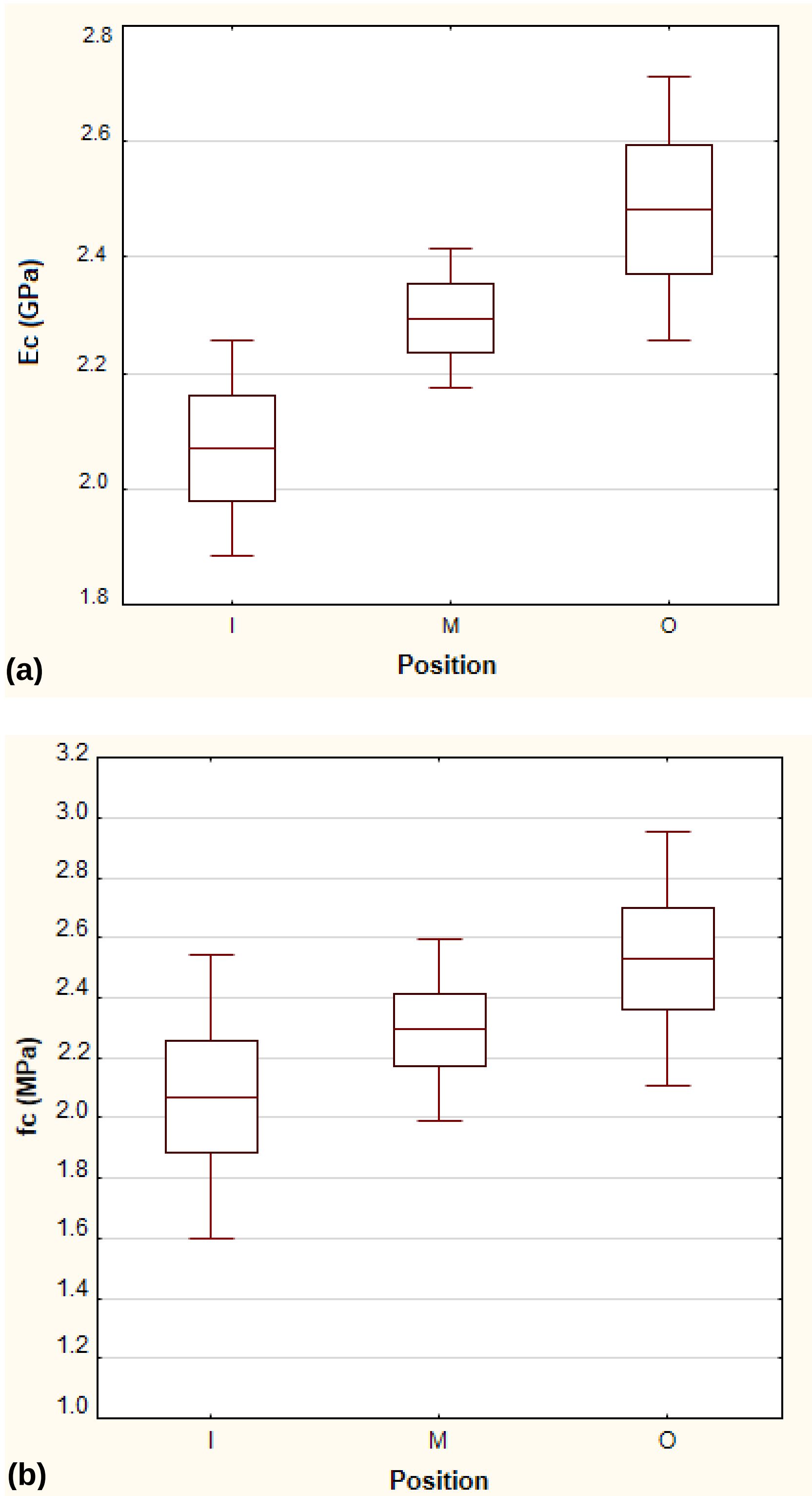


Fig. 3. Compressive properties perpendicular to the fiber of *E. nitens* as a function of the radial position: (a) modulus of elasticity and (b) compressive strength

Table 2 shows the average measured anatomical properties grouped by the radial position and the p-value of the ANOVA test.

Table 2. Summary of Anatomical Properties of *Eucalyptus nitens*

					p-Value		
Property	Direction	Radial Position	Avg.	Standard Deviation	Family	Tree	Position
Cell wall thickness (μm)	Rd	I-W (I)	2.32 a	0.30	0.0001	0.0002	0.1219
		M-W (M)	2.39 a	0.19			
		O-W (O)	2.31 a	0.23			
	Tg	I-W (I)	2.54 a	0.24	< 0.0001	< 0.0001	0.0521
		M-W (M)	2.60 a	0.22			
		O-W (O)	2.49 a	0.21			
Fiber diameter (μm)	Rd	I-W (I)	11.45 a	1.43	0.1512	0.0065	0.8797
		M-W (M)	11.52 a	1.48			
		O-W (O)	11.64 a	1.64			
	Tg	I-W (I)	14.26 a	1.77	0.3228	0.5122	0.8596
		M-W (M)	14.20 a	1.42			
		O-W (O)	14.01 a	1.83			
Vessel diameter (μm)	Rd	I-W (I)	106.71 a	14.01	0.0017	0.0001	< 0.0001
		M-W (M)	150.20 b	17.10			
		O-W (O)	165.49 c	17.44			
	Tg	I-W (I)	175.07 a	27.13	0.1720	< 0.0001	< 0.0001
		M-W (M)	245.07 b	57.28			
		O-W (O)	283.39 c	34.96			
Wall cell area (μm^2)	-----	I-W (I)	149.31 a	31.25	0.0021	0.07	0,05953
		M-W (M)	153.42 a	19.64			
		O-W (O)	151.86 a	23.80			
Vessels area (μm^2)	-----	I-W (I)	15891.15 a	4534.4	0.4777	0.0002	< 0.0001
		M-W (M)	32420.34 b	8143.7			
		O-W (O)	40007.62 c	8691.2			

I-W: inner-wood, M-W: middle-wood, O-W: outer-wood
Rd: radial, Tg: tangential
Averages with a common letter are not significantly different ($p > 0.05$) based on the Tukey test

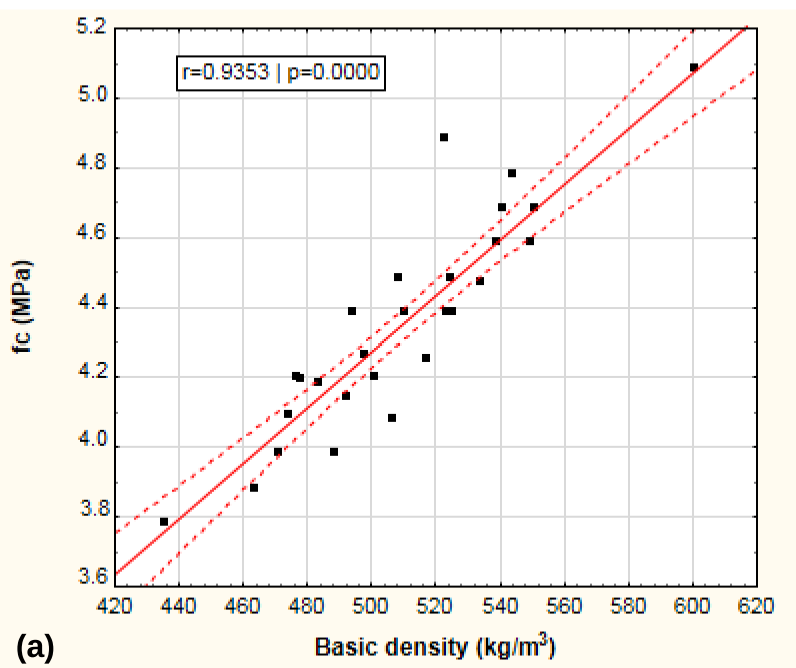
The mean values of radial and tangential cell wall thickness were 2.3 and 2.5 µm, respectively, with the highest values in the middle-wood. These values were similar to the values measured by Leandro *et al.* (2008) and Salvo *et al.* (2017), and higher than those reported by McKenzie *et al.* (2003) and Kibblewhite *et al.* (2004). This difference can be explained by various factors, such as the presence of juvenile wood, provenance and site, and the high variability within and between trees in the *Eucalyptus nitens* families (Salvo *et al.* 2017). The radial and tangential fiber diameters were 11.5 and 14.2 µm, respectively, and there was no significant difference among the wood types. In contrast, the cell wall area increased from 149.3 to 151.9 µm^2, although the difference between the types of wood was not statistically significant.

For vessel diameter, there was a significant difference between the three types of wood. In both cases, the mean value increased from inner-wood to outer-wood. Additionally, the variation between radial and tangential values was statistically significant at the 0.05 level. These results were in agreement with previous studies (McKenzie *et al.* 2003; Leandro et *al.* 2008; Salvo et *al.* 2017). Similarly, the value of vessel area increased from 15,891 µm^2 in core-wood to 40,000 µm^2 in outer-wood. These values were higher than those measured by Hudson *et al.* (1998), who reported values that increased from 500 µm^2 near the pith to approximately 35,000 µm^2 in the near bark zone.

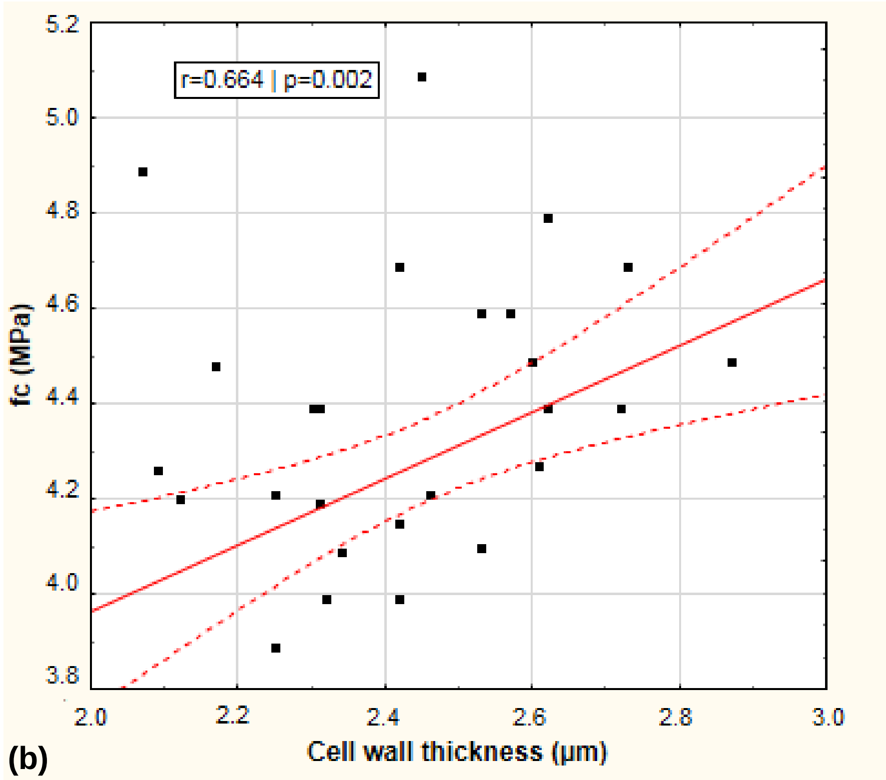
The results obtained with the ANOVA indicated that the radial position only had an effect in the vessels diameter and vessel area. In both properties, significant differences were obtained between the three types of wood.

Also, the width: thickness ratio were calculated, which represent the fiber collapse potential (Kibblewhite *et al.* 1998). The average values obtained were 1.25, 1.24, and 1.22 for respectively inner-wood, middle-wood, and outer-wood, and showing a small decreasing trend from pith to bark. This could therefore be expected and be related with a high compressive strength near to bark.

In contrast, the relationships between compressive strength with basic density and anatomical properties were not statistically significant in inner-wood and middle-wood. However, significant relationships were found in outer-wood. The relationships between compressive strength with basic density and anatomical properties of outer-wood are shown in Fig 4. The basic density was strongly positively correlated with compressive strength, with $r = 0.93$ ($p < 0.05$). Cell wall thickness and wall cell area showed a significant positive correlation with f_c, with r values of 0.66 and 0.65, respectively.



(a)



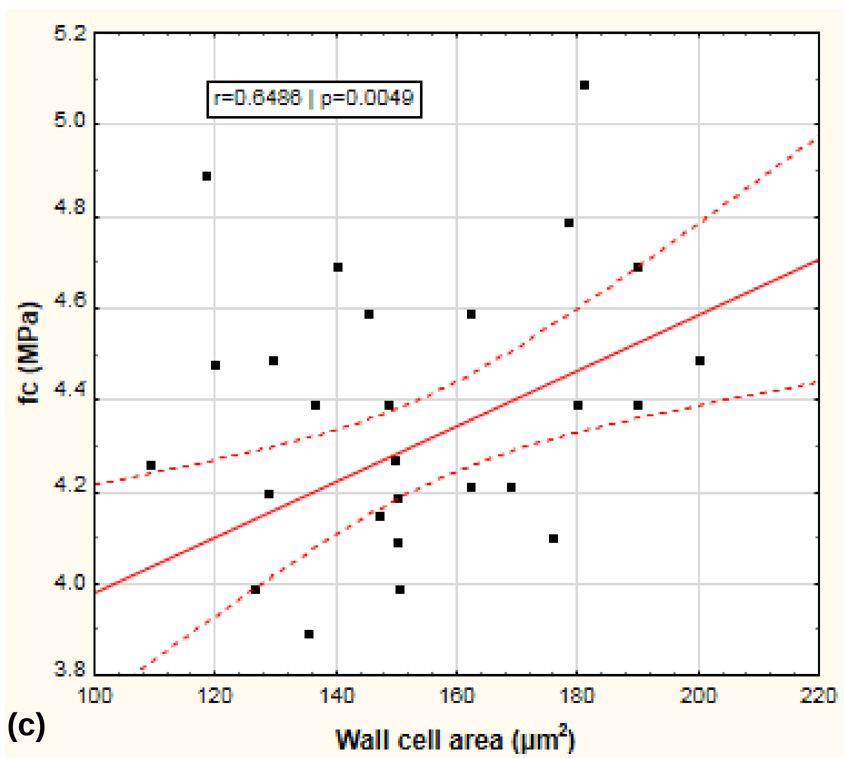


Fig. 4. Relationship between compressive strength and (a) basic density, (b) cell wall thickness, and (c) wall cell area

CONCLUSIONS

The objective of this study was to measure the modulus of elasticity and compressive strength perpendicular to the fiber, and then to relate it with some anatomical features and the density of green *Eucalyptus nitens*. The following are the conclusions that were obtained:

1. The compressive strength properties increased from pith to bark and showed significant differences between the inner-wood and outer-wood.
2. The modulus of elasticity ranged between 1.1 and 3.6 GPa with an average value of 2.3 GPa. The average compressive strength was 4.2 MPa with values of 4.1, 4.2, and 4.4 MPa for inner-, middle-, and outer-wood, respectively.
3. The compressive strength showed a strong and significant relation with basic density of outer-wood, and significant positive relation with cell wall thickness and cell wall area.

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