INFLUENCE OF MOISTURE CONTENT ON LONGITUDINAL, RADIAL, AND TANGENTIAL ULTRASONIC VELOCITY FOR TWO BRAZILIAN WOOD SPECIES

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(Received August 2006)

Abstract. The effects of MC on longitudinal, radial, and tangential ultrasonic wave velocity and on the respective terms of the stiffness matrix were examined for Brazilian pine (*Araucaria angustifolia*) and cupiúba (*Goupia glabra*). The ultrasonic wave velocity tended to increase with a decrease in MC, and the effect of MC on the ultrasonic wave velocity below the FSP was greater than above. Below the FSP, the stiffness terms tended to decrease with increasing MC, but above the FSP, they increased with increasing MC because of the influence of water on the bulk density. This result may be corrected by using the effective density above FSP, which depends on the mobility of free water and differs for the two species.

Keywords: Stiffness terms, fiber saturation point, effective density.

INTRODUCTION

Ultrasonic testing is one of the most useful nondestructive methods used to estimate mechanical properties of wood and wood composites, and it is very important to understand that the ultrasonic wave is significantly affected by the MC of wood and also to quantify its variation among species.

There are some reports on the effects of MC above and below the FSP on the mechanical properties of wood evaluated by both destructive and nondestructive methods (Bucur 2006). The FSP corresponds to a point at which all liquid water in the lumen has been removed but the cell wall is still saturated. This is known to be a critical point, because below this, the properties of wood are altered by changes in MC. Gerhards (1982) studied the stress-wave speed and modulus of elasticity (MOE) for wood with MC ranging from 150 to 15%. He indicated that both stress wave and MOE are reduced by increasing MC below FSP, but the effect on longitudinal wave speed is slightly greater than on MOE. He also indicated that both show a slight variation above FSP. Mishiro (1996a, 1996b) reported the relationships between ultrasonic wave velocities and average MC above and below the FSP in the longitudinal and radial directions of certain Japanese wood species. Wang et al (2002) studied the effects of MC on the ultrasonic wave velocity, dynamic Young's modulus (DMOE), and the mobility of free water during desorption from a water-saturated condition for the longitudinal, radial, and tangential directions of Taiwania (*Taiwania cryptomerioides Hayta*) plantation wood. Based on results of Sobue (1993), Mishiro also calculated the effective density above the FSP and the "k" value, which is the ratio of the mass of free water vibrating simultaneously with the wood cell wall to the mass of total free water. The k values obtained for the ultrasonic wave propagated in the longitudinal, radial, and tangential directions of Taiwania plantation wood were 0.58, 0.33, and 0.01, re-

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spectively, and, using the effective density, the DMOE tended to remain constant with MC above FSP. Sobue (1993), using 200-kHz transducers, obtained k values in the longitudinal direction of 0.78 and 0.79 for Japanese cedar and Hinoki, respectively.

The objectives of this research were to investigate the effects of MC on ultrasonic wave propagation on longitudinal, radial, and tangential directions (velocity and stiffness terms) through wood specimens of Brazilian pine (*Araucaria angustifolia*) and cupiúba (*Goupia glabra*) during the desorption stages from water-saturated to the oven-dry condition.

EXPERIMENTAL PROCEDURE

For the measurements of ultrasonic wave velocities in the three directions (V_{LL}, V_{RR}, and V_{TT}), and to calculate the stiffness terms (C_{LL}, C_{RR}, and C_{TT}), 15 specimens of each wood species (Brazilian pine and cupiúba) with dimensions of 300 mm (longitudinal), 60 mm (radial), and 30 mm (tangential) were used.

Brazilian pine is the only native softwood in Brazil and reaches 40 to 50 m in height. The most common area to find Brazilian pine is in the state of Paraná in southern Brazil, where it is considered the state tree, thus leading some to call it Paraná pine. Cupiúba is available in large quantities in the forests of Precious Woods located in the Amazon region in the north of Brazil. The larger trees have diameters to approximately 1.2 m and heights to 40 m with fairly straight trunks.

The material was obtained from boards belonging to a furniture enterprise that has a particular wood supplier, but it was not possible to know from which specific part of the tree the boards were taken. The specimens had no defects such as knots, decay, or slope of grain, and also lacked juvenile and reaction wood. The specimens were taken from boards with rings well positioned in the radial and tangential directions.

Cupiúba was selected because it is a hardwood largely used in Brazil for structures and Brazilian pine was largely used for furniture in the past. Today, the pine is being planted in sustainable reforestation projects in Brazil, and its use as a construction material is allowed.

A sample was taken from among the initially saturated specimens to be used as controls. This sample was oven-dried to determine its dry mass, which was used as a reference to obtain the initial MCs. From that initial MC, it was possible to estimate the weight of each specimen at the desired MC. At the end of the test, the actual oven-dry mass of each specimen was determined and the MC was then recalculated and corrected, if necessary.

The measurements of the propagation time through the longitudinal, radial, and tangential directions of specimens were taken during desorption. The moisture reduction to reach the EMC (approximately 12%) was done in ambient conditions in the laboratory. After that, the specimens were placed in a dry kiln at an initial temperature of 40°C, which was increased in 10°C steps until reaching 105 ± 1°C for oven drying.

Ultrasonic wave velocities were measured using portable ultrasonic test equipment (Steinkamp BP7) with 45-kHz transducers. The transmitting and receiving transducers were placed facing each other on opposite edges of the specimens and the propagation time was recorded. A medical gel was used for coupling. An apparatus was used to fix the specimen during the measurement to assure constant pressure.

The velocity of ultrasonic wave propagation was calculated in longitudinal, radial, and tangential directions, and the stiffness terms of diagonal matrix were calculated by Eq 1.

$$Cii = \rho\,(V_{ii})^2(\times 10^{-6})\ (\mathrm{MPa}). \tag{1}$$

where C_{ii} = stiffness terms of diagonal matrix in i direction; ρ = bulk density (kg/m^3).

MC during the test was calculated using Eq 2:

$$MC = [(m_u - m_0)/m_0] \times 100. \tag{2}$$

where MC = moisture content of the test specimens at various test stages (%); m_u = the specimen mass at various test stages (kg); and m_0 = the oven-dried mass of specimens (kg).

To adjust stiffness terms of the diagonal matrix above FSP, the effective density (ρ_{eff}) was calculated using Eq 3.

$$\rho_{eff} = \frac{(100 + MC)\rho_0}{(100 + 28\ \rho_0)} \times \left[1 - \frac{(1 - k)(MC - 28)}{(100 + MC)}\right]. \quad (3)$$

where: ρ_{eff} = effective density of wood with MC greater than FSP; and ρ_0 = density of the specimen in the oven-dry condition.

The adjusted ultrasonic wave velocity (V_{adj}) was calculated by Eq 4:

$$V_{adj} = \sqrt{\frac{C_{fsp}}{\rho_{eff}}}. \quad (4)$$

where C_{fsp} = stiffness term of specimen at the FSP.

The least squares method was used to determine the optimal k value of free water mobility. Then, using this k value, the adjusted stiffness term (C_{adj}) above the FSP was calculated using Eq 5:

$$C_{adj} = V^2ii\ \rho_{eff}. \quad (5)$$

RESULTS

Tables 1 and 2 present average values of bulk density and ultrasonic wave parameters measured and determined during desorption for cupiúba and Brazilian pine, respectively. Figures 1 and 2 show the average velocity measured at each MC and the relationship obtained in the longitudinal, radial, and tangential directions during desorption from water-saturated conditions to the oven-dry condition for cupiúba and Brazilian pine, respectively. The equation for each species, expressed by a second-order regression (Tables 3 and 4), was obtained considering the overall values represented by the 15 specimens. As expected, the ultrasonic wave velocity increases with a decrease of MC.

Previous reports (Wang et al 2002; Bucur 2006) show that, mainly for the longitudinal direction, there is a significant point in ultrasonic velocity around the FSP, where the slope of the curve changes. To verify this behavior, the curve that is representative of the relationship between ultrasonic velocities and MC was separated into two stages: below and above FSP (Tables 3

Table 1. *Average ultrasonic wave measurements.*[a]

MC (%)	DAP (kg/m^{-3})	V_{LL} (ms^{-1})	V_{TT} (ms^{-1})	V_{RR} (ms^{-1})	C_{LL} (MPa)	C_{TT} (MPa)	C_{RR} (MPa)
69	1177 (14.8)[c]	4294 (128.4)	[b]	[b]	21,710 (1468.5)	[b]	[b]
68	1176 (25.5)	4269 (162.1)	[b]	[b]	21,420 (1514.6)	[b]	[b]
64	1143 (20.7)	4260 (114.7)	[b]	[b]	20,740 (1234.7)	[b]	[b]
59	1110 (32.3)	4327 (239.7)	[b]	[b]	20,783 (2695.1)	[b]	[b]
51	1055 (49.9)	4322 (140.1)	[b]	[b]	19,701 (1569.8)	[b]	[b]
47	1026 (44.2)	4296 (148.8)	1600 (62.2)	1824 (86.3)	18,935 (1370.5)	2626 (260.8)	3412 (408.8)
42	995 (58.2)	4386 (141.4)	1620 (63.6)	1852 (61.0)	19,131 (1577.2)	2610 (951.1)	3409 (336.2)
39	979 (47.8)	4433 (141.0)	1577 (82.6)	1841 (68.5)	19,237 (1158.0)	2433 (311.1)	3318 (355.1)
34	959 (79.6)	4493 (172.0)	1573 (90.8)	1845 (100.0)	19,359 (1517.4)	2372 (292.4)	3266 (343.8)
22	889 (36.4)	4689 (167.0)	1491 (108.7)	1884 (80.9)	19,549 (1256.0)	1976 (252.5)	3156 (262.9)
20	879 (48.5)	4754 (150.5)	1500 (146.3)	1902 (75.3)	19,868 (1694.1)	1978 (372.0)	3180 (262.7)
15	856 (18.9)	4837 (129.2)	1474 (154.2)	1931 (87.8)	20,024 (1196.8)	1858 (361.9)	3192 (317.6)
9	837 (14.9)	5000 (108.7)	1561 (97.9)	2016 (99.3)	20,935 (1140.8)	2040 (227.7)	3405 (356.8)
2	814 (15.4)	5166 (126.8)	1613 (95.4)	2066 (127.8)	21,717 (1368.9)	2117 (244.5)	3474 (448.1)
1	811 (15.0)	5203 (226.6)	1606 (106.9)	2046 (130.5)	21,968 (2234.0)	2094 (265.0)	3398 (456.2)

[a] Velocities in longitudinal (V_{LL}), radial (V_{RR}), and tangential (V_{TT}) directions and properties determining using ultrasonic wave measurements (terms of the stiffness matrix in longitudinal [C_{LL}], radial [C_{RR}], and tangential [C_{TT}] in different MC conditions). Species: cubiúba. Average of 15 specimens in each MC condition.

[b] Measurement problems.

[c] Numbers in parentheses are standard deviations.

Table 2. *Average ultrasonic wave measurements.*[a]

MC (%)	DAP (kg/m^{-3})	V_{LL} (ms^{-1})	V_{TT} (ms^{-1})	V_{RR} (ms^{-1})	C_{LL} (MPa)	C_{TT} (MPa)	C_{RR} (MPa)
111	976 (43.4)	4698 (176.4)	1135 (42.0)	[b]	21,534 (1336)	1254 (66.7)	[b]
110	977 (43.5)	[b]	1134 (43.8)	[b]	[b]	1256 (132.0)	[b]
109	968 (43.9)	4723 (160.5)	1147 (29.8)	[b]	21,594 (1254.0)	1245 (90.2)	[b]
100	925 (48.9)	4781 (179.9)	1145 (45.5)	1146 (50.4)	21,135 (1401.5)	1195 (111.6)	1214 (116.5)
89	879 (60.2)	4812 (164.0)	1135 (54.1)	1136 (58.5)	20,350 (1345.1)	1134 (113.8)	1146 (134.1)
75	812 (75.1)	4944 (184.8)	1139 (51.2)	1148 (53.3)	19,837 (1277.9)	1063 (68.5)	1070 (96.8)
65	767 (78.6)	5000 (211.0)	1128 (47.4)	1172 (78.8)	19,187 (1440.4)	1010 (62.7)	1054 (150.2)
53	715 (103.6)	5038 (193.4)	1148 (71.6)	1162 (82.3)	18,145 (1907.6)	947 (108.4)	966 (176.6)
42	662 (69.5)	5201 (186.7)	1173 (70.3)	1207 (76.1)	17,916 (1281.6)	883 (45.8)	965 (76.1)
41	652 (62.7)	5120 (183.0)	1137 (58.5)	1196 (62.9)	17,084 (1091.3)	869 (50.8)	932 (68.1)
40	638 (62.5)	5182 (180.1)	1188 (97.4)	1209 (55.9)	17,142 (1469.4)	851 (87.1)	933 (103.6)
38	642 (61.7)	5148 (199.1)	1148 (53.8)	1202 (66.9)	17,018 (985.2)	858 (44.5)	928 (66.2)
34	626 (55.8)	5185 (197.4)	1155 (62.4)	1210 (89.7)	16,826 (926.4)	838 (49.6)	916 (101.0)
33	622 (54.1)	5196 (212.4)	1159 (60.9)	1245 (69.8)	16,779 (915.2)	832 (54.3)	963 (139.7)
30	610 (45.2)	5181 (198.8)	1141 (60.5)	1228 (68.3)	16,366 (831.3)	808 (53.1)	919 (56.9)
28	598 (29.3)	5279 (190.6)	1184 (53.0)	1264 (55.4)	16,652 (845.7)	822 (60.8)	955 (55.6)
10	554 (11.3)	5682 (176.9)	1303 (36.1)	1438 (65.3)	17,878 (1067.7)	948 (58.0)	1145 (89.8)
5	534 (30.7)	5883 (183.7)	1349 (33.0)	1476 (65.2)	18,462 (1338.2)	979 (72.7)	1162 (94.2)
3	529 (10.1)	5890 (179.3)	1373 (33.2)	1503 (58.6)	18,338 (1125.3)	988 (56.3)	1194 (80.1)

[a] Velocities in longitudinal (V_{LL}), radial (V_{RR}), and tangential (V_{TT}) directions and properties determining using ultrasonic wave measurements (terms of the stiffness matrix in longitudinal [C_{LL}], radial [C_{RR}], and tangential [C_{TT}]) in different MC conditions. Species: Brazilian pine. Average of 15 specimens in each MC condition.

[b] Measurement problems.

[c] Numbers in parentheses are standard deviations.

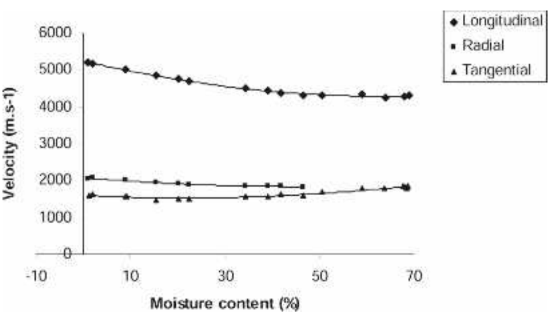

Figure 1. Average velocity measured at each MC and the fit equation obtained in the longitudinal, radial, and tangential directions during desorption from water-saturated conditions to the oven-dry condition for cupiúba.

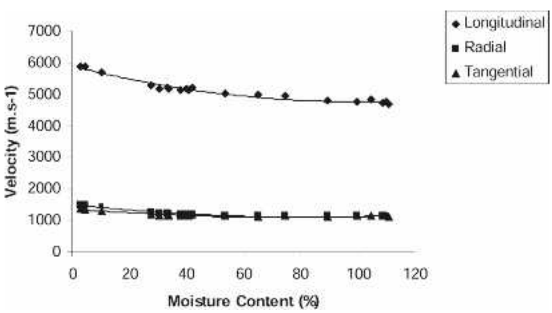

Figure 2. Average velocity measured at each MC and the fit equation obtained in the longitudinal, radial, and tangential directions during desorption from water-saturated conditions to the oven-dry condition for Brazilian pine.

and 4). The ultrasonic wave velocity below the FSP is more strongly affected than above the FSP. This behavior can be seen by the magnitude of the coefficient that takes into account the influence of the MC and is shown in Figures 3 and 4 for the longitudinal direction. As can be seen, this coefficient below FSP is 345% and 338% greater than above FSP for cupiúba and Brazilian pine, respectively.

Mishiro (1996a, 1996b) indicated that during desorption from water-saturated conditions, the pattern of ultrasonic wave velocities vs average MC in the radial and tangential directions varied with species. This behavior could also be observed for the results obtained in this study for the tangential direction. In this direction, above FSP, the velocity increased with the increase of MC for cupiúba. For Brazilian pine, the velocity was almost constant (Tables 3 and 4).

It was also found that the effects of MC on the

Table 3. *Equations for the relations between ultrasonic wave velocity (V) and MC for cupiúba in longitudinal, radial, and tangential directions.*

Direction	MC	Equations	R^2	P
Longitudinal	69–1%	$V_{LL} = 0.23\ MC^2 - 29.8\ MC + 5239$	0.99	0.0000
	> FPS	$V_{LL} = 4619 - 5.3\ MC$	0.74	0.0000
	< FPS	$V_{LL} = 5217 - 23.6\ MC$	0.99	0.0000
Radial	47–1%	$V_{RR} = 0.12\ MC^2 - 10.9\ MC + 2077$	0.98	0.0000
	> FPS	$V_{RR} = 1901 - 1.5\ MC$	0.42	0.0020
	< FPS	$V_{RR} = 2073 - 8.5\ MC$	0.97	0.0003
Tangential	47–1%	$V_{TT} = 0.14\ MC^2 - 6.2\ MC + 1596$	0.94	0.0000
	> FPS	$V_{TT} = 1267 + 8.2\ MC$	0.95	0.0000
	< FPS	$V_{TT} = 1615 - 6.3\ MC$	0.87	0.0000

Table 4. *Equations for the relations between ultrasonic wave velocity (V) and MC for Brazilian pine in longitudinal, radial, and tangential directions.*

Direction	MC	Equations	R^2	P
Longitudinal	111–3%	$V_{LL} = 0.12\ MC^2 - 22.98\ MC + 5899$	0.96	0.0000
	> FPS	$V_{LL} = 5383 - 5.8\ MC$	0.96	0.0000
	< FPS	$V_{LL} = 5974 - 25.4\ MC$	0.99	0.0000
Radial	100–3%	$V_{RR} = 0.06\ MC^2 - 9.8\ MC + 1508$	0.95	0.0000
	> FPS	$V_{RR} = 1478 + 63\ MC$	0.98	0.0000
	< FPS	$V_{RR} = 1868 - 74.9\ MC$	0.99	0.0000
Tangential	111–3%	$V_{TT} = 0.05\ MC^2 - 6.8\ MC + 1362$	0.88	0.0000
	> FPS	$V_{TT} = 1252 - 1.19\ MC$	0.85	0.0016
	< FPS	$V_{TT} = 1531 - 9.8\ MC$	0.99	0.0000

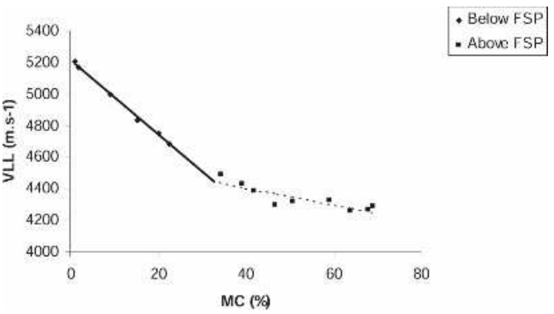

Figure 3. Relationship between ultrasonic velocity in longitudinal direction and MC below and above FSP for cupiúba.

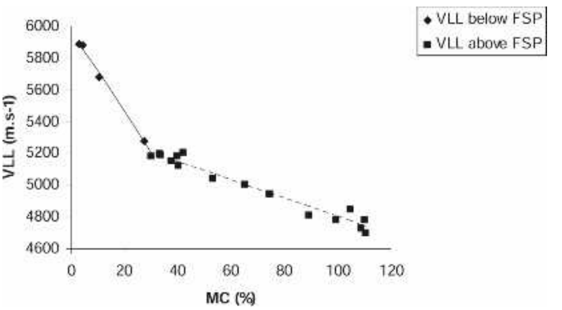

Figure 4. Relationship between ultrasonic velocity in longitudinal direction and MC below and above FSP for Brazilian pine.

ultrasonic wave velocity are greater in the longitudinal direction followed by radial and tangential, demonstrating that the results are in agreement with results of other authors.

The coefficient of influence of the MC on the ultrasonic wave velocity in the longitudinal direction for each 1% MC was calculated using equations obtained for MC below 30% (FSP). The coefficient was 25.4 for Brazilian pine and 23.6 for cupiúba. Therefore, in the longitudinal direction, the influence of MC on the velocity can be considered slightly greater for Brazilian pine than cupiúba. Although the difference is small (1.8 ms^{-1}), it corresponds to 7%, and the precision expected for this ultrasonic measurement varies from 3 to 4% (Bucur 2006).

The relationship between stiffness terms and MC in longitudinal (C_{LL}), radial (C_{RR}), and tangential (C_{TT}) directions was also studied, and Tables 5 and 6 present the equations that represent the relationship between C_{ii} and MC obtained for cupiúba and Brazilian pine, respectively. For both species, as expected, the values of the stiffness coefficients decreased with MC below FSP and increased with MC above FSP.

Those results are similar to the findings reported by Bucur (2006) and Wang et al (2002) and contradict the usual assumption that physical and mechanical properties of wood increase with a decrease in MC below FSP and remain fairly constant with MC above FSP.

Wang et al (2002) indicated that the use of effective density (ρ_{eff}) to calculate stiffness terms could adjust the values above FSP. The ρ_{eff} may be calculated by using an equation proposed by Sobue (1993), which defines the k value as the ratio of the mass of free water vibrating simultaneously with wood cell wall substance to the mass of free water. When the MC is above the FSP, k values assume values between 0 and 1.

The k values obtained for cupiúba were $k_L = 0.33$, $k_R = 0.20$, and $k_T = 0.01$; and for Brazilian pine were $k_L = 0.34$, $k_R = 0.29$, and $k_T = 0.05$. In agreement with what was defined in Wang et al (2002), more free water vibrated simultaneously with cell wall substance when the ultrasonic wave was in the longitudinal direction than in the radial or tangential directions. The cupiúba has less porosity than Brazilian pine (approximately 20%), so greater differences were expected between the species. However, both species are known to be difficult to dry. During the experiment, the cupiúba lost 1% MC/da and Brazilian pine 0.8% MC/da during desorption from saturated condition to FSP. Additionally, both species are rated medium in shrinkage, and values from green to oven-dry are very similar: radially, 4.5% for cupiúba and 4% for Brazilian pine; tangentially, 8.5% for cupiúba and 7.5% for Brazilian pine; and volumetrically, 13% for cupiúba and 12% for Brazilian pine. Although they have different densities, they have similar k values.

The k values obtained for the Brazilian species were smaller than values obtained for Japanese species. These differences were probably related to density and also with the drying properties of the Brazilian species studied. Despite Brazilian pine being a softwood, it is reported to be much more difficult to kiln-dry than most softwoods, and its density is greater than the Japanese species tested by the cited authors.

Figures 5 and 6 present, for cupiúba and Brazilian pine, respectively, the behavior of C_{LL} as a function of the MC for experimental C_{LL} (below and above FSP) and for C_{LL} corrected by effective density (above FSP). It can be noted that by using effective density, C_{LL} has an almost linear behavior above FSP. The same behavior was obtained for C_{RR} and C_{TT} when using effective density.

CONCLUSIONS

The ultrasonic wave velocity in the longitudinal, radial, and tangential directions tended to increase with a decrease in MC. The relationship could be represented by a second-order polynomial equation for the two species studied.

The effect of MC below FSP on ultrasonic wave velocity was greater than that above the FSP.

The variation in ultrasonic wave velocity with

Table 5. *Equations for the relations between C_{LL} and MC for cupiúba in longitudinal, radial, and tangential directions.*

Direction	MC	Equations	R^2	P
Longitudinal	< FPS	$C_{LL} = 21965 - 110.6$ MC	0.98	0.0005
	> FPS	$C_{LL} = 15758 + 82.8$ MC	0.95	0.0003
Radial	< FPS	$C_{RR} = 3469 - 14.4$ MC	0.88	0.0002
	> FPS	$C_{RR} = 2836 + 12.7$ MC	0.85	0.0000
Tangential	< FPS	$C_{TT} = 2100 - 7.7$ MC	0.56	0.0070
	> FPS	$C_{TT} = 1602 + 22.4$ MC	0.84	0.0007

Table 6. *Equations for the relations between C_{LL} and MC for Brazilian pine in longitudinal, radial, and tangential directions.*

Direction	MC	Equations	R^2	P
Longitudinal	< FPS	$C_{LL} = 18679 - 74.9$ MC	0.99	0.0000
	> FPS	$C_{LL} = 14781 + 63$ MC	0.98	0.0016
Radial	< FPS	$C_{RR} = 1224 - 9.8$ MC	0.99	0.0000
	> FPS	$C_{RR} = 780 + 4.1$ MC	0.95	0.0009
Tangential	< FPS	$C_{TT} = 1011 - 6.7$ MC	0.99	0.0000
	> FPS	$C_{TT} = 647 + 5.5$ MC	0.99	0.0001

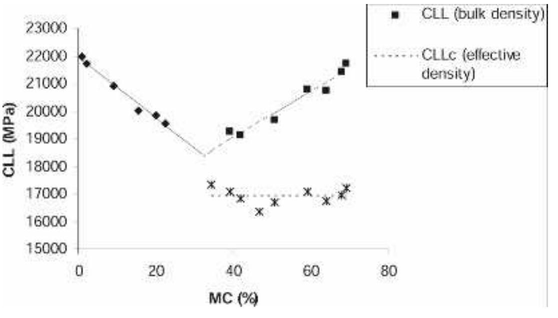

Figure 5. Relationship between stiffness terms and MC in longitudinal direction using bulk density (CLL) and effective density (CLLc). Species: cupiúba.

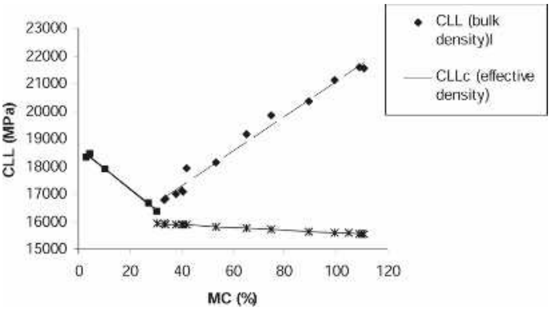

Figure 6. Relationship between stiffness terms and MC in longitudinal direction using bulk density (CLL) and effective density (CLLc). Species: Brazilian pine.

MC is more significant and presents a more constant behavior in the longitudinal direction. In the radial and tangential directions, the patterns of ultrasonic wave velocities vs average MC varied with species.

During desorption from FSP to the oven-dry condition, the ultrasonic wave velocity in the longitudinal direction could be corrected, for each 1% MC, by 23.6 ms^{-1} and 25.4 ms^{-1} for cupiúba and Brazilian pine, respectively.

The magnitude of the stiffness coefficient variation with MC differs among the directions and between the species. The variation was always more significant for the longitudinal direction and for cupiúba.

The k values for ultrasonic waves in the longitudinal, radial, and tangential directions were estimated to be $k_L = 0.33$, $k_R = 0.20$, and $k_T = 0.01$ for cupiúba and $k_L = 0.34$, $k_R = 0.29$, and $k_T = 0.05$ for Brazilian pine. This suggested that, for the longitudinal direction and for both species above the FSP, there is approximately 30% of free water vibrating simultaneously with the cell wall substance when subjected to ultrasonic pulses.

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