J Wood Sci (2011) 57:282–287
DOI 10.1007/s10086-011-1177-y



ORIGINAL ARTICLE

**Raquel Gonçalves · Alex Julio Trinca**
**Gisleiva Cristina dos Santos Ferreira**

# Effect of coupling media on velocity and attenuation of ultrasonic waves in Brazilian wood

Received: September 14, 2010 / Accepted: January 27, 2011 / Published online: May 21, 2011

**Abstract** Coupling media are necessary to ensure that transducers bond to wood specimens to minimize coupling losses and improve the accuracy of ultrasonic measurements. There are several types of coupling media available, and the optimal choice is not known. In this work, we analyzed the results of ultrasonic wave attenuation for 0.1-MHz longitudinal and transverse transducers with six different materials as coupling media in nine species of Brazilian wood with densities in the range 700–1170 kg/m$^3$. Tests were performed using constant pressure on the transducer and with wave propagation in the longitudinal direction. For transverse transducers, the polarization was in the radial and tangential directions. The results were analyzed statistically and showed that, for attenuation in both longitudinal and transverse waves, the material used for coupling had significant effects, whereas the wood species had no effect. For longitudinal waves, the statistical evaluation showed that the coupling material performance was strongly dependent on the species of wood, but it was not possible to observe any tendency of behavior associated with specific anatomical properties.

**Key words** Nondestructive testing · Nondestructive evaluation · Longitudinal waves · Transverse waves

## Introduction

A coupling medium is a liquid or doughy substance that allows the transmission of ultrasonic waves from the transducer to the piece being tested without any air gaps. The choice of coupling medium depends on the superficial conditions of the piece, the type of material that is being tested, and the usage conditions.[1] For a surface with a good finish, a thin layer is sufficient, while for surfaces with excessive irregularity, the coupling media must be more viscous.

Because of the difference in acoustic impedance between the material and the surrounding medium (water or coupling gel), ultrasonic wave propagation is greatly perturbed by physical processes such as the refraction, attenuation, and scattering of the waves.[2] Bucur[1] suggests that for thin coupling media layers, the effect on the velocity may be neglected; however, to obtain accurate measurements, it is necessary to maintain pressure on the transducers, especially to achieve repeatable attenuation measurements. The importance of maintaining constant pressure during the measurements was also mentioned by Gonçalves and Trinca.[3] The authors concluded that the pressure does not affect the wave propagation velocity measurements beyond a minimum value of approximately 18 kPa. Very low pressure values on the transducers during measurements cause the attenuation to vary greatly without a general tendency (neither increasing nor decreasing).

Bucur[1] presented data that describe the influence of the coupling medium on the longitudinal propagation velocity in the tangential direction ($V_{TT}$) on *Pinus* spp at 12% moisture content. Bucur[4] also comments that, when using Cellophane sheets, it is necessary to verify the integrity of the material during testing; moreover, mineral grease can penetrate the test material and might interfere with the readings.

Kamioka and Kataoka[5] also studied the effects of coupling media and coupling penetration in the material for Sitka spruce species during velocity measurements. The measurements were performed with longitudinal waves in the longitudinal, radial, and tangential directions. The authors indicated that there could be reading errors if the coupling media penetrates the wood specimen; in addition, there could also be observed instabilities during the velocity and attenuation measurements. According to the authors, the errors and reading instabilities were due to the impedance alterations in the wood caused by the absorption of the coupling media.

It is known that the acoustic impedance of materials is a matter of great importance to reduce losses during signal

R. Gonçalves (✉) · A.J. Trinca · G.C. dos Santos Ferreira
Laboratory of Nondestructive Testing (LabEND), University of Campinas – UNICAMP, Av. Candido Rondon 501, 13083-875 Campinas, São Paulo, Brazil
Tel. +55-19-35211034; Fax +55-19-35211010
e-mail: raquel@agr.unicamp.br

Part of this article was presented at the 16th International Symposium on Nondestructive Testing and Evaluation, Beijing, China, October 2009

transmission. Ideally, the impedance of the coupling medium would be the same as the impedance of the test material. The acoustic impedance, Z, is defined as the product of the material (or coupling medium) density and the propagation velocity within the material (or coupling medium); in addition, it represents the amount of acoustic energy that is reflected and transmitted to the environment.

The purpose of this work was to evaluate the behavior of longitudinal and transverse ultrasound wave propagation using coupling media with different viscosities and acoustic impedances in different species of native Brazilian wood. Despite the importance of this topic to researchers and applications using contact methods in nondestructive testing and evaluation of wood, there is insufficient information in the literature on the subject. Thus, this work sought to add new information about the relationship between the viscosity and the density of the coupling medium and the influence of wood anatomy on the velocity and attenuation of ultrasonic waves.

## Material and methods

The experimental design was developed using samples of nine wood species acquired from SENAI's Physical Wood Laboratory (National Industry Service, Itatiba, SP, Brazil). The species were chosen to include a wide range of densities. For each species, prismatic specimens with dimensions of 30 mm × 30 mm × 90 mm were used. Table 1 lists the species used, their scientific and common names, their densities, and some anatomical properties obtained from Souza et al.[6] and Richter and Dallwitz[7]. All tests were performed with wood at 12% moisture content (reference moisture content in Brazil). Figure 1 presents transverse sections for some species to illustrate the anatomical differences.

Six types of coupling media were used: medicinal gel, Panametrics SWC gel, starch glucose, maize glucose, 6% carboxy methyl cellulose; and 10% carboxy methyl cellulose. The acquired coupling media were already prepared, except for the carboxy methyl cellulose, which was prepared in 6% and 10% concentrations.

Initially, the viscosities, densities, and impedances of the coupling media were determined. The viscosity was determined with a Brookfield viscometer, and the density was determined using a 20-ml pycnometer and an electronic scale with a ± 0.0005-g precision.

To determine the impedance of the coupling media, a Plexiglas tube was designed with the same diameter as the transducer (Fig. 2). The coupling material was deposited into the tube for wave propagation measurements. Each measurement was repeated six times.

During the tests, a constant pressure of 35 kPa was applied on the transducers with a device with a 1000-N load cell (Fig. 3). For longitudinal and transverse waves, the time of wave propagation and the initial and final wave amplitudes were collected; the measurement procedure was performed five times to determine the repeatability of the tests. After the readings, a careful cleaning of the specimen and transducer was performed using water. Although there was no deep water penetration into the specimen, the specimen remained in a covered and aired location and was only tested again after completely drying (moisture content around 12%) to prevent any interference resulting from the moisture content or by coupling penetration, as cited by Kamioka and Kataoka[5]. For longitudinal waves, the reading was performed in the longitudinal direction (L), and for transverse waves, the propagation of the wave was also in the longitudinal direction (L), and the polarization was in the radial (R) and tangential (T) directions. The ultrasound equipment was a Panametrics Epoch 4 model (Olympus NDT, Waltham, USA) with 110 dB max sensitivity and a reference level sensitivity feature with a 0.1-dB selectable resolution, and longitudinal and transverse 0.1-MHz frequency transducers. The moisture content measurements were performed with a three-pole superficial humidity tester (TCS, model 75).

**Table 1.** Species used in the experiment, their averages densities, and anatomic properties

| Scientific and (common names) | Density (kg/m$^3$) | Rays (per mm) | Fiber length (μm) | Vessels | |
|---|---|---|---|---|---|
| | | | | (per mm$^2$) | Diameter (μm) |
| *Myroxylon balsamum* (cabreúva vermelha) | 820 | 10 | 900 | 15 | 145 |
| *Nectandra* (canelinha) | 702 | 7 | 950 | 14 | 110 |
| *Dipteryx odorata* (cumaru) | 1165 | 13 | 1750 | 8 | 175 |
| *Apuleia leiocarpa* (garapeira) | 820 | 7 | 750 | 25 | 95 |
| *Mezilaurus* (itaúba) | 831 | 8 | 1550 | 17 | 139 |
| *Balfourodendron riedelianum* (marfim) | 859 | 7 | 1545 | 38 | 80 |
| *Caesalpinia echinata* (pau Brasil) | 880 | 10 | 960 | 23 | 140 |
| *Gallesia integrifolia* (pau d'alho) | 695 | – | – | 16 | 87 |
| *Aspidosperma polyneuron* (peroba rosa) | 760 | 8 | 975 | 65 | 55 |

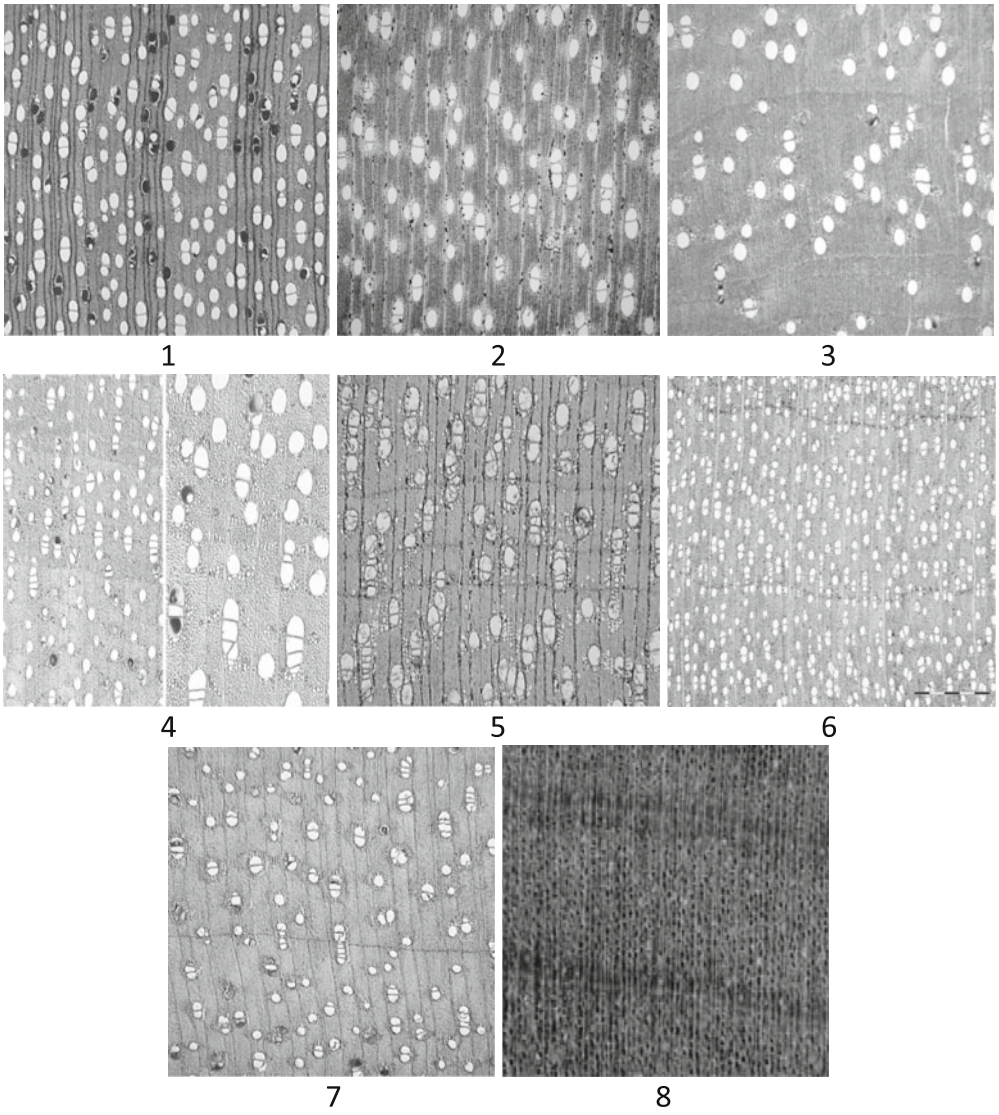


**Fig. 1.** Cross sections (×10):[7] *1*, *Myroxylon balsamum*; *2*, *Nectandra*; *3*, *Dipteryx odorata*; *4*, *Apuleia Leiocarpa*; *5*, *Mezilaurus*; *6*, *Balfourodendron riedelianum*; *7*, *Caesalpinia echinata*; *8*, *Aspidosperma polyneuron*

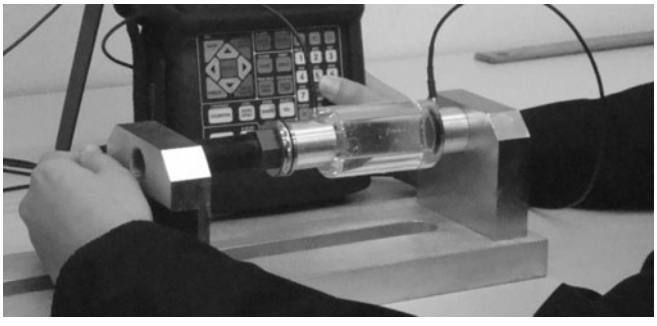

**Fig. 2.** Measuring the time of wave propagation in coupling material to determine the impedance

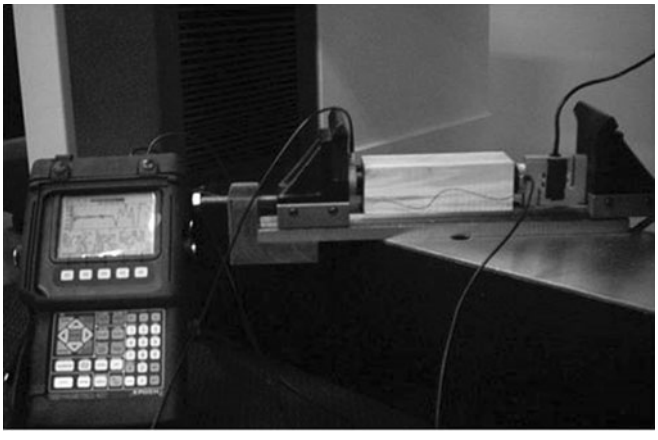

**Fig. 3.** General testing setup

## Results and discussion

Table 2 presents the density, viscosity, and impedance of the coupling media used in this research. Table 3 includes the mean propagation velocity ($V_L$) and attenuation ($A_t$) of longitudinal waves for each species and each coupling medium. The same table shows the species impedances. These values were calculated considering the maximum value of the velocity obtained for each species. For two species (*Balfourodendron riedelianum* and *Caesalpinia*

*echinata*) it was impossible to obtain an adequate result without coupling.

Table 4 presents the mean velocity propagation values of the transverse waves ($V_{LT}$ and $V_{LR}$) and the attenuation ($A_t$) for each species and coupling medium. For transverse waves, it was impossible to obtain the time of wave propagation for all species without coupling.

The average errors of the measurements obtained for five repetitions using the same specimens were 0.4% for longitudinal waves and 0.6% for shear waves. The average coefficient of variation obtained for measurements of the three specimens of each species was 2.8% for the longitudinal waves and 3.7% for the shear waves.

The ratios ($R_V$) of velocities using a coupling medium ($V_{L1}$, $V_{L2}$, $V_{L3}$, $V_{L4}$, $V_{L5}$, $V_{L6}$) and that with no coupling ($V_{L0}$) were 11% for medicinal gel, 11.3% for SWC Panametrics, 10.7% for starch glucose, 8.7% for carboxy methyl cellulose 10%, 13.6% for carboxy methyl cellulose 6%, and 9.1% for maize glucose. These values were superior to those obtained by Bucur[1] for *Pinus* spp., whose data suggest that, without coupling, the velocities were 2.9% inferior when compared to those when 0.03-mm Cellophane sheets were used as the coupling material, 0.4% inferior when compared to those when mineral grease and medical gel were used as the coupling material, and 5% inferior when compared to those when Panametrics SWC gel was used as the coupling material.

The data were also evaluated with Statgraphics Plus 4.1 software using multifactor ANOVA statistics. The confidence level adopted for all statistical analyses was 95%. The contributing factors analyzed were linked to the species (density and anatomical characteristics listed in Table 1), to the coupling (density and viscosity), and also to the ratio between the coupling material impedance and the wood specimen impedance ($R_I$).

For the analysis of longitudinal wave attenuation, we calculated the ratio ($R_{At}$) between attenuation using a coupling medium ($A_{t1}$, $A_{t2}$, $A_{t3}$, $A_{t4}$, $A_{t5}$, $A_{t6}$) and attenuation with no coupling ($A_t$). For transverse waves, the evaluation was made with the absolute values (velocity and attenuation) because it was not possible to measure these parameters without a coupling medium.

For longitudinal waves, there were no statistically significant differences between the mean $R_V$ values of the coupling media or the impedances, but there were statistically significant differences between species. To determine which species were different from others, we applied multiple range tests. The results showed that *Myroxylon balsamum* was different from all the other species. Considering each anatomical parameter (Table 1), although all have a statistically significant influence on the mean $R_V$, it was not possible to observe any particular association with the $R_V$ variation.

The same analysis was carried out for $R_{At}$ and the same results (no significant differences) were obtained for the coupling media and for the impedance. The species had an influence on $R_{At}$, but in this case there were three groups: *Myroxylon balsamum* and *Balfourodendron riedelianum* with smaller $R_{At}$; *Dipteryx odorata*, *Caesalpinia echinata*,

**Table 2.** Density, viscosity, and longitudinal impedance of the coupling media

| Coupling medium | Density (kg/m$^3$) | Viscosity (cP) | Impedance ($10^6$ kg/m$^2$s) |
|---|---|---|---|
| Air (noncoupling medium) | 1.3 | – | 0.00043 |
| Medicinal gel | 990 | 1026 | 1.52 |
| SWC Panametrics gel | >1000[a] | 7546389 | 3.96 |
| Starch glucose | 1650 | 935800 | 4.28 |
| Maize glucose | 1560 | 407912 | 4.09 |
| Carboxy methyl cellulose 6% | 583 | 16796 | 1.45 |
| Carboxy methyl cellulose 10% | 881 | 275941 | 2.18 |

[a] Information provided by the manufacturer

**Table 3.** Propagation velocity values of longitudinal ($V_L$) waves and their attenuation ($A_t$)

| Species | Coupling medium | | | | | | | Impedance ($10^6$ kg/m$^2$s) |
|---|---|---|---|---|---|---|---|---|
| | None | 1 | 2 | 3 | 4 | 5 | 6 | |
| *Myroxylon balsamum* | 4428 | 5140 | 5514 | 5478 | 5428 | 5505 | 5298 | 4.5 |
| | 18.7 | 4.51 | 10.38 | 7.82 | 1.43 | 1.13 | 4.51 | |
| *Nectandra* | 4674 | 4626 | 4983 | 4738 | 5063 | 4911 | 4917 | 3.5 |
| | 52.9 | 9.20 | 4.40 | 4.80 | 8.53 | 3.87 | 5.73 | |
| *Dipteryx odorata* | 4607 | 5319 | 5459 | 5139 | 5165 | 5299 | 4501 | 6.3 |
| | 44.10 | 6.25 | 9.92 | 10.19 | 4.49 | 11.14 | 10.33 | |
| *Apuleia leiocarpa* | 4739 | 4788 | 5183 | 5149 | 4893 | 5183 | 5149 | 4.2 |
| | 53.7 | 10.74 | 9.24 | 11.78 | 6.41 | 9.70 | 11.78 | |
| *Mezilaurus* | 4372 | 4742 | 4866 | 4664 | 4840 | 4884 | 4931 | 4.1 |
| | 49.36 | 6.33 | 13.30 | 3.32 | 11.24 | 5.86 | 10.76 | |
| *Balfourodendron riedelianum* | – | 5125 | 4862 | 5110 | 5140 | 4620 | 4300 | 4.2 |
| | | 9.95 | 9.81 | 10.67 | 10.53 | 11.83 | 10.96 | |
| *Caesalpinia echinata* | – | 3892 | 4240 | 3921 | 4329 | 3767 | 4329 | 3.8 |
| | | 7.87 | 3.73 | 4.83 | 10.35 | 12.84 | 8.00 | |
| *Gallesia integrifolia* | 4037 | 4328 | 4485 | 4393 | 4448 | 4234 | 4374 | 3.1 |
| | 41.5 | 5.64 | 4.23 | 5.49 | 5.79 | 5.94 | 5.71 | |
| *Aspidosperma polyneuron* | 4055 | 4600 | 4605 | 4626 | 4539 | 4376 | 4532 | 3.5 |
| | 46.9 | 12.69 | 14.23 | 9.94 | 13.21 | 13.03 | 10.80 | |

The first line of coupling medium data is $V_L$ in m/s, and the second line is $A_t$ in dB/cm
1, Carboxy methyl cellulose 10%; 2, carboxy methyl cellulose 6%; 3, starch glucose; 4, SWC Panametrics; 5, medicinal gel; 6, maize glucose

**Table 4.** Propagation velocity values of transverse ($V_{LR}$ and $V_{LT}$) waves and their attenuation ($A_t$)

| Species | Coupling medium | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | |
| | LR | LT | LR | LT | LR | LT | LR | LT | LR | LT | LR | LT |
| A | 944 | 867 | 735 | 738 | 969 | 1117 | 1000 | 1074 | 1152 | 1052 | 983 | 1251 |
| | 8.68 | 11.92 | 13.01 | 12.05 | 9.46 | 6.03 | 8.84 | 3.10 | 11.51 | 0.53 | 6.43 | 7.37 |
| B | 965 | 976 | 1096 | 897 | 1070 | 1025 | 1103 | 1056 | 1134 | 1134 | 1077 | 1102 |
| | 11.22 | 11.90 | 12.06 | 9.09 | 7.89 | 9.96 | 1.70 | 1.05 | 6.94 | 9.56 | 8.74 | 8.75 |
| C | 1061 | 980 | 861 | 928 | 1193 | 1064 | 1212 | 1395 | 1410 | 1203 | 1343 | 1063 |
| | 6.89 | 11.34 | 13.0 | 9.76 | 7.81 | 7.22 | 3.13 | 4.13 | 10.82 | 10.91 | 4.60 | 7.74 |
| D | 900 | 1043 | 855 | 736 | 1216 | 1034 | 1154 | 996 | 1256 | 1013 | 1135 | 975 |
| | 11.69 | 10.98 | 14.40 | 14.94 | 5.54 | 3.51 | 2.65 | 0.96 | 5.64 | 6.34 | 7.17 | 6.24 |
| E | 818 | 843 | 837 | 817 | 1088 | 1114 | 1096 | 1034 | 1258 | 1132 | 1088 | 1114 |
| | 14.63 | 9.75 | 15.10 | 13.25 | 6.48 | 4.65 | 4.74 | 2.67 | 11.14 | 5.75 | 6.48 | 4.65 |
| F | 1030 | 936 | 1142 | 945 | 1165 | 1044 | 1206 | 1067 | 1189 | 965 | 1184 | 1049 |
| | 13.5 | 8.54 | 12.07 | 12.88 | 7.86 | 7.03 | 4.77 | 1.63 | 12.09 | 12.09 | 8.73 | 6.55 |
| G | 846 | 915 | 1057 | 947 | 1159 | 1153 | 1436 | 1207 | 1268 | 932 | 1275 | 1277 |
| | 10.46 | 7.34 | 10.16 | 12.73 | 8.17 | 8.95 | 6.85 | 10.08 | 9.61 | 11.67 | 9.34 | 7.37 |
| H | 1801 | 1932 | 1691 | 2053 | 1401 | 1124 | 1312 | 1110 | 1151 | 1302 | 1242 | 1106 |
| | 7.47 | 7.43 | 8.12 | 8.19 | 3.10 | 3.04 | 2.95 | 1.65 | 6.32 | 7.80 | 5.03 | 3.49 |
| I | 970 | 996 | 1097 | 962 | 1019 | 991 | 1132 | 1088 | 1119 | 1083 | 1250 | 1253 |
| | 15.22 | 13.82 | 7.97 | 7.34 | 5.06 | 8.85 | 12.76 | 13.50 | 5.82 | 8.89 | 8.68 | 10.16 |

The first line is V in m/s, and the second line is $A_t$ in dB/cm
A, *Myroxylon balsamum*; B, *Nectandra*; C, *Dipteryx odorata*; D, *Apuleia leiocarpa*; E, *Mezilaurus*; F, *Balfourodendron riedelianum*; G, *Caesalpinia echinata*; H, *Gallesia integrifolia*; I, *Aspidosperma polyneuron*. LR, Longitudinal propagation and radial polarization; LT, Longitudinal propagation and tangential polarization

and *Aspidosperma polyneuron* with medium $R_{At}$; and the remaining four species with larger $R_{At}$. As was the case for $R_V$, although the anatomical characteristics had statistically significant influences on the mean $R_{At}$, it was not possible to observe any particular association with the $R_{At}$ variation. The influence of the coupling medium on transverse wave velocities ($V_{LR}$ and $V_{LT}$) also depended on the species, but again there was no evident association with any anatomical characteristic.

It was observed that, bearing in mind the absolute values, the type of coupling material significantly affected the attenuation for both longitudinal and transverse (LR and LT) wave propagation, independent of the wood species. The wood species had no influence in this case. Table 5 presents the results of multiple range tests for transverse and longitudinal wave attenuation. The order of the coupling material is arranged from smallest to largest attenuation. Therefore, for longitudinal and transverse waves, the SWC Panametrics gel was the coupling with the smallest attenuation, while the 6% carboxy methyl cellulose had the largest attenuation values.

From Table 5 it is also possible to see for which groups the attenuation values were statistically equivalent. For transverse waves, the SWC Panametrics gel exhibited attenuation values different from all other coupling media. For longitudinal waves, the attenuation for SWC Panametrics gel, starch, and maize glucose were statistically equivalent.

Observing the densities and viscosities of the coupling media (Table 2), it was confirmed that, in general, those that have greater values also have lower attenuation values. The exception was the medicinal gel, which had lower attenuation values than 6% carboxy methyl cellulose, even though it had a lower viscosity.

**Table 5.** Multiple range tests for transverse (LR and LT directions) and longitudinal wave attenuation

| Coupling medium | Transverse waves | | Longitudinal waves |
|---|---|---|---|
| | LR | LT | |
| SWC Panametrics | a | a | a |
| Starch glucose | b | b | a |
| Maize glucose | b | b | a |
| Medicinal gel | c | c | b |
| Carboxy methyl cellulose 10% | c | c | b |
| Carboxy methyl cellulose 6% | d | d | c |

Within each column, the same letters form a group of mean wave attenuation values within which there are no statistically significant differences

## Conclusions

For longitudinal and transverse waves, the velocity is very dependent on the species and is not dependent on the coupling media. Although anatomical properties have statistically significant influences on velocity, it was not possible to link this influence with any specific anatomical characteristics. For longitudinal and transversal waves, the coupling media have statistically significant influences on the attenuation, independent of the species.

The couplings with superior densities presented superior attenuation reduction effects for transverse waves. The same was true for viscosity, with the exception of the medicinal gel that had a superior effect than the carboxy methyl cellulose, even though it had lower viscosity.

This study was conducted with coupling media commonly used in nondestructive testing of wood by the contact

method. The results indicate that tests with longitudinal waves could be performed, with the same results, with any of the coupling media tested. However, for transverse waves there must be concern with using more dense and viscous coupling media to obtain lower attenuation. In further studies, it will be important to analyze the influence of the same types of coupling media on velocities and attenuations in the radial and tangential directions as these are more important in field inspections. Furthermore it is necessary to compare the effect of coupling media between hardwoods and softwoods and also between diffuse wood and porous wood within hardwoods.

## References


1. Bucur V (2006) Acoustics of wood. Springer-Verlag, Berlin, pp 80–82
2. Lasaygues P, Franceschini E, Debieu E, Brancheriau L (2007) Non-destructive diagnosis of the integrity of green wood using ultrasonic computed tomography. In: Proceedings of the International Congress on Ultrasonics. Vienna, April 9–12, Paper 1547
3. Gonçalves R, Trinca AJ (2007) Variation of the velocity and attenuation as a function of the pressure on the transducers. In: Proceedings of the 15th International Nondestructive Testing of Wood Symposium. Duluth, September 10–12, p 263
4. Bucur V, Archer RR (1984) Elastic constants for wood by an ultrasonic method. Wood Sci Technol 18:255–265
5. Kamioka H, Kataoka A (1982) The measurement error factor of velocity in wood. Mokuzai Gakkaishi 28:274–283.
6. Souza MH, Magliano MM, Camargos JAA (2002) Brazilian tropical woods. Brazilian Institute of Environment and Renewable Natural Resources, IBAMA, Brasilia, D.F., p 152
7. Richter HG, Dallwitz MJ (2000 onwards) Commercial timbers: descriptions, illustrations, identification, and information retrieval. Version: June 25, 2009. http://delta-intkey.com/wood/index.htm. Accessed July 20, 2010