EFFECT OF TEMPERATURE ON ACOUSTIC EVALUATION OF STANDING TREES AND LOGS: PART 1—LABORATORY INVESTIGATION

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Abstract. The goals of this study were to investigate the effect of environment temperature on acoustic velocity of standing trees and green logs and to develop workable models for compensating temperature differences as acoustic measurements are performed in different climates and seasons. The objective of Part 1 was to investigate interactive effects of temperature and moisture state of wood on acoustic properties in a laboratory-controlled environment. Small clear specimens (25.4 × 25.4 × 407 mm) obtained from a freshly cut red pine (*Pinus resinosa*) log were conditioned to four moisture content levels: green (fresh-cut condition), 24%, 12%, and 0%. All specimens were acoustically tested using an ultrasonic device across a temperature range of −40 to 35°C. Results indicate that wood temperature had a significant effect on acoustic velocity in frozen wood. Below the freezing point, acoustic velocity increased as wood temperature decreased. When wood temperature was well above freezing, velocity decreased linearly at a slow rate as wood temperature increased. We found that wood moisture content had a significant compounding effect on velocity–temperature relationships in the freezing zone (−2.5 to 2.5°C). Temperature effect was much more significant in green wood than in dry wood. In green wood, both velocity and peak energy changed abruptly around the freezing point because of the phase transformation of free water in the cell lumens.

Keywords: Acoustic velocity, peak energy, logs, moisture content, temperature, trees.

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INTRODUCTION

Acoustic wave techniques have been used to nondestructively evaluate the wood quality of logs and trees in terms of prediction of wood mechanical properties and growth characteristics (Wang et al 2001, 2007a, b; Bucur 2005). Recently, considerable efforts have been made to establish a practical, efficient wood grading system and develop more reliable testing equipment for field applications (Carter et al 2005a, 2005b). As acoustic measurements are increasingly being conducted on trees and logs in forests and log yards, the effect of environmental conditions on acoustic measurements has received considerable attention (Bächle and Walker 2006; Wang et al 2008; Gao et al 2009; Wang 2011; Xu and Wang 2011). One key factor that must be considered is field operating temperature and its implication in acoustic data interpretation.

Effects of temperature and moisture content on mechanical properties of wood have been thoroughly investigated, and models for adjusting modulus of elasticity for changes in wood temperature have been developed (Mishiro and Asano 1984a, 1984b; Green et al 1999; Green and Evans 2008). However, research on the effects of temperature and moisture state on acoustic properties of wood is very limited. Researchers lack understanding of how acoustic properties of wood respond to temperature changes when wood materials of different moisture conditions are subjected to subzero temperature condition. This information is critical to increased field use of acoustic tools in assessing wood quality in different geographical locations or different climates.

The goals of this study were to investigate the effect of environment temperature on acoustic measurements on standing trees and felled logs and develop workable models for compensating temperature differences as acoustic measurements are performed in different climates and seasons. The overall study was conducted in two phases: Phase 1—laboratory investigation and Phase 2—field investigation. Laboratory investigation was carried out on small clear specimens in a well-controlled environment with a focus on investigating interactive effects of wood temperature and moisture state on acoustic properties of wood as wood is subjected to a wide range of temperature conditions. Field investigation was built on the basis of laboratory investigation and expanded acoustic experiments to standing trees and green logs in a forest setting. It focused on investigating the real response of acoustic velocity of standing trees and logs to seasonal temperature changes and developing analytical models for adjusting tree/log velocity data to account for temperature differences when acoustic measurements are performed in various climates and seasons.

This study reports the results and findings from Phase 1: laboratory investigation. The specific objectives were the following: 1) investigate how acoustic velocity and peak energy of the acoustic signal response to wood temperature changes on small clear wood samples, especially around the freezing point; 2) investigate the interactive effects of wood temperature and moisture state on acoustic velocity in wood; and 3) develop mathematical models to quantify the relationships between acoustic velocity and wood temperature.

BACKGROUND

Because of the hygroscopic nature of wood, a large amount of water is present in trees and freshly cut logs. Thus, the effects of temperature on acoustic properties of trees and green logs could be considered from two important aspects: 1) the immediate effect of temperature on mechanical properties, hence wave velocity of wood; and 2) the water in wood cells undergoes phase changes, thus affecting the microstructure of wood cells and changing both mechanical and acoustic properties of wood.

In an earlier study, James (1961) studied the effect of temperature and moisture content on internal friction and speed of sound in Douglas-fir (*Pseudotsuga menziesii*) bars below the FSP. The speed of sound was measured at moisture content levels of about 2, 4, 7, 13, 16, 24, and 27% and at a temperature increment of about 22°C. He reported that the speed of sound and the Young's modulus of Douglas-fir decreased with increasing temperature and moisture content between −18 and 93°C. The experimental data showed perfect linear relationships between speed of sound and temperature across the entire temperature range for specimens less than 17% MC and near-linear relationships for specimens with moisture contents of 24 and 27%. When comparing the speed of sound measured at −18°C (below freezing) and 3°C (above freezing), James' data showed an average difference of 91 m/s, or a change rate of 4.3 m/s per °C. James recognized that the data showing the effect of temperature and moisture content on the speed of sound and Young's modulus could be distorted by differences among the average basic properties of the different groups of specimens.

Sandoz (1993) measured the speed of ultrasound on small spruce and fir specimens at a temperature range of −20 to 60°C. The specimens were conditioned to four different moisture content levels: 0%, 8%, 12%, and greater than FSP. He reported a linear relationship between ultrasound speed and wood temperature. Ultrasound speed of spruce and fir specimens continuously decreased when wood temperature increased. His results also indicated a possible influence of moisture content on speed–temperature relationships. Sandoz did not observe any discontinuities around 0°C.

Kang and Booker (2002) investigated the effects of temperature and moisture content on stress wave velocity of a radiata pine (*Pinus radiata*) sapwood board ranging from green to 10% MC and from room temperature (25°C) to 75°C. In the experiments, they noticed a temperature effect on the portable ultrasonic nondestructive digital indicating tester (PUNDIT) transducers that resulted in incorrect PUNDIT readouts. A calibration test was therefore conducted on the metal PUNDIT calibration bar to determine a temperature correction factor. The stress wave velocity of the radiata pine board, after the temperature correction for its effect on the transducer, remained relatively constant in the temperature range tested. This velocity trend appears to be very different from what James (1961) and Sandoz (1993) reported.

van Dyk and Rice (2005) carried out a laboratory experiment to investigate if ultrasonic wave velocity can be used as a measure of moisture content in frozen and unfrozen spruce lumber. Ultrasonic wave velocities of the spruce lumber samples were measured in the radial direction and at five different moisture content levels. They found that wave velocity in frozen wood was consistent and about 5% greater than in unfrozen wood. Average wave velocity through the frozen green lumber was 2173 m/s, and in the unfrozen green lumber, it was 2077 m/s. The velocity difference was found statistically significant. van Dyk and Rice further investigated the effect of temperature on the velocity of an ultrasonic wave propagating through dry wood and a reference material (Plexiglas®; Altuglas International, Bristol, PA) sample in a temperature range of −6.7 to 23.9°C. They reported an inverse linear relationship between wave velocity and temperature for both dry wood and Plexiglas. The percentage change in wave velocity caused by temperature across the range tested was about 11% for dry wood and about 17% for Plexiglas. They speculated that the differing change rates may have been caused by differences in microstructure or anisotropy of the materials. In this study, no attempts were made to test partially frozen wood. However, the authors commented that partially frozen conditions could significantly affect wave velocity.

Wang and Ross (2003) conducted a pilot study to investigate the effect of freezing temperatures on stress wave velocity of full-sized green lumber. Fifty green ponderosa pine (*Pinus ponderosa*) boards were first tested at the laboratory at a room temperature of 15.6°C. The boards were then stored at a commercial cold storage room for 1 month and tested again on-site at −18.3°C. The result showed a significant increase in stress wave velocity as the board temperature decreased from room temperature to a frozen state. Wave velocity of the green ponderosa pine boards at −18.3°C increased by an average of 49% compared with that measured at room temperature. They also reported a strong linear relationship between wave velocity measured at room temperature and that measured in the frozen state ($R^2 = 0.82$) and suggested that an appropriate adjustment can be made to wave velocity to compensate for the temperature effect when stress wave tests are performed on frozen wood in freezing temperature conditions.

Most recently, Chan et al (2010) investigated the effects of temperature and moisture content on acoustic velocity and dynamic modulus of elasticity of radiata pine sapwood boards at −71 to 58°C and 17-159% MC. They noticed a marked difference in velocity patterns between temperatures below and above freezing. Acoustic velocity was found to decrease linearly with increasing temperature but with an abrupt discontinuity at the freezing point for wood above the FSP. They reported that the decreases in acoustic velocity with increasing temperature below freezing were twice the decreases observed above freezing for wood above the FSP.

Previous studies on small wood samples and structural lumber suggest an immediate effect of temperature on acoustic properties of wood. The observed effect of temperature on acoustic velocity of wood below FSP is in agreement with generally accepted information on this subject, but conflicting results were reported for wood above FSP when wood temperature transitioned from above freezing to below freezing. Information on effect of environment temperature change on acoustic velocity of standing trees and green logs is lacking.

MATERIALS AND METHODS

Material Preparation

Three 1-m-long log sections were obtained from a 45-yr-old red pine (*Pinus resinosa*) tree that was cut from a plantation stand located in Arena, WI. The diameter of the log sections ranged from 19 to 24 cm. Ends of the log sections were immediately coated with Anchor-Seal (end sealer for logs and lumber; Anchor-Seal, Inc., Gloucester, MA) to maintain moisture content after they were cut from the tree stem. Each log section was then cut into 25.4- × 25.4- × 407-mm small clear wood samples in the laboratory. These small samples were marked by wood types (sapwood or heartwood) during the cutting process. Samples cut from the same log section were numbered as one group, resulting in a total of three groups of small clear wood samples. The wood samples were numbered from 1 to 30 in Group I, 31 to 60 in Group II, and 61 to 90 in Group III. To determine initial wood moisture content, a 106-mm-long moisture block was cut from the end of each sample. Moisture content was subsequently determined according to the primary oven-drying method outlined in ASTM (2007). Samples of Group I were wrapped individually using thin plastic films and moved to a cold room (–18°C) to maintain their green condition by freezing. Groups II and III were put into two conditioning rooms that were set with an equilibrium moisture content (EMC) of 24%, which is the FSP of red pine (Bodig and Jayne 1982), and 12%, respectively. After target equilibrium moisture contents were reached, samples of Groups II and III were wrapped individually and moved to the cold room waiting for acoustic measurements.

Sample Selection

We conducted initial ultrasonic measurements on all three groups of samples with varying temperature conditions. The refrigerator we used to cool the samples caused great temperature fluctuation during the cooling process, and target temperatures were difficult to reach. The other drawback was that the temperature of the wood samples changed fast during the testing process (after being removed from the refrigerator), which caused great errors on temperature measurement. To obtain more accurate and reliable experimental data, we subsequently developed a special testing system with much better control of wood temperatures. The ultrasonic measurements using the new test system were much more accurate than the initial measurements but were also time-consuming. Therefore, for the formal data collection, we only selected three sapwood samples from each group. Three additional sapwood samples were selected from the 12% EMC group and oven-dried to 0% and numbered as Group IV. The selected samples were renumbered from 1 to 12 and placed in plastic bags by groups.

Instrumentation

Figure 1 shows the testing system we developed to measure acoustic properties of the red pine wood samples under different temperature conditions. A sealed foam box was constructed and used as an environmental chamber throughout the testing process. A wrapped wood sample was placed in the lower chamber and set between two ultrasonic probes with two wood block supports. Dry ice or a hot water glass was placed in the upper chamber as a cooling or heating source during testing. Temperature of the wood sample was controlled by regulating air circulation between the upper chamber and the lower chamber using two small electric fans. Two thermocouples (TCs) were inserted into the wood sample to monitor wood temperatures with TC No. 1 being at the midspan and center depth and TC No. 2 at the quarter span and quarter depth. A third TC was placed in the lower chamber to measure air temperature. During the testing process, a microprocessor thermometer (Omega Model HH23; OMEGA Engineering, Inc., Stamford, CT) was used to monitor wood temperatures (TC Nos. 1 and 2) and air temperature in the lower chamber (TC No. 3). A temperature controller (Chromalox, Pittsburgh, PA) was used to control air circulation and reach the desired wood temperatures.

A Sylvatest Duo (CBS-CBT, Les Ecorces, France) unit was used to measure ultrasonic velocity and peak energy in the selected wood samples. The transmitter probe and the receiver probe were positioned at the center of the sample ends. A constant pressure of 207 kPa was applied to the probes during each measurement cycle through compressed air control. This probe–wood contact pressure was determined based on a series of repeatability tests with different pressures and proved to enable good coupling between the red pine samples and the probes.

Measurement Procedures

Dimension and weight of each selected sample were measured before it was put into the testing chamber. Then each sample was placed in the

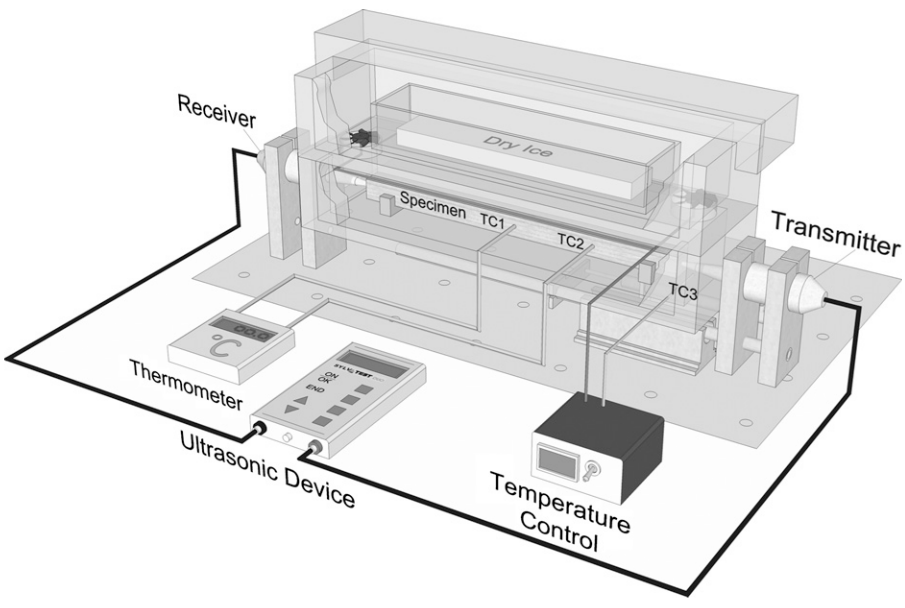

Figure 1. Ultrasonic testing system for measuring velocity and peak energy of red pine at various temperatures.

lower chamber with the thin plastic film on and only two ends exposed to ensure direct contact with the probes. The testing process was started by placing dry ice into the upper chamber. The wood sample in the lower chamber was cooled to below −40°C by blowing air through the dry ice and guiding it into the lower chamber. Ultrasonic measurement of each wood sample began with wood temperature at −40°C and was repeated at 5°C increment as wood temperature gradually increased to 35°C, except when wood temperature was close to the freezing point (0°C). Then ultrasonic measurement was performed at a 2-3°C increment. When chamber temperature reached room temperature, a glass of hot water was placed in the upper chamber to help raise wood temperature to about 35°C. Through the testing cycle, the fans were manually controlled to obtain targeted wood temperatures with a great degree of uniformity, which was indicated by the close readings of three TCs. After the testing process was completed, we weighed each specimen again. Moisture decrease of the wood samples during the test was found minimal (1.1-3.1% for Group I, 0.7-1.4% for Group II, 0.1-2.1% for Group III, and 0.2% for Group IV).

At each targeted wood temperature, the wood sample was tested five consecutive times. An average ultrasound propagation time (UPT) and an average peak energy of the ultrasound signals were recorded. Ultrasonic velocity of each wood sample was calculated based on thickness of the sample (t) and average UPT value:

$$V = \frac{t}{\mathrm{UPT}}\,(\mathrm{m/s}) \quad (1)$$

The peak energy recorded was the peak voltage (mV) of the ultrasound signals detected by the receiver probe, and it represents the relative energy loss (attenuation) or propagation efficiency of the ultrasound waves traveling through the sample.

Data Analysis

To quantify the effects of wood temperature on ultrasonic velocity in the sampled red pine, we developed mathematical regression models relating measured velocity values to the wood temperature. In this process, we treated each moisture content level individually. Each sample in Group I was considered an individual moisture content level because moisture content values among them were very different. Moisture contents of the samples for Groups II, III, and IV were very uniform within each group, thus each of these groups was treated as an individual moisture content level.

Based on the observation of velocity transition around the freezing point in Group I (green samples), we used the following three segmented linear regression models to describe the velocity–temperature relationships for green wood across the entire temperature range (−40 to 35°C):

$$\begin{aligned} V_1 &= k_1T + h_1 \quad -40^\circ C \le T \le -2.5^\circ C \\ V_2 &= k_2T + h_2 \quad -2.5^\circ C \le T \le 2.5^\circ C \\ V_3 &= k_3T + h_3 \quad 2.5^\circ C \le T \le 35^\circ C \end{aligned} \quad (2)$$

The selection of temperature breakpoints was based on our experimental observations that the velocity–temperature trend between −2.5 and 2.5°C showed distinct differences from the trends below −2.5°C and above 2.5°C. With respect to the dramatic shift in velocity observed in the freezing zone, we permitted discontinuities at the breaking points in the segmented regression models.

Although no apparent velocity discontinuity was observed for dry wood samples, we used the same segmented regressions for three moisture content levels represented by Groups II, III, and IV to examine how the velocity transition in the freezing zone was affected by moisture content of wood.

RESULTS AND DISCUSSION

Acoustic Properties of Red Pine at −40 and 35°C

Table 1 summarizes basic information about the red pine samples used in this study. Moisture content of the green samples in Group I ranged

Table 1. The dimension and physical properties of the red pine samples at the time of ultrasonic testing.

Group no.	MC condition	Sample no.	MC (%)	Dimension (mm) Height	Width	Length	Weight(g)	Density (kg/m^3)	Oven-dry weight[a](g)	Ring count (no./mm)
I	Green	1	118.3	25.38	25.91	407.02	231.08	863.35	105.85	2.9
		2	91.4	25.34	25.67	407.12	195.62	738.68	102.19	2.6
		3	78.6	25.74	25.16	407.10	191.99	728.21	107.47	3.6
II	24%	4	24.9	25.14	25.93	407.00	138.83	523.26	111.19	1.9
		5	23.7	25.12	23.15	407.41	139.53	477.88	91.50	2.6
		6	25.4	24.37	27.47	407.19	113.22	511.87	111.25	2.0
III	12%	7	11.2	24.71	25.93	407.10	131.8	505.39	118.54	2.0
		8	12.0	25.12	25.72	407.20	127.91	486.29	114.16	2.1
		9	15.2	25.44	29.38	407.00	140.22	461.11	121.75	1.6
IV	0%	10	0.1	23.34	24.94	407.20	105.9	446.87	105.83	1.7
		11	0.2	25.36	23.28	406.90	103.17	429.47	102.94	2.3
		12	0.3	24.18	24.13	407.14	108.32	456.08	107.95	1.9

[a] Oven-dry weights of wood samples were obtained after completion of acoustic testing.
MC, moisture content.

from 78.5 to 118.3%. Moisture content of other groups was relatively uniform. Average EMC of Groups II, III, and IV was 24.7, 12.8, and 0.2% with a standard deviation of 0.87, 2.12, and 0.10%, respectively.

Table 2 shows average ultrasonic velocity and peak energy of each group at two different temperature conditions, −40 and 35°C, as well as percentage changes in velocity and peak energy from −40 to 35°C. We found a large difference in both velocity and peak energy between these two temperatures. Velocity and peak energy were high at −40°C and low at 35°C. When wood temperature increased from −40 to 35°C, average velocity and average peak energy decreased in all four groups but at different rates for different moisture content groups. Percentage change in velocity was −14.4, −7.8, −7.3, and −3.5% for Groups I, II, III, and IV, respectively. Percentage change in peak energy was −55.4, −34.2, −26.7, and −13.6% for Groups I, II, III, and IV, respectively, which was much greater than that in velocity. The difference of percentage change in both velocity and peak energy among the four groups of samples suggests that moisture content of wood plays an important role in examining temperature effect on acoustic properties of wood. The influence of temperature on acoustic properties was magnified when moisture content of wood increased.

Response of Ultrasonic Velocity and Peak Energy to Wood Temperature Change

Scatterplots of ultrasonic velocity and wood temperature for all four moisture groups are illustrated in Fig 2. As shown in the plots of Group II, III, and IV, the overall trend of changes in velocity was similar for all dry wood samples; ie velocity decreased gradually with increasing temperature and vice versa. The velocity–temperature trend flattened progressively as moisture content of wood changed from 24 to 0%. However, in Group I (green wood), we observed a different velocity–temperature trend; ie velocity changed abruptly around the freezing point (0°C). Because of this unusual transition, velocity–temperature relations

Table 2. Comparison of velocity and peak energy of the red pine samples measured at −40 and 35°C.

Group	MC (%)	Ultrasonic velocity (m/s)			Peak energy (mV)		
		−40°C	35°C	Percentage change	−40°C	35°C	Percentage change
I	96.1	4747	4068	−14.4	453	202	−55.4
II	24.7	5789	5338	−7.8	377	248	−34.2
III	12.8	6101	5655	−7.3	408	299	−26.7
IV	0.2	6302	6081	−3.5	382	330	−13.6

MC, moisture content.

can be best characterized based on three temperature zones: 1) below freezing point, ultrasonic velocity decreased as wood temperature increased; 2) around the freezing point (−2.5 to 2.5°C), velocity changed abruptly as wood temperature changed; and 3) above freezing temperature, ultrasonic velocity decreased slightly as wood temperature increased.

The dramatic shift in velocity around the freezing point is attributable to the phase transformation of free water in wood cells. Velocity changes observed between −2.5 to 2.5°C suggest that the phase transformation of free water within cell lumens did not happen instantly because temperature of the wood samples was not exactly uniform. These findings agree with Sellevold et al (1975), in which a similar transition was found in the plot of modulus of elasticity–temperature relationships for fully saturated beams. Sellevold et al (1975) described this as a capillary transition and attributed the large modulus change near 0°C to ice formation in the cell lumens. In physics, ice formation and

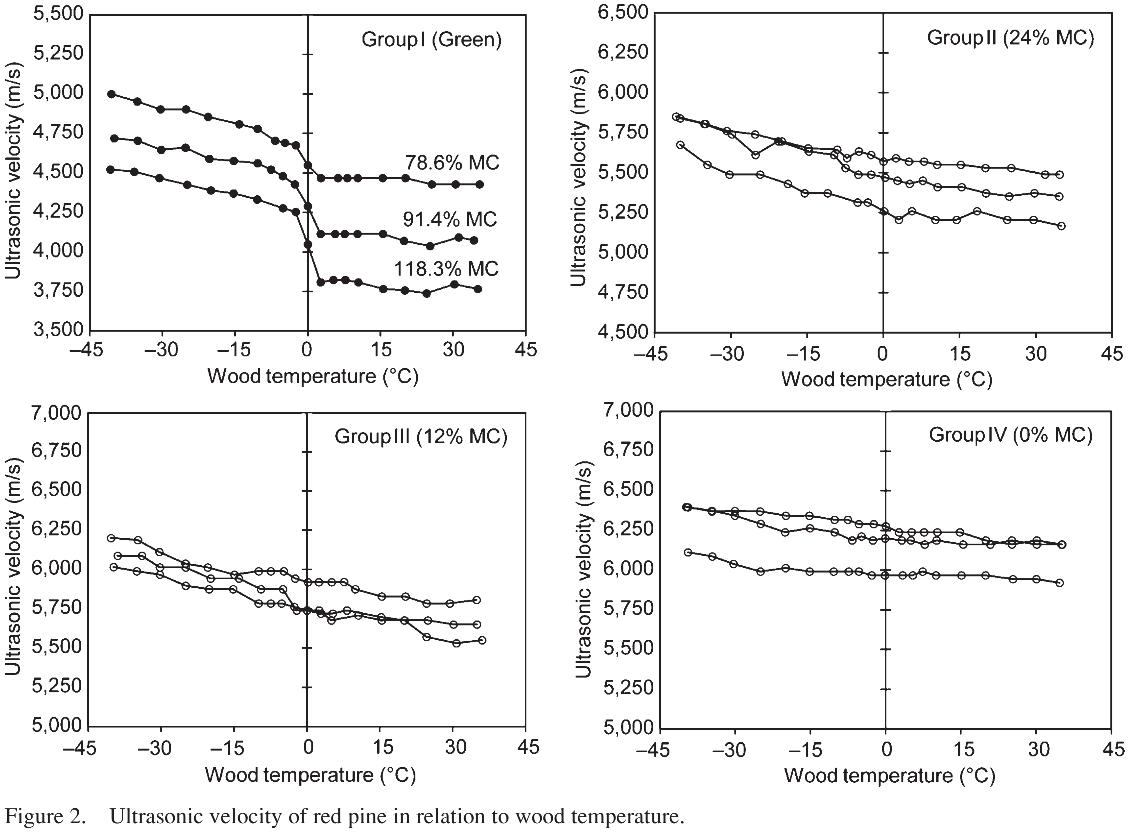

Figure 2. Ultrasonic velocity of red pine in relation to wood temperature.

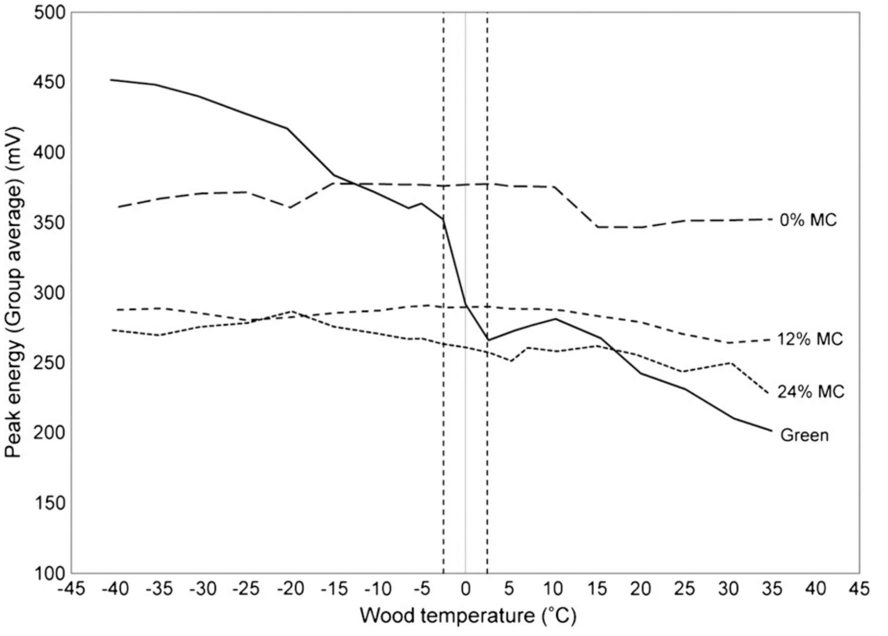

Figure 3. Peak energy of red pine in relation to wood temperature.

its percentage of occupation in wood cells contribute to variation in velocity changes for wood at different moisture content levels and around the freezing point.

Figure 3 shows the response of peak energy of red pine to wood temperature changes. Peak energy of the oven-dry wood samples (Group IV) and 12% EMC wood samples (Group III) stayed relatively flat as wood temperature increased. As wood moisture content increased to 24% EMC (Group II), peak energy began to show a decreasing trend with increasing wood temperature. This decreasing trend became more clear and significant in green wood samples (Group I). Similar to the velocity transition in green wood, peak energy also exhibited an abrupt change around the freezing point (−2.5 to 2.5°C). Apparently, peak energy was affected by wood temperature changes in the same way as ultrasonic velocity.

Relationships between Ultrasonic Velocity and Wood Temperature

Figure 4 shows the relationships between ultrasonic velocity of red pine and wood temperature through three segmented linear regression lines. The regression coefficients (k, h) and the coefficients of determination (R^2) of each segment are summarized in Table 3.

The slope of the segmented linear regression lines in Fig 4, as represented by regression coefficient k, indicates the magnitude of the temperature effect on velocity. For the convenience of analysis, we defined the regression coefficient k as a temperature impact factor f_T. Figure 5 shows the plot of the temperature impact factor in relation to moisture content for three different temperature zones, which highlights the differences of temperature impact at different temperature zones and different moisture content levels. Around the freezing point (−2.5 to 2.5°C), the temperature impact factor (f_{T2}) increased exponentially with increasing moisture content, whereas above 2.5°C and below −2.5°C, temperature impact factors (f_{T1} and f_{T3}) were not affected much by moisture content level. This has a significant implication to the field acoustic measurements on trees and green logs. The results indicate that tree or log acoustic velocities measured in ambient conditions can be adjusted

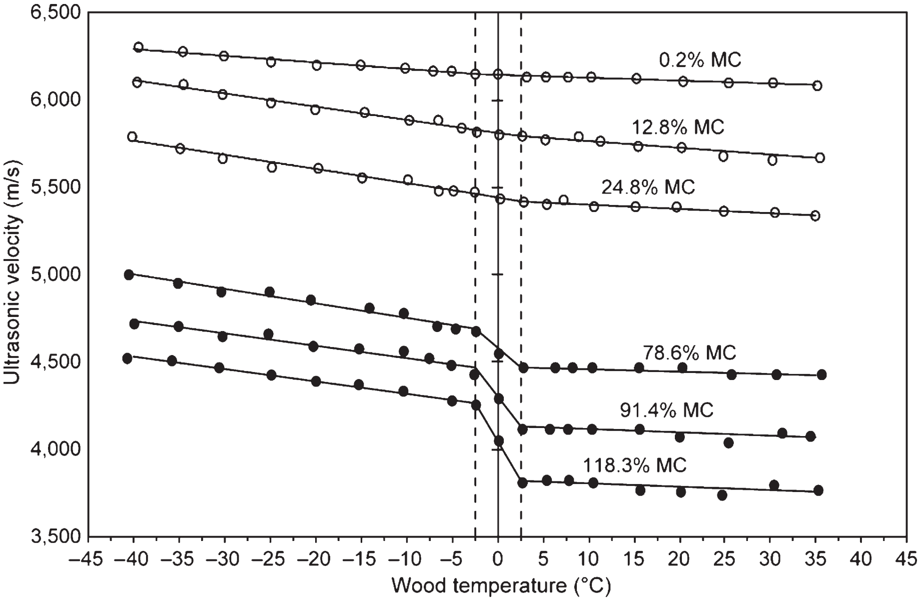

Figure 4. Plot of ultrasonic velocity of red pine as a function of wood temperature at different moisture content (MC) levels.

to a standard temperature if measurements are conducted well above or well below the freezing point. However, measurements conducted around the freezing point could cause complications in making temperature adjustments because acoustic properties can vary widely near the freezing point, causing a large degree of uncertainty. A small error in measured temperature can lead to a relatively large error in velocity values when adjusted to a standard temperature.

CONCLUSIONS

This study investigated the effects of wood temperature and moisture state on acoustic properties of red pine in laboratory-controlled conditions. Based on the experimental data and analysis, we concluded the following:

Wood temperature had a significant effect on acoustic velocity in frozen wood. Below the freezing point, acoustic velocity continuously increased as wood temperature decreased.

When wood temperature was well above freezing, velocity decreased linearly at a slow rate as wood temperature increased; this increase might have been slightly larger for dry wood than for green wood.

In green wood, both velocity and peak energy changed abruptly around the freezing point (−2.5 to 2.5°C) because of the phase transformation of free water in the cell lumens.

Table 3. Linear regression coefficients of experimental models at different moisture content (MC).

	$f_i(T) = k_iT + h_i$						R^2		
MC (%)	k_1	k_2	k_3	h_1	h_2	h_3	−40 to −2.5°C	−2.5 to 2.5°C	2.5 to 35°C
0.2	−3.87	−3.17	−1.61	6137	6143	6141	0.97	0.81	0.95
12.8	−7.44	−4.42	−4.49	5810	5803	5807	0.98	0.96	0.92
24.8	−8.02	−10.62	−2.39	5441	5442	5426	0.97	0.97	0.89
78.6	−8.36	−39.67	−1.52	4667	4566	4481	0.97	0.98	0.76
91.4	−7.03	−59.01	−1.70	4454	4276	4123	0.94	0.99	0.49
118.3	−7.03	−87.24	−1.84	4249	4040	3819	0.99	0.99	0.45

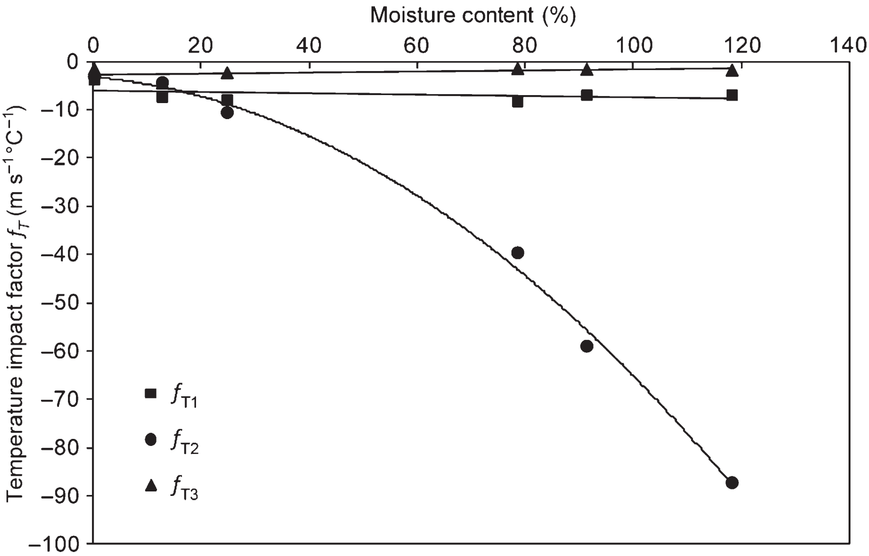

Figure 5. Linear regression coefficient in relation to moisture content of wood.

This phase transformation did not happen instantly because temperature of the wood samples was not exactly uniform.

Wood moisture content had a significant compounding effect on the velocity–temperature relationships between −2.5 and 2.5°C. Temperature effect was much more significant in green wood than in dry wood around the freezing point. The velocity–temperature trend flattened progressively as moisture content of wood changed from green condition to 0%.

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