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Modeling Temperature and Moisture State Effects on Acoustic Velocity in Wood

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Abstract Previous research has proved the concept of acoustic wave propagation methods for evaluating wood quality of trees and logs during forest operations. As commercial acoustic equipment is implemented in field for various purposes, one has to consider the influence of operating temperature on acoustic velocity — a key parameter for wood property prediction. Our field study on acoustic monitoring of standing trees and logs over one-year cycle showed a significant change in acoustic velocity as seasonal temperature changed. The purpose of this study is to further investigate the effects of temperature and moisture state of wood on acoustic properties in a laboratory-controlled environment. Small clear specimens (25.4 x25.4 x407 mm) obtained from a freshly-cut red pine (*Pinus resinosa*) log were conditioned to four moisture content (MC) levels: green (fresh-cut condition), 24% MC, 12% MC and 0% MC. All specimens were acoustically tested using an ultrasonic device over a temperature range of -45 °C and 35 °C. The results indicated 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 in green wood was not significantly affected by temperature change. It was found that wood moisture content had a significant compounding effect on the velocity-temperature relationships. Temperature effect was much more significant in green wood than in dry wood. In green wood, both velocity and energy loss changed abruptly around the freezing point (-2.5°C ~ 2.5°C) due to the phase transformation of free water in the cell lumens.

Keywords Acoustic velocity, energy loss, logs, moisture content, temperature, trees

1. INTRODUCTION

Acoustic wave techniques have been used to nondestructively evaluating the wood quality of logs and trees in terms of prediction of wood mechanical properties and growth characteristics (Wang et al. 2001, 2007a). In recent years, considerable efforts have been made to establish a practical yet efficient wood grading system and develop more reliable testing equipment for field applications (Wang et al. 2004; Carter el al. 2005). As acoustic tests are increasingly being conducted on trees and logs in

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forests and log yards, the effect of environmental conditions on acoustic measurements has received considerable attention. One of the key factors that must be considered is field operating temperature and its implication to acoustic data interpretation (Gao et al. 2010, 2011).

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

Our field study on acoustic monitoring of standing trees and logs over one-year cycle showed a significant change on acoustic properties of wood as seasonal temperature changed (Gao et al. 2010, 2011). A dramatic shift in acoustic velocity was observed when the ambient temperature changed through the freezing point (both from above-zero to sub-zero and from sub-zero to above-zero). The goal of this laboratory study is to further investigate the interactive influence of temperature and moisture state on the acoustic properties of wood as wood is subject to a wide range of temperature conditions. The specific objectives are 1) investigate how acoustic velocity and energy loss response to wood temperature changes in small clear wood samples; 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.

2. MATERIALS AND METHODS

2.1 Material preparation

Three 1-m long log sections were obtained from a 45-year old red pine (*Pinus resinosa*) tree that was cut at a plantation stand located in Arena, Wisconsin, USA. The diameter of the log sections ranged from 19 to 24 cm. The ends of the log sections were immediately coated with the Anchorseal (end sealer for logs and lumber) to maintain moisture content after they were cut from the tree stem. Each log section was then cut into 25.4 x 25.4 x 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 3 groups of small clear wood samples. The wood samples were numbered from No. 1 to No. 30 within group I, from No. 31 to No. 60 within group II, and from No. 61 to No. 90 within group **III.** To determine the initial wood moisture content (MC) , a 10.6-cm long moisture block was cut from the end of each sample. The MC was subsequently determined according to the primary oven-drying method outlined in ASTM standard D4442-92 (ASTM 2003). The 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. Group II and group III were put into two conditioning rooms that were set with an equilibrium moisture content (EMC) of 24%, which is the fiber saturation point (FSP) of red pine, and 12% respectively. After the target EMCs were reached, the samples of group **II** and III were wrapped individually and moved to the cold room waiting for acoustic measurements.

2.2 Sample selection

We conducted initial ultrasonic measurements on all 3 groups of samples with varying temperature conditions. The refrigerator we used to cool the samples was found to cause a great temperature fluctuation during the cooling process. The wood temperature data obtained during this initial measurement was not satisfactory. To obtain more accurate and reliable experimental data, we subsequently developed a special testing system that has a much better control of wood temperatures. The ultrasonic measurements using the new test system were much more accurate than the initial measurements but also time consuming. Therefore, for the formal data collection, we only selected 3 sapwood samples from each group. Additional 3 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 No. 1 to No. 12 and placed in plastic bags by groups.

2.3 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 hot water glass was placed in the upper chamber as a cooling or heating source during testing. The 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 (TC) were inserted into the wood sample to monitor the wood temperatures, with TC No. 1 being at the mid-span and center depth and TC No.2 at the quarter span and quarter depth. Thermocouple No. 3 was placed in the lower chamber to measure the air temperature. During the testing process, a microprocessor thermometer (Omega Model HH23) was used to monitor the wood temperatures (TC No.1 and No.2) and the air temperature in the lower chamber (TC No.3). A temperature controller (Chromalox) was used to control the air circulation and reach the desired wood temperatures.

A Sylvatest Duo unit was used to measure the ultrasonic velocity and energy loss 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 (30 psi) was applied to the probes during each measurement cycle through a compressed air control. This probe-wood contact pressure was determined based on a series of repeatability tests with different pressures and proved to be appropriate for the red pine samples we used.

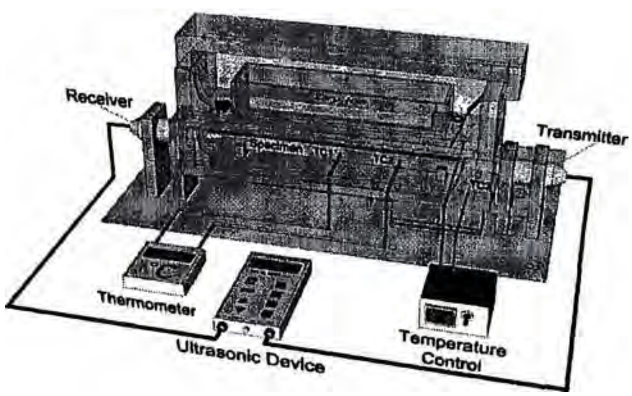

Figure 1– Schematic of the ultrasonic testing system for measuring velocity and energy loss of red pine at variuos temperature conditions.

2.4 Measurement procedures

The dimension and weight of each selected sample were first measured before it was put into the testing chamber. The testing process was started by placing the dry ice into the upper chamber. The wood sample in the lower chamber was cooled down to below -40 °C by blowing air through the dry ice and guided into the lower chamber. The ultrasonic measurement of each wood sample was began with the wood temperature of -40 °C and then repeated at a 5 °C increment as the wood temperature gradually increased to 35 °C. One exception was that when wood temperature was close to the freezing point (0 °C), ultrasonic measurement was performed at a 2 to 3 °C increment. When the chamber temperature reached the room temperature, a glass of hot water was placed in the upper chamber to help to raise the wood temperature to about 35 °C. Through the testing cycle, the fans were manually controlled to obtain the targeted wood temperatures with a great degree of uniform, which was indicated by the close readings of three thermocouples. Under each targeted wood temperature, the wood sample was tested five consecutive times. An average ultrasound propagation time *(UPT)* and an average energy loss of the ultrasound signal were recorded. The ultrasonic velocity of each wood sample was calculated based on the thickness of the sample *(t)* and the average *UPT* value:

(1)

3. RESULTS AND DISCUSSION

3.1 Acoustic properties of red pine at -40 °C and 35 °C

Table 1 summarizes the basic information of the red pine samples used in this study. The moisture content of the green samples in Group I ranged from 78.5% to 118.3%. The moisture content of other groups was relatively uniform. The average EMC of Group H, **III,** and IV were 24.7%, 12.8%, and 0.2% respectively. Table 2 shows the average ultrasonic velocity and energy loss of each group at two different temperature conditions -40 °C and 35 °C, as well as the percentage change in velocity and energy loss from -40 °C to 35 °C. A significant difference was found in both velocity and energy loss between these two temperatures, with velocity and energy loss being high at -40 °C and low at 35 °C. When wood temperature increased from -40 °C to 35 °C, the average velocity and average energy loss decreased in all four groups, but at a different rate for different MC groups. The percentage change in velocity was found to be **-14.4%,** -7.8%, -7.3%, and -3.5% for Group I, II, HI, and IV respectively. The percentage change in energy loss was found to be -55.4%, -34.2%, -26.7%, and -13.6% for Group I, II, III, and IV respectively, much greater than that in velocity. The significant difference of percentage change in both velocity and energy loss among four groups of samples suggests that the moisture content of wood plays an important role in examining the temperature effect on acoustic properties of wood. The influence of temperature on acoustic properties was magnified when the moisture content of wood increased.

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 Height (mm)	Width (mm)	Length (mm)	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
Oven-dry		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 the wood samples were obtained after the completion of acoustic testing.

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

Group	MC (%)	Ultrasonic velocity (m/s) -40 °C	35 °C	Percentage change (%)	Energy loss (my) -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

3.2 Response of ultrasonic velocity and energy loss to wood temperature change

The scatter plots of the ultrasonic velocity and wood temperature for all four moisture groups were illustrated in Figure 2. As shown in the plots of Group II, III, and IV, the overall trend of the changes in velocity was similar for all the dry wood samples, i.e. velocity decreased gradually with increasing temperature, or vice versa. The velocity-temperature trend fattened progressively as moisture content of wood changed from 24% to 0%. However in Group I (green wood), we observed a different velocity-temperature trend, i.e. velocity changed abruptly around the freezing point (0 °C). Because of this unusual transition, velocity-temperature relations can be best characterized based on three temperature zones: 1) Below freezing point, ultrasonic velocity decreased as wood temperature increased; 2) around freezing point (-2.5 °C 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 green wood velocity around freezing point is attributed to the phase transformation of the free water in wood cells. The velocity changes observed between -2.5 °C to 2.5 °C suggests that the phase transformation of free water within the cell lumens did not happen instantly because the temperature of the wood samples was not exactly uniform. These findings are in agreement with the study of Sellevold et al. (1975) where a similar transition was found in the plot of MOE-temperature relationship for fully saturated beams. Sellevold et al. described this as a capillary transition and attributed the large modulus change near 0 °C to the ice formation in the cell lumens. In physics, the ice formation and its percentage of occupation in wood cells contribute to the variation in velocity changes for wood at different MC levels and around the freezing temperature.

Figure 3 shows the response of energy loss of red pine to wood temperature changes. The energy loss 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), the energy loss began to show a decreasing trend with the 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, energy loss also exhibited an abrupt change around the freezing point (-2.5 °C to 2.5 °C). Apparently, energy loss was affected by wood temperature changes in the same way as ultrasonic velocity did.

33 Relationships between ultrasonic velocity and wood temperature — Empirical models

To quantify the effects of wood temperature on ultrasonic velocity in red pine, we developed mathematical regression models relating measured velocity values to the wood temperature. In this process, we treated each MC level individually. Each sample in Group I was considered as an individual MC level because the MC values among them were very different. The moisture content of the samples for Group II, III, and N was very uniform within each group, thus each of these groups was treated as an individual MC level. Based on the observation of velocity transition at the freezing point in Group I, we used following three segmented linear regression models to describe the velocity-temperature relationships for the green wood over the entire temperature range (-45 °C to 35 °C):

$$
\begin{aligned}
f_1(T) &= k_1 T + l_1 \qquad | \, 40°C \, | \, T \, | \, 12.5°C \\
f_2(T) &= k_2 T + l_2 \qquad | \, 2.5°C \, | \, T \, | \, 2.5°C \\
f_3(T) &= k_3 T + l_3 \qquad 2.5°C \, | \, T \, | \, 35°C
\end{aligned} \tag{2}
$$

Although no apparent velocity discontinuity was observed for dry wood samples, we used the same segmented regressions for three MC levels represented by Group II, III, and IV, in order to examine how the velocity transition in freezing zone was affected by the moisture content of wood. 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 were summarized in table 3. Strong linear relationships were found existing between ultrasonic velocity and temperature at all MC levels when wood temperature is below -2.5 °C (R^2 = 0.94 — 0.99) and between -2.5 °C and 2.5 °C (R^2 = 0.81 — 0.99). Good linear relationships between ultrasonic velocity and temperature were also existed for dry wood when wood temperature was above 2.5 °C (R^2 = 0.89 — 0.92). However, the velocity-temperature relationships were not strong for green wood when wood temperature was above 2.5 °C.

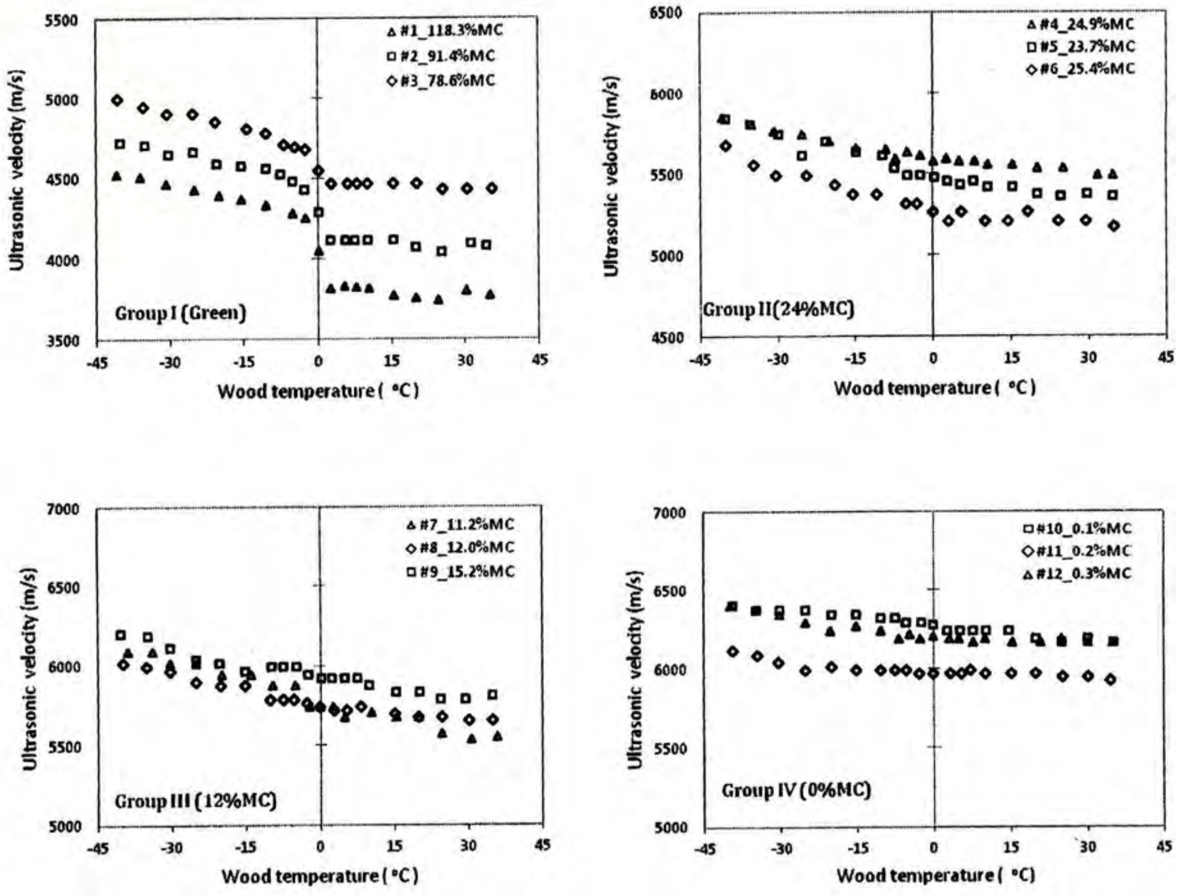

Figure 2— Ultrasonic velocity of red pine in relation to wood temperature.

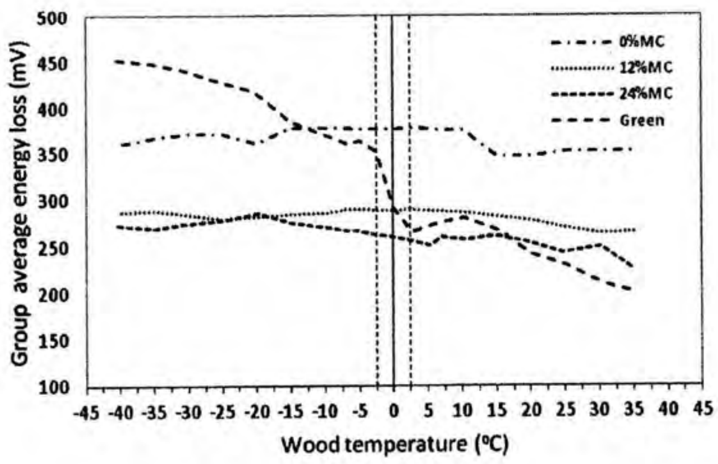

Figure 3— Energy loss of red pine in relation to wood12%MCrature.

Table 3 - Linear regression coefficients of experimental models at different moisture content.

MC	$f_i(T) = k_iT + h_i$						R^2		
(%)	k_1	k_2	k_3	h_1	h_2	h_3	-40 ~-2.5 °C	-2.5 ~2.5 °C	2.5 ~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

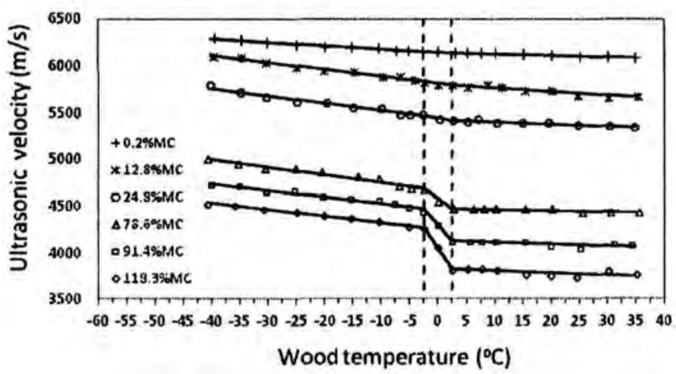

Figure 4 - Plot of ultrasonic velocity as a function of wood temperature at different MC levels.

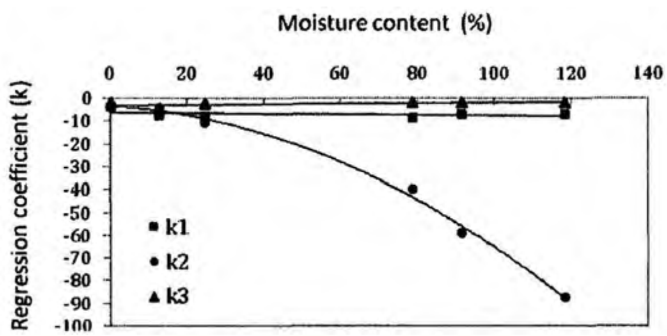

Figure 5 - Linear regression coefficients in relation to moisture content of wood.

The slope of the segmented linear regression lines in Figure 4, as represented by the regression coefficient *k*, indicates the magnitude of the temperature effect on velocity. Figure 5 shows the plot of the regression coefficient in relation to MC for three different temperature zones, wfiich highlights the differences oh1temperature impact at different temperature zones and different MC levels. Around freezing point (-2.5 °C-2.5 °C), the slope (k_2) of the linear regression line was found to increase exponentially with increasing MC. Whereas above 2.5 °C and below -2.5 °C, the slopes (lcand k_3) were not affected much by MC level. This has a significant implication to the field acoustic measurements on trees and logs.0.2%MC

4. CONCLUSIONS

This study12.8%MCigated the effects of woo4.73.5%MCre and moi.91.4%MCe on acoustic properties of red pine in laboratory-controlled conditions. The results indicated that tree or log acoustic velocities measured in ambient conditions can be adjusted to a standard temperature if measurements were conducted well above freezing or well below freezing. However, measurements around freezing point could cause complications in making temperature adjustment because the moisture content of wood could be different by individual trees/logs, species, stands, or geographic locations. Users should try to avoid conduct field testing on trees and logs when the wood temperature is around the freezing point unless the moisture content of wood is accurately measured and its compounding effect is taken into consideration.

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