EVALUATION OF MOISTURE CONTENT CHANGES IN TAIWAN RED CYPRESS DURING DRYING USING ULTRASONIC AND TAP-TONE TESTING

Lee Chia-Ju

Research Assistant
The Experimental Forest
National Taiwan University
557 Nan-Tou, Taiwan

Wang Song-Yung†

Professor
School of Forestry and Resource Conservation
National Taiwan University
106 Taipei, Taiwan

*Yang Te-Hsin**

Assistant Professor
Department of Forestry
National Chung Hsing University
402 Taichung, Taiwan

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Abstract. Moisture content affects most of the important properties of wood, therefore it is important to control during drying and in use. The purpose of this study was to investigate moisture content changes in Taiwan red cypress during drying. Two types of nondestructive testing were used, ultrasonic and tap-tone. The results showed that ultrasonic and tap-tone velocities increased with decreasing moisture content with the major effect below the FSP. A second-order regression relationship was found between ultrasonic and tap-tone velocities with moisture content desorption during drying with a coefficient of determination of 0.77 and 0.88, respectively. Moreover, the effects of moisture content desorption on dynamic moduli, calculated from ultrasonic and tap-tone methods, were demonstrated. Finally, a new parameter (Vi/Vx), the ratio of initial velocity (before drying) to the velocity at any moisture content, was effectively applied to evaluate moisture content changes in wood during drying. The tap-tone method was found to be a reliable tool to measure moisture content changes during the drying of wood.

Keywords: Moisture content, drying, ultrasound, tap-tone, dynamic modulus.

INTRODUCTION

Wood, as a biological material, has highly variable properties. Among these variations, moisture content plays an important role in wood characteristics. Moisture content affects most of the important properties of wood, and it varies with both environmental conditions and the history of wood (FPL 1999). During kiln drying, sample boards are used to determine the moisture content, but this method is inefficient and wastes time and materials. More efficient and reliable methods are needed.

Many properties of wood have been evaluated using nondestructive evaluation (NDE) (Keunecke et al 2005; Alfredsen et al 2006). Recently, Yin et al (2010) evaluated mechanical properties of Chinese fir plantation wood by three acoustic-based NDE techniques: stress wave, ultrasonic wave, and vibration testing. Moisture meters are nondestructive electrical resistance instruments that accurately measure moisture content between 7 and 25%. Above 25%, however, the resistance of wood varies only slightly with

* Corresponding author: tehsinyang@nchu.edu.tw
† SWST member

changes in moisture content as the path for electrical conduction shifts from water in cell walls to the cell cavities. Hence, at above 25% MC, it is common to see differences that exceed 20% with oven-dry values (Chen et al 1994).

In addition to electrical resistance techniques, acoustic velocity can be used to determine moisture content. It has been found that the speed of sound through wood varies with moisture content even above FSP (Gerhards 1975). James et al (1982) used speed of sound in wood to monitor moisture content during kiln drying and found continuous decreases in transit time. Norton and Greenhalgh (1990) estimated moisture content using ultrasonic waves and determined that they could be used to monitor variations during the drying process in a kiln environment. A relationship between the speed of sound and moisture content of red oak and hard maple was established by Simpson (1998).

A similar study by Simpson and Wang (2001) examined a linear relationship that was found between the relative transit time and average moisture content of sugar maple and ponderosa pine boards dried by typical kiln schedules. Oliveira et al (2005) demonstrated that ultrasonic wave velocity was sensitive to changes in moisture content of lumber during drying. Relationships between velocity and dynamic modulus of wood with moisture content changes from saturated to oven-dry conditions were reported by Wang and Chuang (2000) and Wang et al (2003).

The objective of this study was to monitor moisture content and changes in velocity and dynamic modulus of elasticity (DMOE) during drying using ultrasonic and tone-tap velocities to develop a more efficient moisture monitoring system.

MATERIALS AND METHODS

Experimental Materials

Forty-year-old Taiwan red cypress (*Chamaecyparis formosensis*) plantation trees were selected. From this, 420 specimens of straight-grain clear wood were cut successively in the longitudinal direction (1 m) with a cross section of 50 mm (R) × 50 mm (T). Air-dry density of the test specimens ranged 436-524 kg/m^3.

Testing Equipment

Ultrasonic velocities were measured at 24 kHz using a portable ultrasonic PUNDIT unit (CNC Electronics Ltd, London, UK). A tap-tone instrument (portable lumber grader; Fakopp Enterprise, Agfalva, Hungary) was used to measure sound velocity.

Testing Methods

Specimens were treated by the Bethell (full-cell) method several times to bring them to the water-saturated state. They were air-dried in the laboratory under average conditions of 24°C and 74% RH. The ultrasonic and tap-tone waves propagated in the longitudinal direction of specimens were measured and recorded for 40-80 g weight loss from the water-saturated condition to FSP (about 30% MC) during the air-drying process. When the moisture content dropped below FSP, velocities were measured in 20- to 40-g increments to oven dry.

The ultrasonic method required placing piezoelectric transducers (transmitter and receiver) in contact with opposite ends, and the velocity (V_u) and DMOE$_u$ were calculated based on:

$$V_u = \frac{L}{t} \tag{1}$$

$$DMOE_u = V_u^2 \times \rho \tag{2}$$

where V_u = ultrasonic velocity in the direction parallel to the grain of the specimen, L = distance between the two transducers, t = propagation time of the pulse from the transmitting transducer to the receiving transducer, DMOE$_u$ = dynamic modulus of elasticity in the direction parallel to the grain of specimen, and ρ = density based on the ratio of total mass to volume at a given moisture content.

Tap-tone velocity (V_f) was calculated from natural frequency (f_n) and mode number (n) obtained from an FFT analyzer. The range of frequency detected was 1-10 kHz. The V_f and $DMOE_f$ were calculated from:

$$V_f = 2 \times \frac{f_n}{n} \times L \quad (3)$$

$$DMOE_f = V_f^2 \times \rho \quad (4)$$

Moisture content was calculated as follows:

$$MC = \frac{(W_x - W_o)}{W_o} \times 100\% \quad (5)$$

where MC and W_x are the moisture content and weight of the test specimens at various test stages, respectively. W_o is the oven-dry weight.

RESULTS AND DISCUSSION

Effects of Moisture Content on Velocities

Table 1 shows the experimentally obtained ultrasonic and tap-tone velocities, which increased with a decrease in moisture desorption from water-saturated to oven-dry. Figures 1 and 2 show the differences in velocity above and below FSP. The correlations showed two different linear relationships from water saturation to FSP and from FSP to oven dry. This was confirmed by Sakai et al (1990), who extensively studied the effect of moisture content on longitudinal stress wave velocity for nine species. They also showed that the relationship of velocity vs moisture content consisted of two straight line segments. Mishiro (1995, 1996a, 1996b) conducted a series of studies on the relationship between ultrasonic velocity and moisture content. He pointed out that in most species, the increase in ultrasonic velocity from green to FSP was not very large, however from FSP to oven dry, the increase was much greater. Keunecke et al (2005) also indicated that ultrasonic velocity decreased dramatically with increasing moisture content to 22.0-27.3%.

Recently, Oliveira et al (2005) published a technical note on the relationship between ultrasonic velocity and moisture content of Brazilian wood.

Table 1. Moisture content, density, and acoustic properties of wood during drying.[a]

MC (%)	Density[b] (kg/m³)		V_u (m/s)		V_f (m/s)		$DMOE_u$ (GPa)		$DMOE_f$ (GPa)		V_{ui}/V_{ux}		V_{fi}/V_{fx}	
110	861	(28)	4215	(347)	3808	(154)	15.4	(2.7)	12.5	(1.3)	1.00	(0.00)	1.00	(0.00)
108	852	(32)	4253	(358)	3829	(147)	15.5	(2.9)	12.5	(1.3)	0.99	(0.01)	0.99	(0.01)
98	810	(33)	4343	(404)	3937	(148)	15.5	(3.3)	12.6	(1.4)	0.97	(0.02)	0.97	(0.02)
91	783	(36)	4425	(380)	4008	(131)	15.5	(3.2)	12.6	(1.3)	0.95	(0.02)	0.95	(0.02)
80	740	(42)	4522	(362)	4124	(127)	15.3	(3.2)	12.6	(1.3)	0.93	(0.03)	0.92	(0.02)
73	710	(44)	4596	(366)	4215	(140)	15.2	(3.2)	12.7	(1.5)	0.92	(0.04)	0.90	(0.03)
67	688	(49)	4701	(336)	4290	(136)	15.4	(3.0)	12.7	(1.5)	0.90	(0.04)	0.89	(0.03)
63	670	(51)	4772	(357)	4345	(103)	15.4	(3.1)	12.7	(1.4)	0.88	(0.04)	0.88	(0.03)
58	647	(51)	4842	(355)	4434	(103)	15.3	(3.0)	12.8	(1.5)	0.87	(0.03)	0.86	(0.03)
52	626	(52)	4930	(298)	4506	(83)	15.3	(2.5)	12.7	(1.4)	0.85	(0.04)	0.84	(0.03)
49	613	(51)	4986	(242)	4559	(105)	15.3	(2.1)	12.8	(1.5)	0.84	(0.05)	0.84	(0.02)
43	588	(51)	5079	(264)	4647	(131)	15.3	(2.5)	12.8	(1.7)	0.83	(0.04)	0.82	(0.02)
34	563	(47)	5241	(257)	4818	(122)	15.6	(2.4)	13.1	(1.4)	0.80	(0.04)	0.79	(0.03)
28	548	(54)	5358	(294)	5020	(148)	15.9	(3.1)	13.9	(2.0)	0.79	(0.04)	0.76	(0.02)
22	528	(52)	5528	(329)	5126	(202)	16.3	(3.1)	14.0	(2.6)	0.76	(0.03)	0.74	(0.02)
18	512	(50)	5642	(356)	5252	(234)	16.5	(3.3)	14.3	(2.7)	0.75	(0.04)	0.73	(0.02)
12	487	(35)	5840	(327)	5458	(247)	16.7	(2.7)	14.6	(2.3)	0.72	(0.03)	0.70	(0.02)
9	475	(34)	5912	(355)	5571	(296)	16.7	(2.9)	14.9	(2.5)	0.71	(0.04)	0.68	(0.02)
7	463	(34)	6025	(377)	5706	(338)	16.9	(2.7)	15.2	(2.8)	0.70	(0.03)	0.67	(0.02)
4	452	(33)	6106	(426)	5846	(394)	17.0	(3.1)	15.6	(3.3)	0.69	(0.02)	0.65	(0.03)
0	435	(31)	6395	(375)	6009	(404)	17.9	(2.8)	15.9	(3.0)	0.66	(0.03)	0.64	(0.03)

[a] Number in parentheses is standard deviation.

[b] Density based on total mass (wood and moisture) and volume at the given moisture content.

MC, moisture content; Vu, ultrasonic velocity calculated from Eq 1; V_f, tap-tone velocity calculated from Eq 3; $DMOE_u$, dynamic modulus of elasticity calculated from ultrasonic velocity; $DMOE_f$, dynamic modulus of elasticity calculated from tap-tone velocity.

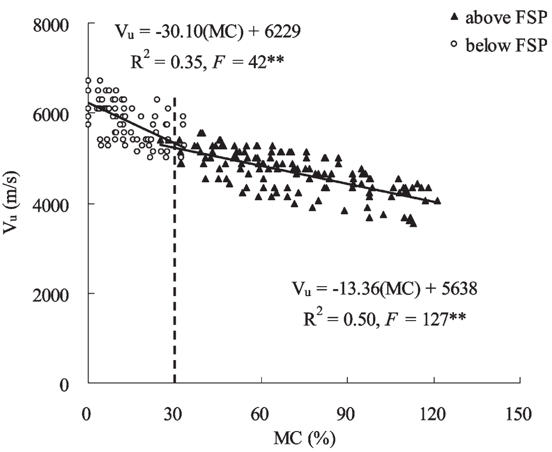

Figure 1. Effect of moisture content desorption on the ultrasonic velocity during drying.

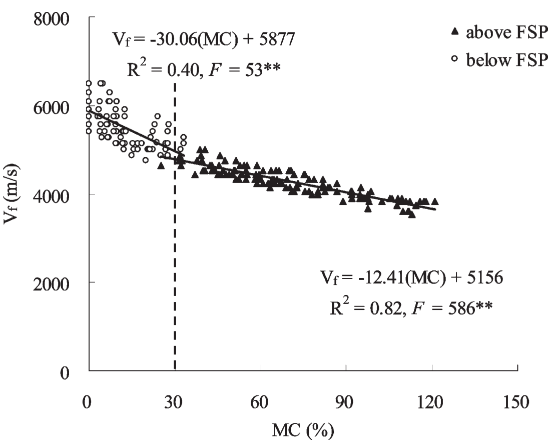

Figure 2. Effect of moisture content desorption on the tap-tone velocity during drying.

They stated that ultrasonic velocity of longitudinal waves was sensitive to changes in moisture content of specimens. The ultrasonic velocity not only decreased with increasing moisture content in the longitudinal direction but also tangentially. To understand the variation of ultrasonic velocity with moisture content, they used the relative velocity (V_{green}/V_{dry}) as a parameter to calculate two regression lines (the first moisture content group was 7-20% and the second 20-55%) and established the apparent FSP at 18%.

The results in Table 1 indicate that during drying, velocities increased with moisture content desorption 4.22-6.40 km/s for ultrasound and 3.81-6.01 km/s for tap-tone. Previous research found a continuous increase in the velocity for Taiwanian lumber over 200-10% MC with the total increase being about 2.5 times (Huang and Chen 1996). In the current study, the total increase in the ultrasonic and tap-tone velocities of red cypress specimens from 110-0% MC was about 1.52 and 1.58 times, respectively.

We also found that ultrasonic and tap-tone velocities of specimens decreased 13.9 and 14.8 m/s for a moisture content change of 110% to FSP (28%) and 37.0 and 35.3 m/s for a moisture content change from FSP to oven dry, respectively. The velocities decreased with increasing moisture content and had a second-order regression relationship (Table 2) with coefficients of determination of 0.77 and 0.88, respectively.

Effect of Density on Velocities

As shown in Table 1, density increased from 435 kg/m^3 at the oven-dry state to 861 kg/m^3 at 110% MC, however the ultrasonic and tap-tone velocities tended to decrease linearly with increasing density. This was because the density of the wood was increasing, which was caused by free water increase, not an increase in the thickness of the cell wall. Since the sound velocity in wood is greater than in water, it decreases with increasing moisture content. The linear regressive relationships are shown in Table 2 with R^2 of 0.56 (density and V_u) and 0.68 (density and V_f), respectively. Similar results were reported earlier by Chiu et al (2000) and Wang et al (2003). In addition, sound velocity could be affected by basic density. Statistical analyses for the relationships among moisture content, velocity (V_u and V_f), and density (ρ) are shown in Table 2. A polynomial regression model fit the experimental data (R^2 values were 0.82 for those variables and V_u and 0.91 for those variables and V_f, respectively). The statistical analysis also showed that the relationships among moisture content, density, and V_u (or V_f) were significant at the 0.01 level. Furthermore, the

Table 2. Relationship between moisture content and ultrasonic and tap-tone velocities.

Methods	MC (%)	Regression equation	R^2	*F* value
Ultrasonic testing	0-110%	$V_u = 0.10(MC)^2 - 29.4\ (MC) + 6192$	0.77	346**
		$V_u = -3.99\rho + 7609$	0.56	269**
		$V_u = 0.11(MC)^2 - 44.5\ (MC) + 3.70\rho + 4593$	0.82	311**
		$V_{ui}/V_{ux} = 0.003\ (MC) + 0.690$	0.90	1876**
	>FSP	$V_u = -13.36\ (MC) + 5638$	0.50	127**
	<FSP	$V_u = -30.10\ (MC) + 6229$	0.35	42**
Tap-tone testing	0-110%	$V_f = 0.13\ (MC)^2 - 32.5\ (MC) + 5863$	0.88	772**
		$V_f = -4.22\rho + 7363$	0.68	444**
		$V_f = 0.14\ (MC)^2 - 42.5\ (MC) + 2.46\rho + 4800$	0.91	656**
		$V_{fi}/V_{fx} = 0.003\ (MC) + 0.664$	0.93	2814**
	>FSP	$V_f = -12.41\ (MC) + 5156$	0.82	586**
	<FSP	$V_f = -30.06\ (MC) + 5877$	0.40	53**

MC, moisture content.

relationships showed reliable regressions for prediction purposes.

Effects of Moisture Content on Dynamic Moduli

The relationships between moisture content and dynamic moduli are shown in Fig 3. Below FSP, the relationships were similar to that of the ultrasonic and tap-tone velocities, decreasing rapidly as moisture content increased. Keunecke et al (2005) determined the elastic constants by ultrasonic waves and found that the elastic constants (E_L, E_R, and E_T) decreased with increasing moisture content of 8.7-22.0% for yew and 9.5-27.3% for spruce, respectively. However, above FSP, the values were relatively constant. This trend also agrees with the general phenomenon that the mechanical properties of wood remain fairly constant above the FSP.

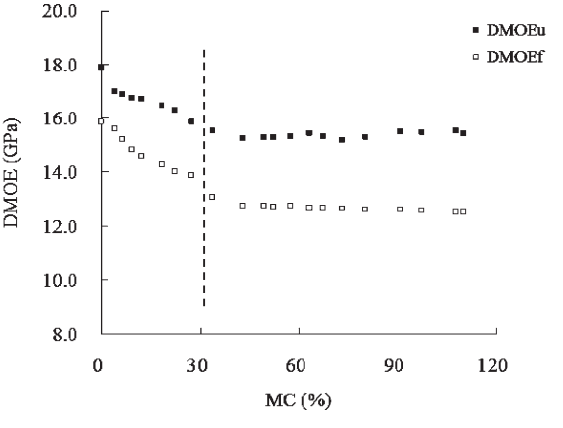

Figure 3. Relationship between dynamic modulus of elasticity and moisture content changes in wood.

Use of Ultrasonic and Tap-Tone Velocities to Evaluate Moisture Content Changes

The data of ultrasonic and tap-tone velocities can be analyzed differently to evaluate moisture content changes in wood during drying. The V_i/V_x ratio can be used as a parameter to predict the moisture content, where V_i is the initial velocity before drying and V_x is the velocity at any moisture content. The mean values of the V_i/V_x ratios are shown in Table 1. It was found that while moisture content desorption during drying decreased 110-28%, V_{ui}/V_{ux} fell 1-0.79 for ultrasonic tests and V_{fi}/V_{fx} decreased 1-0.76 for tap-tone tests. Moreover, while moisture content decreased 28-12%, V_{ui}/V_{ux} dropped 0.79-0.66 for ultrasonic tests and V_{fi}/V_{fx} 0.76-0.63 for tap-tone tests.

Figure 4 shows the relationships between moisture content and the V_i/V_x ratio for ultrasonic (V_{ui}/V_{ux}) and (V_{fi}/V_{fx}) tap-tone tests. All the relationships appeared linear, and the regressions between moisture content and the V_i/V_x ratios are presented in Table 2. The relationships of moisture content and the V_{ui}/V_{ux} ratio had an $R^2 = 0.90$ and for moisture content and the V_{fi}/V_{fx} ratio $R^2 = 0.93$, a slightly closer relationship. Consequently, the V_i/V_x ratio could be a good indicator to determine moisture content

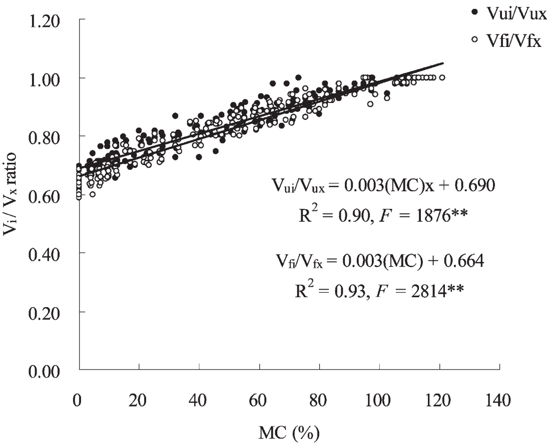

Figure 4. Relationship between the parameter ratio of initial velocity (before drying) to the velocity at any moisture content (V_i/V_x) and moisture content changes in wood.

changes more easily in wood during drying. As can be seen from these results, the V_{fi}/V_{fx} ratio obtained by the tap-tone method was found to be a good predictor of moisture content.

CONCLUSIONS

The relationship among moisture content, dynamic moduli, and ultrasonic and tap-tone velocities was investigated. The results showed that ultrasonic and tap-tone velocities were sensitive to changes in moisture content, both decreasing with increasing moisture content. Also, there was a well-established relationship between moisture content and ultrasonic and tap-tone velocity both above and below FSP. The effect of moisture content below FSP on ultrasonic and tap-tone velocities was stronger than that above. A second-order regression model fit the curve of experimental data, with R^2 of 0.77 and 0.88 for ultrasonic and tap-tone testing, respectively. In another regression combining moisture content and density variables, R^2 increased to 0.82 and 0.91, respectively, however measuring wood density during drying is not practical. Therefore, a new parameter (V_i/V_x) was applied to evaluate moisture content changes in wood during drying with $R^2 = 0.93$ for moisture content, and the V_{fi}/V_{fx} ratio that had a closer relationship with moisture content changes than did the other parameters. Consequently, the V_{fi}/V_{fx} ratio as determined by the tap-tone method could be an effective and reliable indicator to measure the moisture content changes in wood during drying.

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