VARIATIONS IN ULTRASONIC WAVE VELOCITY AND DYNAMIC YOUNG'S MODULUS WITH MOISTURE CONTENT FOR TAIWANIA PLANTATION LUMBER

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ABSTRACT

The effects of moisture content (MC) on the ultrasonic wave velocity, dynamic Young's modulus (DMOE), and the mobility of free water during desorption from a water-saturated condition were examined for the longitudinal, radial, and tangential directions of Taiwania (*Taiwania cryptomerioides* Hayta) plantation lumber. The ultrasonic wave velocity in the longitudinal and radial direction tended to increase with decrease in MC, and the effect of MC on the ultrasonic wave velocity of Taiwania lumber below the fiber saturation point (FSP) was stronger than above the FSP. Above the MC of 70%, the ultrasonic wave velocity in the tangential direction tended to decrease with decreasing MC, whereas below the MC of 70%, the ultrasonic wave velocity tended to increase with decreasing MC.

The DMOE curve also showed a significant change around the FSP in a two-stage relationship with MC values. Above the FSP, DMOE values tended to decrease rapidly with decreasing MC, whereas below the FSP, the DMOE values tended to increase gradually with decreasing MC. The k values for the ultrasonic wave propagated through the longitudinal, radial, and tangential direction of Taiwania plantation lumber were equivalent to 0.58, 0.33, and 0.01, respectively. Using the effective density and ultrasonic wave velocity to calculate the longitudinal, radial, and tangential DMOE, it was found that the DMOE tended to remain constant with MC during the MC reducing process from a water-saturated condition to FSP.

Keywords: Taiwania (*Taiwania cryptomerioides* Hayta), ultrasonic wave velocity, dynamic Young's modulus, moisture content, effective density.

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INTRODUCTION

Ultrasonic wave is one of the most useful nondestructive tools being applied to living trees, logs, sawn-timbers, and wood-based materials to estimate their strength properties. However, when applied to living trees, green logs, and green sawn-timbers, the ultrasonic wave is significantly affected by water in the wood (Mishiro 1996a). Therefore, it is of interest to understand the effect of moisture content (MC) on the ultrasonic wave velocity and dynamic Young's modulus (DMOE) of wood in the MC range above and below the fiber-saturation point (FSP) when estimating some physical properties of wood using the ultrasonic wave technique.

There have been some reports regarding the effects of MC, above and below the FSP, on the ultrasonic wave velocity in wood. Gerhards (1975) studied the stress wave speed and MOE of sweetgum ranging from 150% to 15% MC. He indicated that both longitudinal and flexural stress waves are slowed by the increasing MC below FSP, but the effect on speed of longitudinal waves is slightly greater than on speed of flexural waves. He also indicated that both types of stress wave DMOEs show minimums above the FSP. The minimum is much more sharply defined for the longitudinal wave than for the flexural wave. Below FSP, the calculated DMOEs for both types of waves increase as MC decreases, as expected. Mishiro (1996a, 1996b) also reported the relationships between ultrasonic wave velocities and average MC above and below the FSP in the longitudinal and radial directions of certain Japanese wood species.

Young's modulus is a measure of the stiffness of a material, and it has a strong correlation with material strength (Booker et al. 1996). Since wood is an anisotropic material, the ultrasonic wave velocities and the elastic modulus vary in the longitudinal, radial, and tangential direction. In addition, Young's modulus also changes with MC. Thus the objectives of this study were to investigate the effects of MC on longitudinal, radial, and tangential ultrasonic waves propagated through wood specimens during the desorption stages from water-saturated to oven-dried status, and to investigate the correlation between DMOE and viscoelasticity of free water in the Taiwania plantation wood.

MATERIALS AND METHODS

Experimental material

This experimental plantation is located in compartment No 3, Liukuei Experimental Forest of the Taiwan Forestry Research Institute (TFRI), Kaoshiung Country, Taiwan, R.O.C. Three 27-yr-old Taiwania (*Taiwania cryptomerioides* Hay.) plantation trees were selected for study by ultrasonic velocity and DMOE.

The dimensions of specimens for measurements of ultrasonic wave velocities and DMOE in the longitudinal direction were 20 mm in tangential, 20 mm in radial, and 320 mm in longitudinal. For measurements in a radial direction, they were 20 mm in tangential, 30 mm in longitudinal, and 100 mm in radial. For measurements in a tangential direction, they were 20 mm in radial, 30 mm in longitudinal, and 100 mm in tangential (Fig. 1). The number of specimens and their average air-dried densities and MC are shown in Table 1.

Test instrument

Ultrasonic wave velocities and DMOE were measured using a portable ultrasonic nondestructive testing (PUNDIT) meter, at a frequency of 54 kHz (C.N.C. Electronic LTD). The transmitting transducer and the receiving transducer were placed facing each other with the specimen placed in between, and the travel time (transmitting time), as displayed on the meter screen, was recorded (Fig. 2).

Measurements of ultrasonic velocities and DMOE

Specimens were treated by the Bethell process method several times to bring them to the water-saturated status. Measurements were taken of ultrasonic wave propagated through

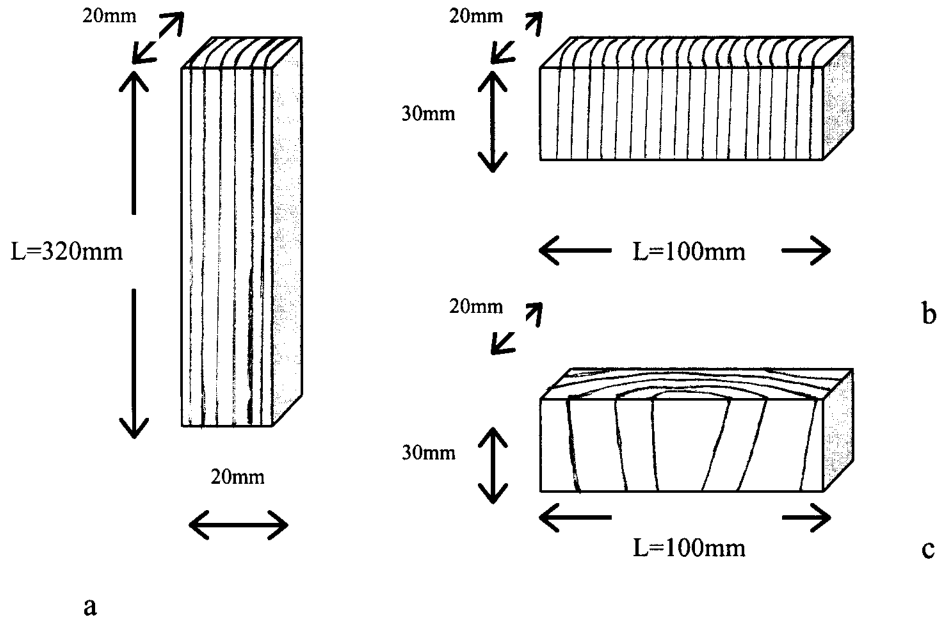

FIG. 1. Dimensions of specimens. a: for longitudinal transmission; b: for radial transmission; c: for tangential transmission; L: direction of measurement.

the longitudinal, radial, and tangential direction of specimens. They were conducted each time when a weight loss of 10–15 g for each longitudinal specimen and 5–8 g for each radial and tangential specimen occurred from water-saturated to FSP.

The detail of the test is shown in Fig. 2.

The ultrasonic wave velocity (Vu) was measured by Eq. (1),

$$Vu = L/T, \quad (1)$$

where L = length of the specimen, and T = travel time of the pulse through specimen.

The dynamic modulus of elasticity (DMOE) was derived from the equation expressed as follows (Wang and Chuang 2000):

$$DMOE = (Vu)^2 \times \rho/g \quad (2)$$

Where Vu was the velocity of ultrasonic wave in the longitudinal, radial, and tangential direction (m/s), and ρ was the bulk density (g/cm^3), g was acceleration of gravity (9.8 m/s^2), respectively.

When the moisture content (MC) of specimens dropped below the FSP, the ultrasonic wave tests were conducted every time a

TABLE 1. *Fundamental data of three different type specimens of Taiwania in air-dried condition.*

Specimens	Air-dried density (g/cm^3)	Density (oven-dry weight/ green volume)	Moisture content (%)	Ultrasonic wave velocity (m/sec)	Dynamic modulus of elasticity × 10^3 (kgf/cm^2)	Number of specimens
Longitudinal direction	0.41[a]	0.335	14.83	4803.5	95.2	50
	(0.03)[b]	(0.03)	(1.01)	(236.5)	(8.5)	
Radial direction	0.42	0.354	14.55	2535.3	27.9	20
	(0.03)	(0.03)	(1.02)	(67.9)	(2.6)	
Tangential direction	0.42	0.345	14.43	1550.6	10.3	31
	(0.02)	(0.02)	(0.29)	(106.2)	(1.8)	

[a] Average values.
[b] Number in ( ) is standard deviation.

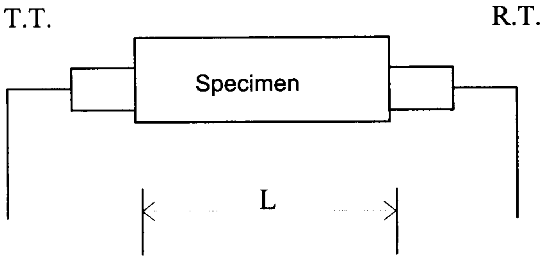

FIG. 2. Measuring method for ultrasonic velocity and dynamic modulus of elasticity of wood specimen. L: length of specimen; T.T.: transmitting transducer; R.T.: receiving transducer.

weight loss of 2–4 g for each longitudinal specimen and 1–2 g for each radial and tangential specimen occurred.

MC during the test was calculated as follows:

$$MCu\ \% = (Wu\text{-}Wo)/Wo \times 100\% \quad (3)$$

Where MCu(%) was the MC of the test specimens in various test stages (%), Wu was the specimen weight of various test stages (10^{-3} kg) and Wo was the oven-dried weight of specimens during the last test condition (10^{-3} kg).

Measurement of efficient density and adjusted DMOE above FSP

The DMOE tends to decrease gradually with a decrease in MC above the FSP. This phenomenon contradicts the fact that the physical and mechanical properties of wood remain fairly constant when MC is above the FSP. Therefore, it is necessary to adjust the DMOE in the MC range above the FSP using the effective density when estimating certain physical properties of wood by ultrasonic wave.

The effective density (ρ_{eff}) of wood with MC greater than the FSP may be expressed by Eq. (4) (Sobue 1993).

$$\rho_{eff} = (100 + MCu)\rho_o \cdot (100 + 28\rho_o)^{-1} \times [1 - (1 - k)(MCu - 28) \times (100 + MCu)^{-1}], \quad (4)$$

where

MCu = moisture content,

k = empirical values ranging from 0.0 to 1.0, and

ρ_o = density of the specimen in oven-dried condition.

The ultrasonic wave velocity (V) could be calculated by Eq. (5)

$$V = \sqrt{E_{fsp}/\rho_{eff}} \quad (5)$$

where E_{fsp} = dynamic Young's modulus of specimen at the FSP.

The least-squares method was used to search for the optimal k value of free water mobility, which was fit for ultrasonic wave. Then, the adjusted dynamic Young's modulus (DE) above the FSP can be calculated by Eq. (6)

$$DE = V^2 \times \rho_{eff}/g \quad (6)$$

RESULTS AND DISCUSSION

Effects of moisture content on ultrasonic wave velocity

Figures 3–5 showed the relationship between ultrasonic velocity and MC in the longitudinal, radial, and tangential direction during desorption from a water-saturated condition to oven-dried status for Taiwania lumber. During the desorption stage (Figs. 3–4), the ultrasonic wave velocity increased with a decrease of MC and could be expressed by a second-order regressive relationship, the determined coefficient (R^2) being 0.98 and 0.91 as shown in Table 2. Statistically the ultrasonic wave propagated velocity with MC correlation was significant (0.01 level). This was in accordance with previous reports (Bucur 1995; Chuang 1999; Nakamura and Nanami 1993; Wang 1984; Wang and Chuang 2000). In other words, the ultrasonic-wave velocity propagated through wood substance increased with the MC reducing process from the water-saturated to the oven-dry condition.

A typical graph for the tangential specimens is shown in Fig. 5. For the tangential specimens, the velocity decreases with decreasing MC from the water-saturated condition to 70%, but from 70% to oven-dry, the velocity

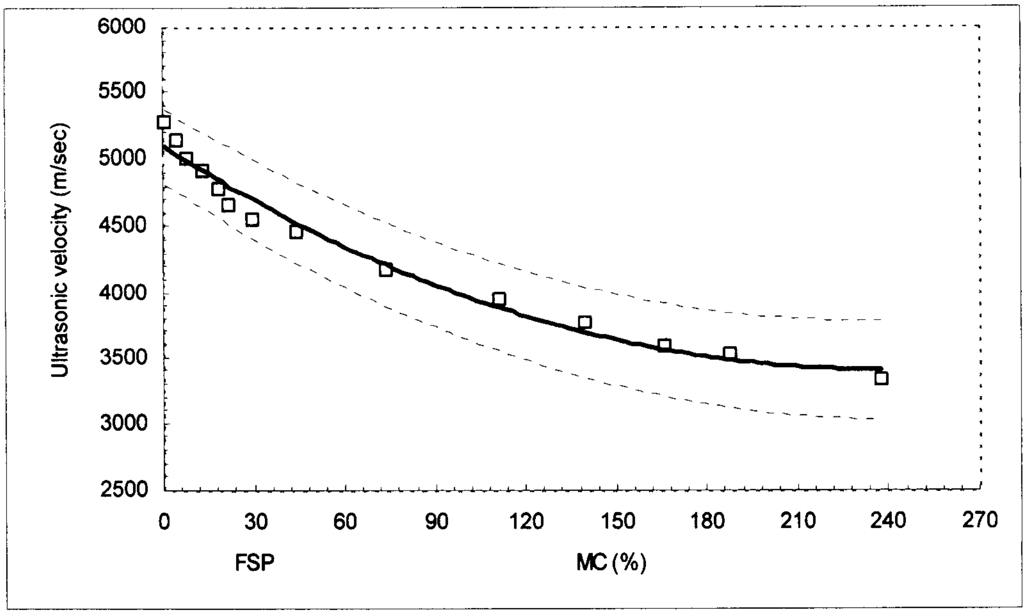

FIG. 3. Relationship between ultrasonic velocities and MC in the longitudinal direction.

again increases. During the desorption stage, the ultrasonic velocity and MC could be represented by a third-order regressive relationship, the determining coefficient (R^2) being 0.89 as shown in Table 2.

Figures 3–4 also showed a significant point in ultrasonic velocity around the FSP reflected as a two-stage linear relationship; thus, the effects of MC on ultrasonic velocity below and above the FSP were different. The velocity of

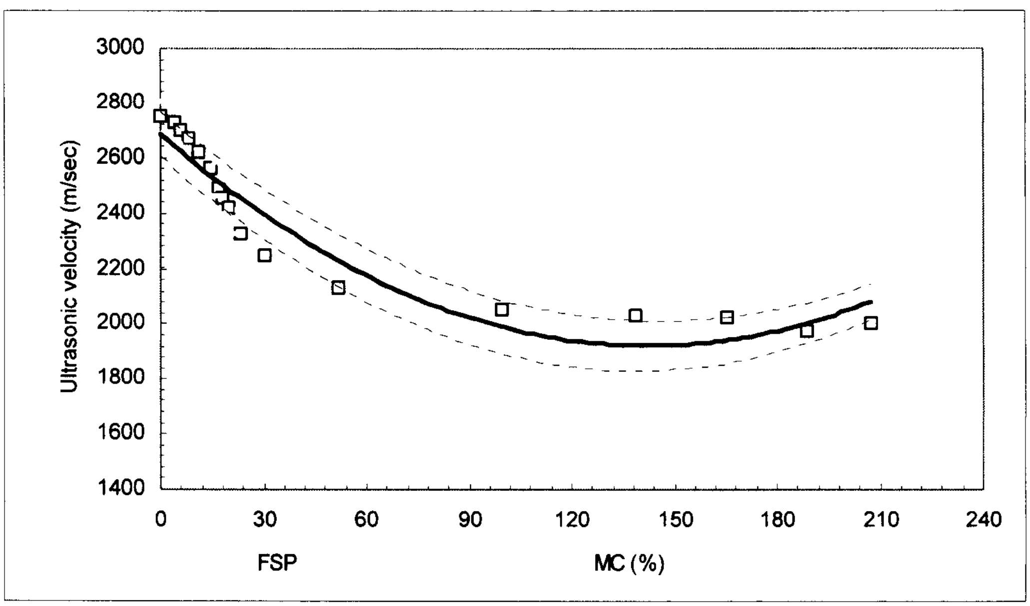

FIG. 4. Relationship between ultrasonic velocities and MC in the radial direction.

TABLE 2. *The equations for the relations between ultrasonic wave velocity (V) and MC of various specimens.*

Specimens	Moisture content (MC)	Equations	Coefficients of determination (R^2)	*F* value
Longitudinal	0%~240%	$V = 0.03(MC)^2 - 14.26(MC) + 5098.7$	0.98	249.9**
	>FSP	$V = -5.79(MC) + 4622$	0.97	181.6**
	<FSP	$V = -24.91(MC) + 5249.6$	0.97	194.3**
Radial	0%~220%	$V = 0.04(MC)^2 - 10.74(MC) + 2684.1$	0.91	45.9**
	>FSP	$V = -1.25(MC) + 2223.3$	0.84	25.4**
	<FSP	$V = -18.71(MC) + 2799.4$	0.97	245.2**
Tangential	0%~230%	$V = 0.0003(MC)^3 + 0.132(MC)^2 - 15.556(MC) + 1738.4$	0.89	31.4**
	>FSP	$V = 1.46(MC) + 1210.1$	0.56	5.2$^{(-)}$
	<FSP	$V = -16.87(MC) + 1769.1$	0.97	20.5**

Notes: V in m/s and MC in %.
** and $^{(-)}$ represent significant (0.01 level) and no significant difference by *F* value test, respectively.

the ultrasonic wave increased slowly with decreasing MC above the FSP, but rather abruptly below FSP; their relationships between ultrasonic wave velocity and MC were expressed by the linear regression as shown in Table 2. It was also found that the effects of MC on the ultrasonic wave velocity propagated through the tangential direction were different, compared to those of the longitudinal and radial direction as shown in Fig. 5.

Chuang (1999) indicated that the path of ultrasonic wave propagation in wood was via its solid i.e., cell-wall substance; and the effect of free water in cell cavities on the ultrasonic wave velocity was indirect when MC was above the FSP. The ultrasonic wave velocity changed rapidly with MC below the FSP. Mishiro (1996b) indicated that during the desorption from water-saturated conditions, the patterns of ultrasonic wave velocities versus average MC in the radial and longitudinal directions varied very much with species and could be divided into three groups. Kodama et al. (1996) and Booker et al. (1996) reported a

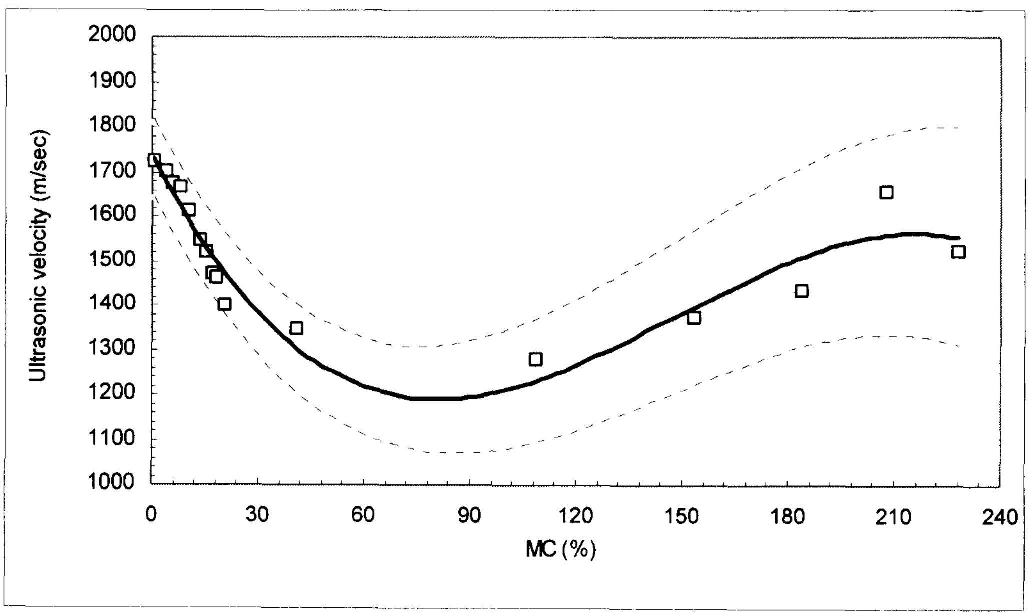

FIG. 5. Relationship between ultrasonic velocities and MC in the tangential direction.

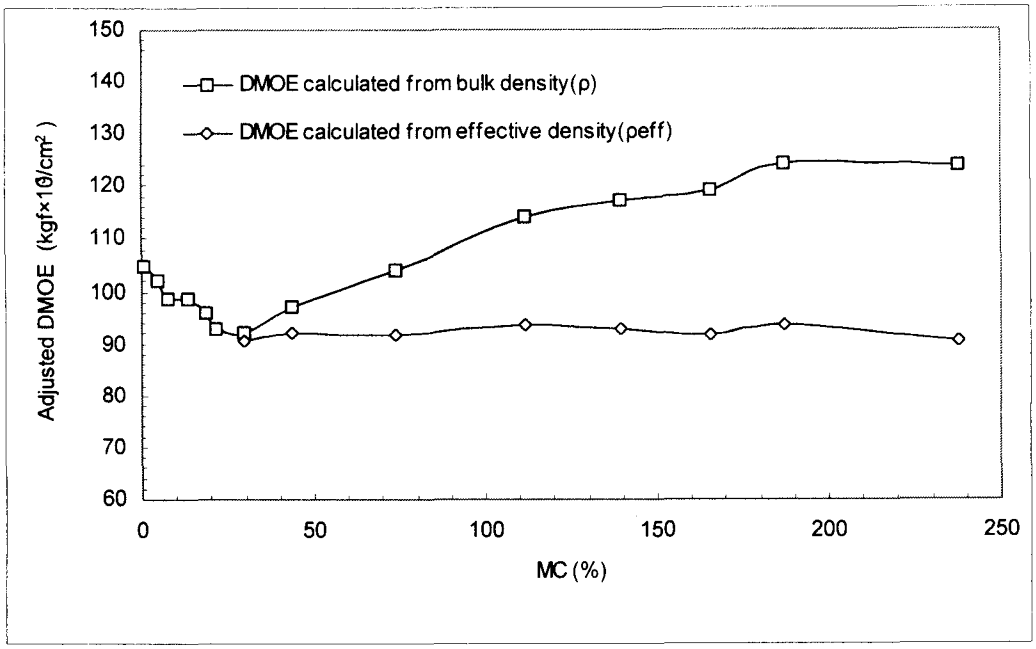

FIG. 6. Relationships between the corrected DMOE and MC in the longitudinal direction.

linear relation between increasing sound velocity and decreasing MC when MC was below the FSP. The sound velocity decreased exponentially when free water existed in wood. Similarly, Sakai and Takagi (1993) reported that the velocity of ultrasonic waves decreased relatively rapidly with an increase in MC ranging from 0% to 30%, but relatively slowly with MC from 30% to 170%.

Effect of moisture content on the dynamic Young's modulus

The relationships between dynamic Young's modulus (DMOE) and MC in longitudinal, radial, and tangential directions obtained from Eq. (2) are shown in Figs. 6–8. The curves also show a significant change around the FSP in a two-stage linear relationship. In the first stage, DMOE values decrease rapidly with decrease in MC above the FSP, whereas in the second stage, the DMOE values increase as MC decreases below FSP. This result is similar to the findings reported by Booker et al. (1996), Bucur (1995), and Sakai and Takagi (1993). This result contradicts the usual assumption that physical and mechanical properties of wood remain fairly constant when MC is above FSP.

Chuang (1999) and Wang and Chuang (2000) reported that above the FSP, wood density and DMOE decreased with decrease in MC. Although ultrasonic wave velocity increases slightly with decrease in MC above the FSP, the reverse trend in DMOE may be due to the fact that wood density is used to calculate DMOE. DMOE values were calculated using the parameter of density. Thus, the effect of free water in the cell cavity on the ultrasonic wave velocity needs further study in order to evaluate wood quality in living trees more efficiently by ultrasonic wave.

Effect of the free water in cell cavity on ultrasonic-wave velocity

The effective density and ultrasonic wave velocity at various test stages were substituted into the theoretical equation in order to calculate the DMOE, which tended to remain constant as MC was reduced from a water-saturated condition to the FSP. The effective

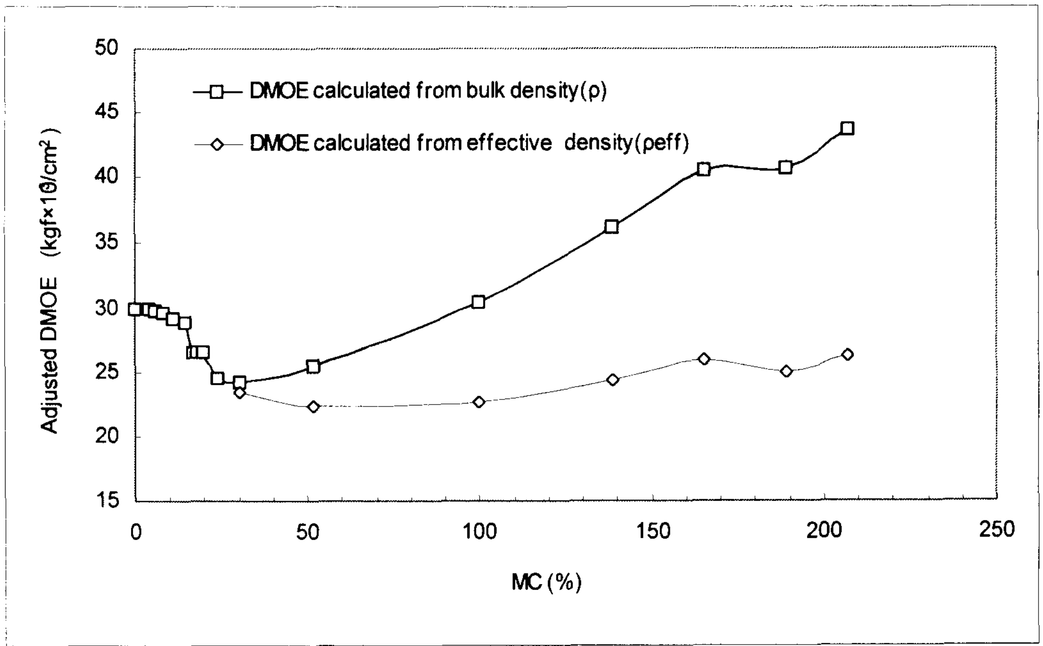

FIG. 7. Relationships between the corrected DMOE and MC in the radial direction.

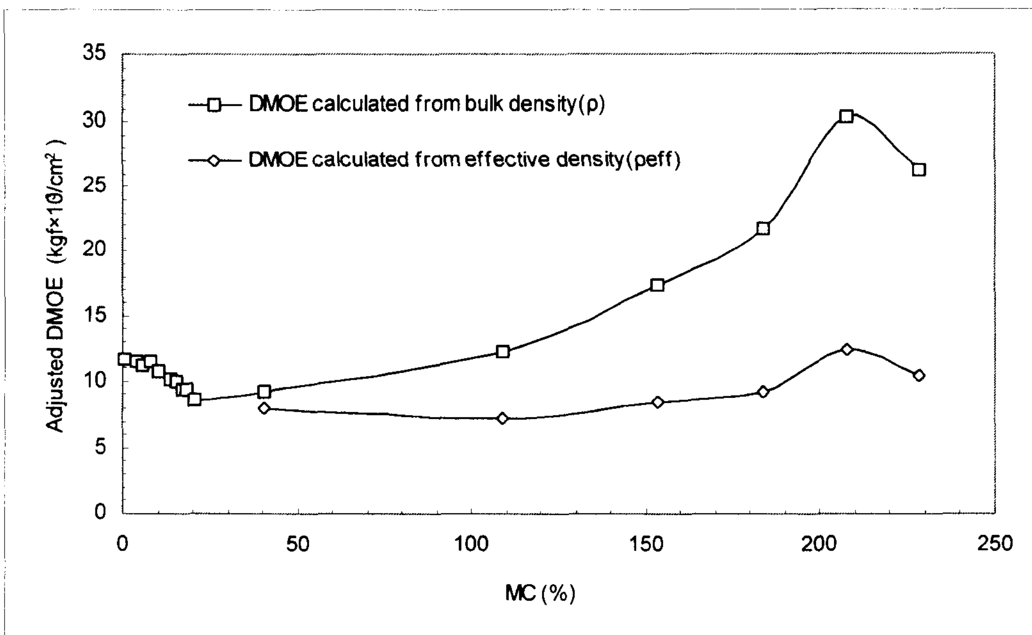

FIG. 8. Relationships between the corrected DMOE and MC in the tangential direction.

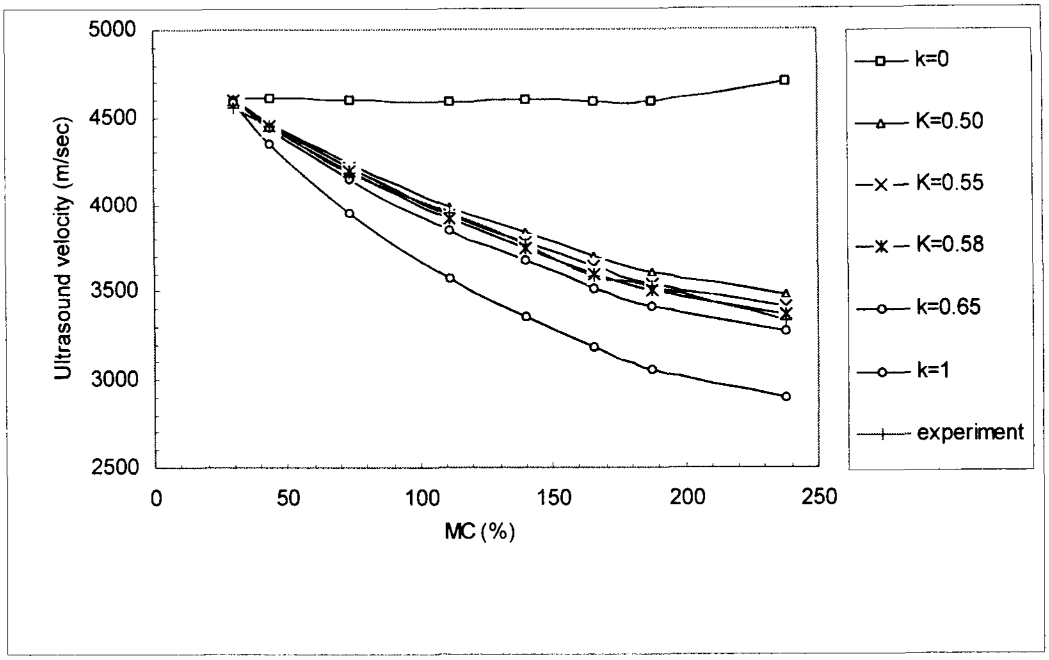

FIG. 9. Relationships between moisture content and velocity for ultrasonic wave to calculating the optimum value of the mobility of free water for the longitudinal specimens.

density (ρ_{eff}) above the FSP may be calculated by Eq. (4) (Sobue 1993), which defines the "k" value as the ratio of the weight of free water vibrating simultaneously with wood cell-wall substance to the weight of total free water. Above the FSP, the mobility of free water can be expressed by k values.

When the MC is above the FSP, k values are defined as $0 \leqq k \leqq 1$. When $k = 0$, all free water vibrates adversely with the cell-wall substance; when the $k = 1$, all free water vibrates simultaneously with the cell-wall substance. When k value increases, the relationship between the effective density and MC is significant (Chuang 1999; Wang and Chuang 2000).

The average of MC at various test stages and the average oven-dried densities measured from the Taiwania specimens were substituted into Eq. (4) to calculate effective density, using k values from 0.0 to 1.0. The effective densities were further substituted into Eq. (5) to calculate ultrasonic wave velocities at various MCs. The least-squares method was used for searching the optimal k value of free water mobility. The relationships between the adjusted longitudinal, radial, and tangential ultrasonic wave velocities and MC above FSP for Taiwania specimens at various k values show that the empirical curves for $k = 0.58$, 0.33, and 0.01 best fit the actual curves. Relationships between the experimental velocity and the velocity of various test stages obtained by equations with MC are shown in Figs. 9–11. These values were somewhat lower than those of 0.78 and 0.79 for Japanese cedar and Hinoki at 200 kHz reported by Sobue (1993), and 0.7 for Japanese cedar at 16 kHz reported by Chuang (1999) and Wang and Chuang (2000). However, it was obvious that more free water vibrated simultaneously with cell-wall substance when the ultrasonic wave was in the longitudinal direction than when it was in the radial or tangential direction. This confirms that the attenuation coefficients increase with the frequency of both longitudinal and shear waves. Attenuation is lowest in the longitudinal direction and highest in the tangen-

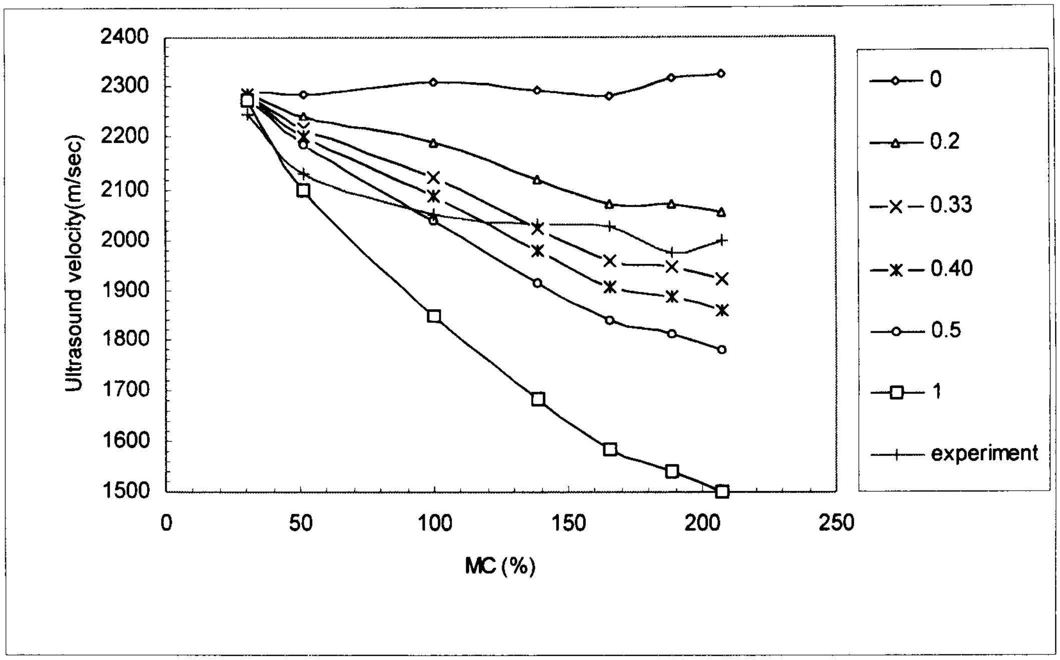

FIG. 10. Relationships between moisture content and velocity for ultrasonic wave to calculating the optimum value of the mobility of free water for radial specimens.

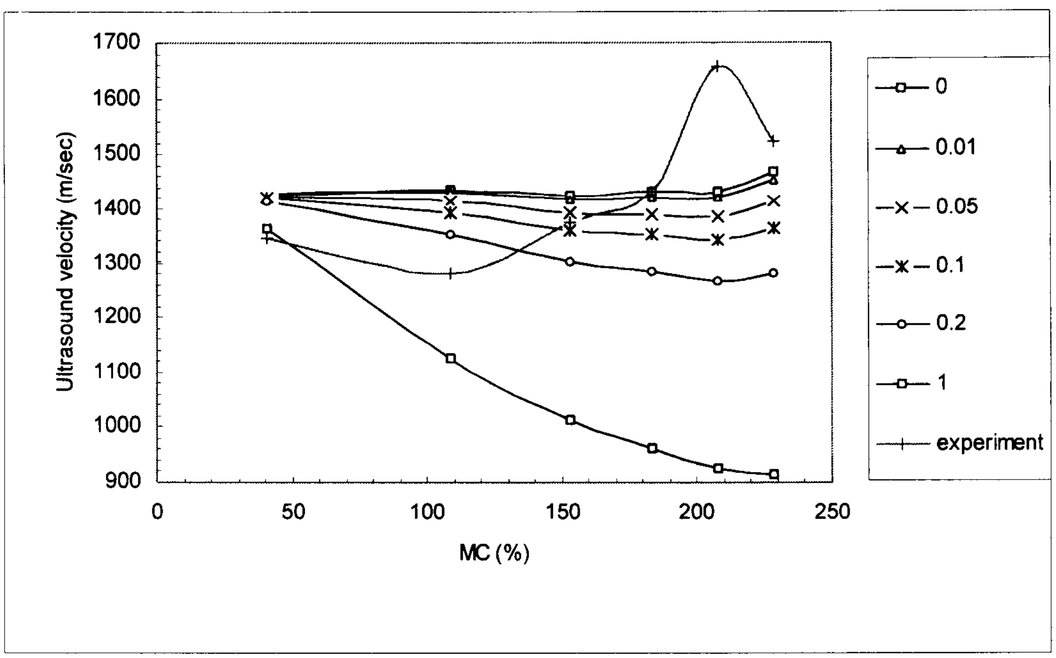

FIG. 11. Relationships between moisture content and velocity for ultrasonic wave to calculating the optimum value of the mobility of free water for tangential specimens.

TABLE 3. *The ultrasonic wave properties of three different type specimens of Taiwania above the FSP.*

Specimens	Moisture content (%)	Ultrasonic wave velocity (m/sec)	Dynamic modulus of elasticity × 10^3 (kgf/cm^2)	Effective density (m/sec)	Adjusted DMOE × 10^3 (kgf/cm^2)
Longitudinal direction	29.9[a]	4555.9 (287.7)[b]	92.3 (9.8)	0.428	90.6
	43.8	4455.6 (261.7)	97.3 (8.4)	0.455	92.2
	74.1	4178.6 (288.6)	103.9 (12.0)	0.515	91.8
	111.4	3944.5 (340.9)	114.9 (18.1)	0.591	93.9
	139.8	3762.7 (355.0)	117.1 (18.9)	0.645	93.1
	166.0	3588.7 (415.6)	119.1 (25.3)	0.697	91.7
	187.5	3525.4 (354.2)	123.8 (22.5)	0.739	93.7
	237.8	3335.4 (354.0)	123.7 (24.2)	0.798	90.6
Radial direction	30.3	2245.6 (96.9)	24.2 (3.1)	0.454	23.3
	51.6	2128.9 (85.3)	25.4 (3.7)	0.482	22.3
	99.73	2052.7 (76.5)	30.5 (4.7)	0.527	22.6
	138.5	2030.3 (105.7)	36.2 (6.7)	0.578	24.3
	165.6	2027.6 (75.1)	40.5 (5.4)	0.617	25.9
	189.0	1975.3 (107.2)	40.6 (6.7)	0.625	24.9
	207.1	1999.5 (40.8)	43.6 (3.9)	0.641	26.1
Tangential direction	40.6	1346.3 (102.0)	9.2 (1.8)	0.436	8.1
	108.8	1280.5 (111.6)	12.2 (3.0)	0.436	7.3
	153.4	1372.6 (151.4)	17.3 (4.5)	0.440	8.5
	183.7	1433.6 (266.2)	21.7 (9.2)	0.439	9.2
	207.8	1655.9 (198.4)	30.3 (7.5)	0.445	12.4
	228.3	1522.8 (240.1)	26.3 (8.8)	0.443	10.5

[a] Average values.
[b] Number in ( ) is standard deviation.

tial direction of wood. The attenuation illustrates that the higher internal friction is observed in the tangential direction (Bucur 1995).

The adjusted dynamic Young's modulus for ultrasonic wave

Skaar (1988) indicates that below the FSP the mechanical properties of wood appear to increase with decreasing MC, whereas above the FSP, the mechanical properties were independent of MC.

Using k = 0.58, 0.33, and 0.01, the effective densities and ultrasonic velocities at various stages were substituted into Eq. (6) to calculate the dynamic Young's moduli in the longitudinal, radial, and tangential directions. Figures 6–8 show the relationships between the adjusted dynamic Young's modulus (DE) measured from apparent and effective densities and average MC. The adjusted dynamic Young's moduli remain constant above the FSP. This result is in agreement with the fact that the physical and mechanical properties of wood remain fairly constant beyond the FSP. It is strongly recommended to use the effective density and adjusted DMOE in the MC range above the FSP when estimating physical properties for living trees, logs, and sawn-timbers by ultrasonic wave. The variation of ultrasonic wave velocity, DMOE, and adjusted DMOE with different MC stages in the three different type specimens are shown in Table 3.

CONCLUSIONS

The effects of average MC on the ultrasonic velocity, dynamic Young's modulus, and the mobility of free water during desorption from a water-saturated condition were examined for Taiwania plantation lumber. The results are summarized as follows:

1) The ultrasonic wave velocity in the longitudinal and radial directions tended to increase with a decrease in MC. The relationship could be expressed as a second-

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

2) The ultrasonic wave velocity in the tangential direction tended to decrease with decreasing MC to 70%; below 70%, the ultrasonic wave velocity tended to increase with decreasing MC.
3) The DMOE versus MC curve showed a significant change point around the FSP—that is, above the FSP, DMOE values tended to decrease rapidly with a decrease in MC, whereas below the FSP, DMOE values tended to increase gradually with decrease in MC.
4) The k values for ultrasonic waves in the longitudinal, radial, and tangential directions of Taiwania lumber were estimated to be 0.58, 0.33, and 0.01, respectively. This suggested that above the FSP there is about 58%, 33%, and 1% of free water vibrating simultaneously with the cell-wall substance when subjected to ultrasonic pulse.
5) The adjusted DMOE tended to remain constant with MC during the desorption process from the water-saturated condition to the FSP. This result is in agreement with the fact that the physical and mechanical properties of wood remain fairly constant when the MC is above the FSP.

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