Application of Nondestructive Methods to Evaluate Mechanical Properties of 32-Year-Old Taiwan Incense Cedar (*Calocedrus formosana*) Wood

Chih-Ming Chiu,[a] Chih-Hsien Lin,[b] and Te-Hsin Yang [b,]*

The objective of this work was to assess the physical and mechanical properties of standing Taiwan incense cedar (*Calocedrus formosana*) using nondestructive techniques (NDT). In addition, the relationship between characteristics of standing trees and wood properties was established. Results indicated that the velocity values and bending properties decreased as tree height increased. In addition, velocity values of specimens were greater than those of logs and standing trees. After regressive analysis, the correlation coefficients (*r*) were 0.79 for standing trees and logs and 0.70 for logs and specimens. Not only the velocities measured by ultrasonic wave (V_u), tap tone (V_f), and vibration (V_t) methods, but dynamic MOE also correlated well with the static bending properties of specimens. In addition, the values of dynamic and static MOE showed the following trend: $DMOE_u$ > $DMOE_f$ > $DMOE_t$ > MOE. For all specimens, the *r* values were found to be 0.92 for MOE and $DMOE_t$, and 0.75 for MOR and $DMOE_t$. Therefore, it was assumed that the nondestructive testing methods can provide basic information about standing trees and specimens for future management practices and utilization of Taiwan incense cedar.

Keywords: Calocedrus formosana; Nondestructive techniques; Ultrasonic wave method; Tap tone method; Vibration method

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Nomenclature

V_u	ultrasonic wave velocity
V_f	tap tone sound velocity
V_t	longitudinal vibration velocity
ρ	density based on the mass-to-volume ratio
$DMOE_u$	dynamic MOE calculated by $V_u^2 \times \rho$
$DMOE_f$	dynamic MOE calculated by $V_f^2 \times \rho$
$DMOE_t$	dynamic MOE calculated by $V_t^2 \times \rho$
DBH	diameter at breast height
CW	crown width
CL	length of log below the live crown
H	total tree height

INTRODUCTION

Taiwan incense cedar (*Calocedrus formosana*), a conifer endemic to Taiwan, is a highly valuable species widely used in furniture, artistic carvings, decoration, construction, and building materials. Because of its good physical and mechanical performance, *C. formosana* has been considered as one of the most important plantation tree species in Taiwan during the last 20 years (Tsai *et al*. 2010). In addition, Taiwan incense cedar was also listed as endangered on the IUCN's (International Union for Conservation of Nature) global red list of conifers (Lu and Pan 1998). Therefore, the restoration of this species is very important. The extensive planting of Taiwan incense cedar under the Overall Reforestation Program can be the first step towards restoration. According to the requirements of the International Conifer Conservation Program (ICCP) of the IUCN, the restoration of Taiwan incense cedar should include a high level of genetic diversity, which is a prerequisite for subsequent sustainable management and effective utilization. However, decreasing the tending cost and improving the wood quality of plantations are the management problems that have attracted the most attention.

In recent years, the nondestructive evaluation method has been widely used to inspect the properties of wood and wood products. Nondestructive evaluation of materials is, by definition, the science of identifying the physical and mechanical properties of a piece of material without altering its end use capabilities and using this information to make decisions regarding its appropriate application. Such evaluations rely on nondestructive testing technologies (NDT) to provide accurate information pertaining to the properties, performance, or condition of the material in question (Ross *et al.* 1998). Currently, worldwide research and development efforts are underway to examine the potential use of a wide range of NDT techniques for evaluating standing trees and wood members. A wide range of NDE techniques, including low frequency vibration, stress waves, ultrasound, near infrared, X-ray, and mechanical probing technologies, have been investigated and are being adopted by industry (Brashaw *et al*. 2009). Among these NDT techniques, the ultrasonic and stress wave test has become widely used to evaluate the strength properties of living trees, logs, sawn timbers, and wood-based materials because of its rapid, portable, cost-effective, and easily used performance.

In previous studies, Ross *et al.* (1997) established the relationship between the modulus of elasticity of log and lumber using longitudinal stress wave techniques. Chuang and Wang (2001) evaluated the standing tree quality of Japanese cedar using the stress and ultrasonic wave methods and pointed out that the dynamic MOE of the standing Japanese cedar was somewhat affected by the testing methods used. They also indicated that the dynamic MOE of the wood in the standing trees varied with the growth conditions, including DBH class, percentage of latewood, density, *etc.* Wang *et al.* (2002) indicated small-diameter jack pine and red pine logs can be successfully evaluated by the longitudinal stress wave technique. The dynamic MOE of logs correlated well with the static MOE for both species. Bucur (2005) assessed the wood quality of standing trees using ultrasonic velocity methods and ultrasonic tomographic imaging techniques. Karlinasari *et al.* (2008) investigated the usefulness of the nondestructive ultrasonic method for evaluating wood strength and the stiffness of *Gmelina* from several positions in the tree, both vertically and horizontally. The results indicated the effect of the position of a specimen within a tree can be identified by the ultrasonic wave velocity. In addition, dynamic MOE followed a similar trend as the MOE and MOR. There was good correlation between ultrasonic velocity and static bending test values. Yin *et al*. (2010) investigated the mechanical properties of Chinese fir plantation wood with three acoustic-based NDTs and established the methods of evaluating plantation wood properties at standing trees and at logs. Yin *et al*. (2011) also predicted the plantation wood quality of green logs using vibration frequency and stress wave method and indicated that both acoustic techniques were effective predictors of wood quality.

These results influenced the hypothesis that nondestructive techniques may be useful to assess the wood quality in Taiwan incense cedar standing trees. The objectives of this study were to assess the properties of Taiwan incense cedar standing tree using nondestructive techniques, as well as the relationships among the different velocity values, dynamic MOE, and static bending properties.

MATERIALS AND METHODS

Study Site and Tree Measurements

The study site was located in the Lianhuachih Research Center of the Taiwan Forestry Research Institute (TFRI), Nantou County, Taiwan. The site altitude was approximately 750 m above sea level. According to the Lienhuachih Station, mean annual precipitation since 1961 has been approximately 2285 mm, mean annual relative humidity has been approximately 87.1%, and mean annual temperature has been 20.8 °C. From this site, a total of 12 sample trees that were about 32 years old were selected for study. Tree levels were also classified by their DBH; suppressed tree group, intermediate tree group, and dominant tree group.

Figure 1 shows the experimental procedure of this study. A vertical line was painted near the base of each sample tree on the north side before felling. The outside bark diameter at breast height (DBH) and crown width (CW), which was calculated from crown projection length in two opposite directions (north to south and east to west), were measured. After noting the east-, west-, south- and north-facing stem surfaces, the transversal ultrasonic wave velocity of standing trees was measured from north to south ($V_{n\text{-}s}$) and east to west ($V_{e\text{-}w}$) at DBH. In addition, the longitudinal ultrasonic wave velocity of standing trees was also measured at each side of DBH. After ultrasonic testing of standing tree, each sample tree was felled with a chainsaw, and the total tree height (*H*) and the length of log below the live crown (CL) were then measured and recorded.

After basic standing tree measurement, four logs 60 cm in length were cut from the felled trees. They were defined as: 1.3 meter (DBH), one quarter height of tree (1/4*H*), half height of tree (1/2*H*), and three-quarter height of tree (3/4*H*). Figure 2 shows the positions of heartwood (No. 1 to No. 4) and sapwood (No. 5 to No. 8). The ultrasonic wave velocities were measured in these eight positions for the four logs. Figure 2 also shows the cutting pattern for the horizontal position sample with dimensions of 20 × 20 mm in cross-section and 400 mm long in accordance with CNS 454 (2005) for nondestructive and static bending tests.

A total of 219 specimens were prepared. All specimens were also conditioned in a controlled-environment room at 20±1°C and 65±3% relative humidity to have a moisture content of 12% before nondestructive and static bending tests.

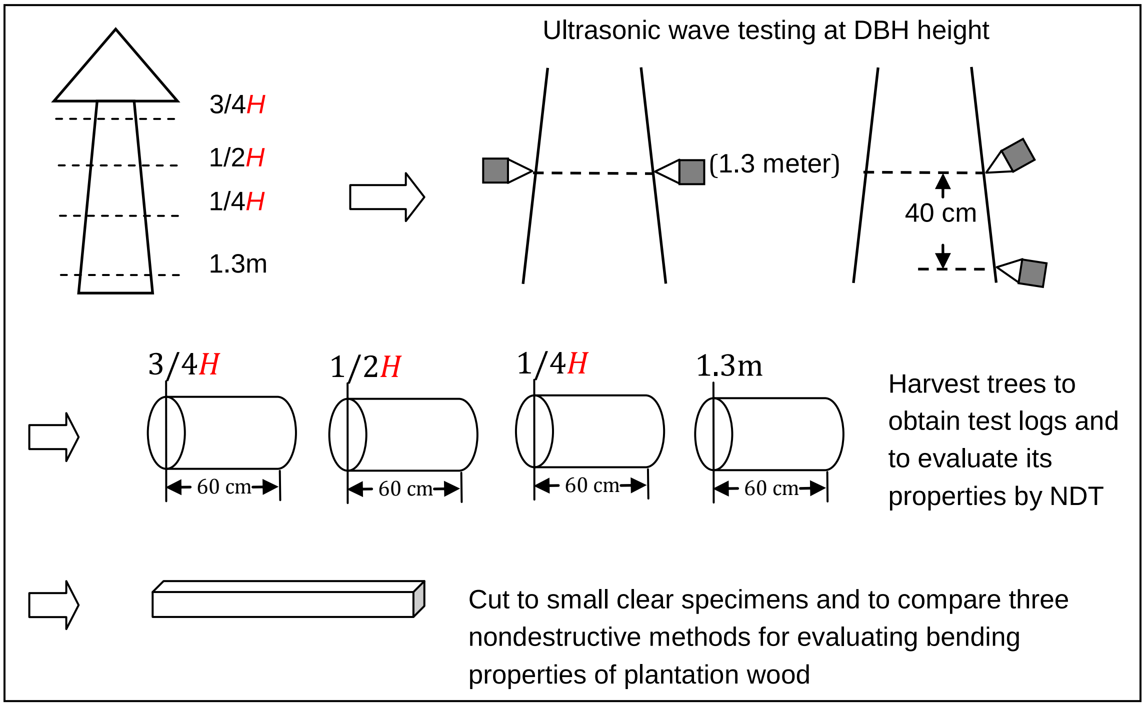

Fig. 1. Experimental Procedure

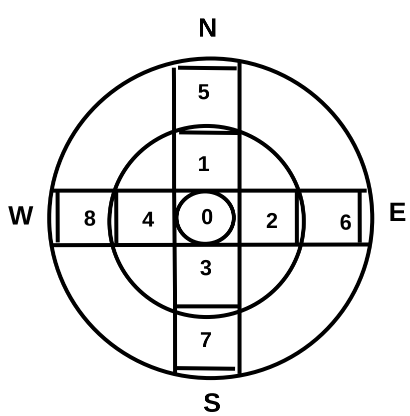

Fig. 2. Notation of specimen logs cut for horizontal position samples. Number 0 represents the pith, numbers 1 to 4 represent heartwood, and numbers 5 to 8 represent sapwood.

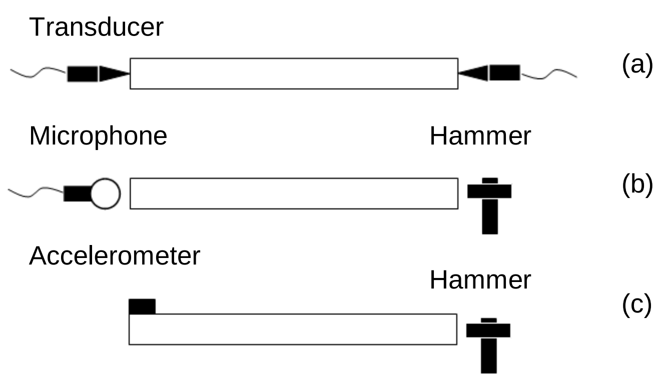

Fig. 3. Three kinds of nondestructive testing methods: (a) ultrasonic wave method, (b) tap tone method, (c) longitudinal vibration

Ultrasonic Wave Testing

A nondestructive test was carried out to measure ultrasonic wave velocity using Sylvatest Duo equipment with a frequency of 22 kHz. The ultrasonic wave method required the placement of two piezoelectric transducers (transmitting and receiving transducers) in contact with opposite ends (Fig 3a). The ultrasonic wave velocity (V_u) and $DMOE_u$ were calculated based on the following formulae,

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

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

where V_u is the ultrasonic wave velocity in the direction parallel to the grain of the specimens, L is the distance between the two transducers, t is the propagation time of the pulse from the transmitting transducer to the receiving transducer, $DMOE_u$ is the dynamic modulus of elasticity in the direction parallel to the grain of specimens, and ρ is the density based on the mass-to-volume ratio of the specimens.

Tap Tone Testing

Tap tone sound velocity (V_f) was calculated from the natural frequency (f_r), which was obtained from the FFT analyzer (Fig. 3b). The tap tone sound velocity (V_f) and dynamic modulus of elasticity ($DMOE_f$) were calculated using the following formulae,

$$V_f = 2 \times f_r \times L \tag{3}$$

$$DMOE_f = V_f^2 \times \rho \tag{4}$$

Longitudinal Vibration Testing

The longitudinal vibration test was carried out using impact-induced vibrations in the direction of the wood fibers made by a small, hard, rubber hammer striking 1 end of the specimen, held horizontally by 2 knife-edge rubber prisms in the center (Fig. 3c). The resulting vibrations were detected by a miniature accelerometer, which was mounted on the specimen using a layer of beeswax, and transmitted into the FFT analyzer to measure the fundamental resonance frequency of each specimen. The $DMOE_t$ of the lumber was calculated by the following formulae,

$$V_t = 2 \times f_t \times L \tag{5}$$

$$DMOE_t = V_t^2 \times \rho \tag{6}$$

where $DMOE_t$ is the modulus of elasticity determined by the transverse vibration, f_t is the fundamental frequency of the longitudinal vibration (Hz), L is the total length of the specimens, and ρ is the density based on the mass-to-volume ratio of the specimens.

Static Bending Testing

The static bending tests were conducted in accordance with the Chinese National Standards CNS 454 (2005), using a Shimadzu UH-10A universal-type testing machine. A concentrated bending load was applied to the center with a span of 14 times the thickness of the specimen (In this study, the span was 280 mm). The proportional limit, ultimate load, and deflection were obtained from the load-deflection curves, and the bending modulus of elasticity (MOE) and modulus of rupture (MOR) were calculated.

$$\mathrm{MOE} = \frac{\Delta P \ell}{4 \Delta y b h^3} \quad (7)$$

$$\mathrm{MOR} = \frac{3 P_{max} \ell}{2 b h^2} \quad (8)$$

where ℓ is the span, ΔP is the difference between upper and lower loads within the proportional limit, Δy is the difference of deflections corresponding to ΔP, P_{max} is the ultimate load, b is the width of the specimen, and h is the thickness of the specimen.

Analysis of Variance

All results were expressed as the mean ± standard deviation (SD). The significance of difference was calculated by Scheffe's test; P values < 0.05 were considered significant.

RESULTS AND DISCUSSION

Physical Characteristics of Standing Trees

Table 1 shows that the average DBHs for suppressed tree, intermediate tree, and dominant tree were 13.6, 19.4, and 26.9 cm, respectively. In addition, total tree height tended to increase with tree DBH. The tree heights (H) for these three classes were 17.1, 19.3, and 20.0 meters, respectively. The differences in tree height were not significant. Table 1 also shows the tree crown width (CW) and tree crown length (CL) values of the three classes. The ANOVA test indicated that there were significant differences in CW values between the suppressed tree and dominant tree classes. The CL values followed a similar pattern.

Table 1. The Tree Characteristics for the Sample Tree

Characteristics	Sample size	DBH (cm)	H (cm)	CL (m)	CW (m)	V_{n-s} (m/s)	V_{e-w} (m/s)
Suppressed tree	3	13.6[a] (0.9)	17.1[a] (1.3)	3.8[a] (1.8)	1.4[a] (0.5)	1393[a] (18)	1409[a] (26)
Intermediate tree	6	19.4[b] (1.7)	19.3[a] (1.2)	7.0[ab] (1.6)	1.8[ab] (0.2)	1580[b] (62)	1631[b] (77)
Dominant tree	3	26.9[c] (0.9)	20.0[a] (1.3)	9.2[b] (0.5)	2.5[b] (0.3)	1647[b] (7)	1656[b] (39)

Values within parentheses are SD.
Different letters within a column indicate a significant difference (P < 0.05).

Ultrasonic Wave Velocity of Standing Trees and Logs

The average horizontal ultrasonic wave velocity, $V_{e\text{-}w}$ (ultrasonic wave velocity measured from east to west in DBH), for the suppressed tree, intermediate tree, and dominant tree were 1409 m/s, 1631 m/s, and 1656 m/s, respectively. The value of $V_{e\text{-}w}$ was also slightly greater than the values of $V_{n\text{-}s}$ (ultrasonic wave velocity measured from north to southern direction in DBH) (1393, 1580, and 1647 m/s for suppressed tree, intermediate tree, and dominant tree, respectively). The longitudinal ultrasonic wave velocities of the logs are shown in Table 2. The dominant tree group had the highest average ultrasonic wave velocity values (4001 m/s for heartwood and 3956 m/s for sapwood specimens). Table 2 also shows the ultrasonic wave velocities of logs decreased from the bottom to top of the tree. The ultrasonic wave velocities of the logs in the tree height position showed a decreasing order as follows: 1.3m > 1/4*H* > 1/2*H* > 3/4*H*.

Table 2. The Longitudinal Ultrasonic Wave Velocities of Logs

Logs		Ultrasonic wave velocity (m/s) in tree height position				
		1.3m	1/4*H*	1/2*H*	3/4*H*	Mean
Heartwood	Suppressed tree	3974^{a}	3971^{a}	3618^{a}	3231^{a}	3699
		(270)	(144)	(210)	(361)	(246)
	Intermediate tree	4355^{b}	4108^{b}	3762^{ab}	3183^{a}	3852
		(153)	(157)	(122)	(325)	(189)
	Dominant tree	4501^{b}	4126^{b}	3972^{b}	3406^{a}	4001
		(160)	(384)	(325)	(187)	(264)
Sapwood	Suppressed tree	4010^{a}	4088^{a}	3685^{a}	3268^{a}	3763
		(263)	(137)	(176)	(358)	(233)
	Intermediate tree	4267^{b}	4151^{a}	3797^{a}	3223^{a}	3860
		(196)	(215)	(218)	(328)	(239)
	Dominant tree	4202^{ab}	4170^{a}	4076^{b}	3377^{a}	3956
		(187)	(178)	(170)	(216)	(187)

Values in parentheses are SD.
Different letters within a column indicate a significant difference ($P < 0.05$).

Selected Velocity Values of Specimens

Tables 3 and 4 present the V_u, V_f, and V_t values of the specimens. The average V_u values of sapwood for the intermediate and dominant tree were greater than those of heartwood by about 7.7% and 5.6%, respectively. Similar results were also shown in the V_f and V_t values. The average velocity values of sapwood for the intermediate and dominant tree were about 8.2% and 5.9% (for V_f values), and about 8.5% and 5.6% (for V_t values) greater than those of heartwood. The V_u, V_f, and V_t values of specimens decreased as tree height increased. Compared to the V_u values of the logs and standing trees, it was found the V_u values of specimens were greater than those of logs and standing trees. It could be generalized that the logs cut from standing trees had green moisture content and growth stress, in addition, the logs showed more variation in surface conditions and more frequent occurrences of wood defects than the small, clear specimens (Wang *et al.* 2002).

Table 3. Physical Characteristics, Dynamic MOE, and Static Bending Properties for Heartwood of Taiwan Incense Cedar Specimens

		Density (g/cm^3)	V_u (m/s)	V_f (m/s)	V_t (m/s)	$DMOE_u$ (GPa)	$DMOE_f$ (GPa)	$DMOE_t$ (GPa)	MOE (GPa)	MOR (MPa)
Suppressed tree						Ns				
Intermediate tree	1.3H	0.68[a]	4402[a]	4041[a]	3874[a]	13.14[a]	11.08[a]	10.20[a]	8.18[a]	99.8[a]
		(0.06)	(386)	(395)	(363)	(1.78)	(1.70)	(1.62)	(1.26)	(19.6)
	1/4H	0.69[a]	4304[a]	3924[a]	3794[a]	12.70[a]	10.55[a]	9.88[a]	7.80[a]	94.7[a]
		(0.04)	(307)	(297)	(279)	(1.47)	(1.26)	(1.26)	(0.81)	(15.3)
	1/2H	0.63[a]	4315[a]	3911[a]	3729[a]	11.77[a]	9.65[a]	8.77[a]	7.31[a]	92.3[a]
		(0.02)	(281)	(179)	(159)	(1.40)	(0.77)	(0.67)	(0.73)	(4.2)
	Mean	0.67	4340	3959	3799	12.54	10.43	9.62	7.76	95.6
		(0.04)	(324)	(291)	(267)	(1.55)	(1.24)	(1.18)	(0.93)	(13.0)
Dominant tree	1.3m	0.64[a]	4816[b]	4356[b]	4179[b]	14.87[c]	12.17[b]	11.20[b]	8.86[b]	100.7[b]
		(0.03)	(295)	(311)	(294)	(1.57)	(1.52)	(1.38)	(1.02)	(9.7)
	1/4H	0.66[a]	4548[a]	4126[ab]	3976[ab]	13.70[b]	11.30[b]	10.49[b]	8.35[b]	93.3[ab]
		(0.06)	(376)	(411)	(370)	(1.54)	(1.69)	(1.46)	(0.99)	(16.7)
	1/2H	0.62[a]	4377[a]	3970[a]	3871[a]	11.92[a]	9.82[a]	9.33[a]	7.52[a]	84.0[a]
		(0.02)	(229)	(247)	(183)	(0.93)	(0.94)	(0.69)	(0.75)	(24.3)
	Mean	0.64	4580	4151	4009	13.50	11.10	10.34	8.25	92.7
		(0.04)	(300)	(323)	(282)	(1.34)	(1.39)	(1.18)	(0.92)	(16.9)

Values in parentheses are SD.
Ns means no heartwood sample available due to small diameter
Different letters within a column indicate a significant difference ($P < 0.05$).

Dynamic and Static Properties of Specimens

The values of dynamic MOE ($DMOE_u$, $DMOE_f$, and $DMOE_t$) and static MOE are shown in Tables 3 and 4. Dynamic MOE and static MOE showed similar trends, in that the average MOE values of sapwood were greater than those of heartwood. In addition, the strength variations (SD values) of the dominant tree group were lower than those of the intermediate tree group.

Relative to the height of the tree, the values of dynamic and static MOE showed similar trends to the velocity values. They presented a decreasing trend as follows: ¼ *H* > ½ *H* > ¾ *H*. This result is in agreement with a previous study (Zhang *et al.* 2006) that illustrated lumber MOE decreased from the butt to top logs for their test stand densities. In addition, an increased proportion of juvenile wood at the top of the standing tree was considered a reason for MOE decreasing from butt to top logs.

Table 4. Physical Characteristics, Dynamic MOE, and Static Bending Properties for Sapwood of Taiwan Incense Cedar Specimens

		Density (g/cm^3)	V_u (m/s)	V_f (m/s)	V_t (m/s)	$DMOE_u$ (GPa)	$DMOE_f$ (GPa)	$DMOE_t$ (GPa)	MOE (GPa)	MOR (MPa)
Suppressed tree	1.3m	0.59^{a}	4703^{b}	4486^{b}	4283^{b}	13.06^{b}	11.90^{b}	10.87^{b}	8.34^{b}	92.0^{a}
		(0.05)	(211)	(205)	(215)	(1.29)	(1.37)	(1.45)	(1.07)	(10.6)
	1/4H	0.58^{a}	4896^{b}	4583^{b}	4313^{b}	14.05^{b}	12.31^{b}	10.95^{b}	8.43^{b}	84.5^{a}
		(0.04)	(386)	(305)	(353)	(2.36)	(1.91)	(2.06)	(1.09)	(19.3)
	1/2H	0.59^{a}	4496^{b}	4180^{b}	3984^{b}	11.92^{ab}	10.33^{ab}	9.38^{ab}	7.37^{ab}	85.5^{a}
		(0.04)	(357)	(339)	(323)	(2.19)	(1.98)	(1.83)	(1.39)	(13.8)
	3/4H	0.58^{a}	3949^{a}	3683^{a}	3472^{a}	9.12^{a}	8.03^{a}	7.16^{a}	5.66^{a}	71.8^{a}
		(0.03)	(324)	(472)	(509)	(1.79)	(2.30)	(2.24)	(0.82)	(10.5)
	Mean	0.58	4511	4233	4013	12.04	10.64	9.59	7.45	83.5
		(0.04)	(320)	(330)	(350)	(1.91)	(1.89)	(1.89)	(1.09)	(13.6)
Intermediate tree	1.3m	0.65^{a}	4949^{c}	4591^{c}	4422^{c}	15.91^{c}	13.68^{c}	12.70^{c}	9.64^{c}	104.6^{b}
		(0.04)	(284)	(201)	(197)	(1.79)	(1.25)	(1.27)	(0.79)	(12.0)
	1/4H	0.64^{a}	4986^{c}	4555^{c}	4346^{c}	15.92^{c}	13.30^{c}	12.12^{c}	9.48^{c}	104.0^{b}
		(0.04)	(241)	(254)	(216)	(1.26)	(1.28)	(1.16)	(0.91)	(9.6)
	1/2H	0.64^{a}	4641^{b}	4263^{b}	4107^{b}	13.69^{b}	11.56^{b}	10.74^{b}	8.49^{b}	98.6^{b}
		(0.03)	(273)	(253)	(270)	(1.37)	(1.23)	(1.31)	(0.82)	(8.2)
	3/4H	0.64^{a}	4119^{a}	3740^{a}	3618^{a}	10.88^{a}	8.98^{a}	8.40^{a}	6.58^{a}	84.9^{a}
		(0.04)	(328)	(300)	(276)	(1.38)	(1.20)	(1.07)	(0.93)	(13.1)
	Mean	0.64	4674	4287	4123	14.10	11.88	10.99	8.55	98.0
		(0.04)	(281)	(252)	(240)	(1.45)	(1.24)	(1.20)	(0.86)	(10.8)
Dominant tree	1.3m	0.63^{a}	5079^{b}	4576^{b}	4389^{b}	16.33^{c}	13.26^{b}	12.20^{b}	9.28^{b}	100.3^{b}
		(0.02)	(210)	(208)	(214)	(1.10)	(0.96)	(0.97)	(0.87)	(11.0)
	1/4H	0.63^{a}	4964^{b}	4512^{b}	4350^{b}	15.52^{bc}	12.84^{b}	11.92^{b}	9.19^{b}	98.5^{ab}
		(0.03)	(278)	(281)	(259)	(1.31)	(1.33)	(1.12)	(0.58)	(7.1)
	1/2H	0.61^{a}	4908^{b}	4448^{b}	4285^{b}	14.61^{b}	12.00^{b}	11.14^{b}	8.47^{b}	95.2^{ab}
		(0.02)	(176)	(181)	(169)	(0.94)	(0.89)	(0.86)	(0.68)	(6.3)
	3/4H	0.61^{a}	4399^{a}	4046^{a}	3917^{a}	11.79^{a}	9.97^{a}	9.34^{a}	7.29^{a}	87.4^{a}
		(0.01)	(173)	(49)	(61)	(0.82)	(0.17)	(0.19)	(0.43)	(3.7)
	Mean	0.62	4838	4396	4235	14.56	12.02	11.15	8.56	95.3
		(0.02)	(209)	(180)	(176)	(1.04)	(0.84)	(0.79)	(0.64)	(7.0)

Values within parentheses are SD.
Different letters within a column indicate a significant difference ($P < 0.05$).

The values for dynamic and static MOE showed the following trend: $DMOE_u$ > $DMOE_f$ > $DMOE_t$ > MOE. The modulus of elasticity values obtained using nondestructive testing methods were usually higher than those from the static test. This is because wood is a visco-elastic and highly impact-adsorbent material (Halabe *et al.* 1997). Concerning the wood vibration characteristics, the restored elastic force is proportional to the displacement, and the dissipative force is proportional to the velocity. Therefore, when force is applied to wood for a short time, the wood displays solid elastic behavior. With a longer application of force, its behavior equals that of a viscous liquid. This behavior can be seen more clearly in the static bending test (long duration) than in the ultrasonic test. Thus, the modulus of elasticity determined by the ultrasound method is usually greater than that obtained by static deflection (Oliveira *et al.* 2002). The same authors also pointed out that the results of the dynamic test were 20 percent higher than those of the static test. Similar results were also reported by Haines *et al.* (1996) and Haines and Leban (1997), who found that the mean value of Young's modulus from the longitudinal ultrasonic method exceeded the MOE by about 17 to 22%. In these three nondestructive tests, the values of $DMOE_v$ measured by the vibration test were close to the static MOE values. This result agrees with a previous report by Burdzik and Nkwera (2002) who pointed out that the $DMOE_t$ was around 5% higher than the MOE. In a previous study (Wang *et al.* 2008), it was also found that the values of $DMOE_t$ were only 0.7%, 5.7%, 1.4%, and 1.8% greater than those of MOE for Japanese cedar, Taiwania, Douglas fir, and Southern pine, respectively. Compared to the MOE values, the values of MOR also decreased as tree height increased. The average MOR values of sapwood (98.0 MPa and 95.3 MPa for the intermediate and dominant trees) were about 2.5% and 2.8% greater than those of heartwood, which were 95.6 MPa and 92.7 MPa for the intermediate and dominant trees.

Correlation among Velocities, Dynamic, and Static Properties

Table 5 presents the results obtained from regression analyses among the values for velocity, dynamic MOE, and static MOE of specimens. There were good correlations between velocity (measured from ultrasonic test, tap tone test, and vibration test) and static MOE. The r values were found to be 0.77 (MOE and V_u), 0.83 (MOE and V_f), and 0.85 (MOE and V_t). The correlation between dynamic and static MOE is also shown in Table 5, in which it showed a better relationship than between velocity and static MOE values. The r values were 0.86 (MOE and $DMOE_u$), 0.92 (MOE and $DMOE_f$), and 0.92 (MOE and $DMOE_t$) for combined specimens. Similar results were also reported by Karlinasari *et al.* (2008), who determined the bending strength properties of *Gmelina arborea* wood using a nondestructive ultrasonic test method, indicating the correlation coefficient was 0.96 for $DMOE_u$ and static MOE. Ayarkwa *et al.* (2000) indicated that the dynamic MOE measured from longitudinal vibration was well correlated to static MOE for tropical African hardwoods. Erikson *et al.* (2000) determined the $DMOE_t$ and MOE values of grand fir and lodgepole pine and found the r^2 values to be 0.87 and 0.89, respectively. Burdzik and Nkwera (2002) selected *Eucalyptus grandis* to determine the $DMOE_t$ and MOE; the r^2 value was 0.813.

From Table 5, the regression coefficients of velocity (measured from the ultrasonic test, tap tone test and vibration test) and MOR were positive, indicating the values of MOR increased with increasing velocity values. In addition, the relationship between dynamic MOE and MOR is also shown in Table 5. It was found that the relationship between DMOE and MOR was positively correlated; the r values were 0.69

(MOR and $DMOE_u$), 0.72 (MOR and $DMOE_f$), and 0.75 (MOR and $DMOE_t$) for combined specimens. Although the determined coefficients were lower, the linear regression analyses for these relationships meant the developed regression models were statistically significant at a 0.001 confidence level. Similar results were also reported by Wang *et al.* (2005), who evaluated the bending properties of young Taiwania trees grown with different thinning and pruning treatments using a nondestructive method. The results showed interrelations among V_u, DMOE, and MOR and can be represented by positive linear regression models. The r^2 values were 0.36 for MOR and V_u, and 0.52 for MOR and DMOE. The results also agreed with previous experimentation (Wang *et al.* 2005). Therefore, it is highly recommended that the ultrasonic wave test, tap tone test, and vibration test be used to nondestructively evaluate the bending properties of wood. Furthermore, the relationships and statistical models between MOE, MOR and DMOEt of wood are shown in Figs. 4 and 5, respectively. Based on these models, it was found that DMOEt could be a better predictor to evaluate the bending properties of Taiwan incense cedar wood suitably.

Table 5. Correlations Among V_u, V_f, V_t, $DMOE_u$, $DMOE_f$, $DMOE_t$, MOE, and MOR Analyzed by Linear Regression Formulae

Correlation coefficients (r)		V_u	V_f	V_t	$DMOE_u$	$DMOE_f$	$DMOE_t$	MOE
Suppressed tree	MOE	0.69**	0.83**	0.87**	0.81**	0.90**	0.92**	1.00**
	MOR	0.42*	0.61**	0.70**	0.59**	0.73**	0.79**	0.75**
Intermediate tree	MOE	0.82**	0.89**	0.89**	0.89**	0.95**	0.93**	1.00**
	MOR	0.63**	0.64**	0.66**	0.72**	0.71**	0.72**	0.74**
Dominant tree	MOE	0.75**	0.78**	0.72**	0.80**	0.80**	0.77**	1.00**
	MOR	0.58**	0.62**	0.62**	0.64**	0.68**	0.66**	0.71**
Combined	MOE	0.77**	0.83**	0.85**	0.86**	0.92**	0.92**	1.00**
	MOR	0.54**	0.57**	0.63**	0.69**	0.72**	0.75**	0.75**

* Significant at 0.01 level
** Significant at 0.001 level

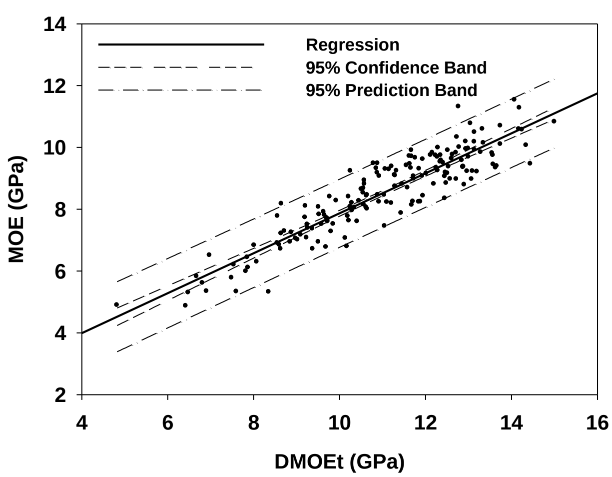

Fig. 4. Relationship between MOE and $DMOE_t$

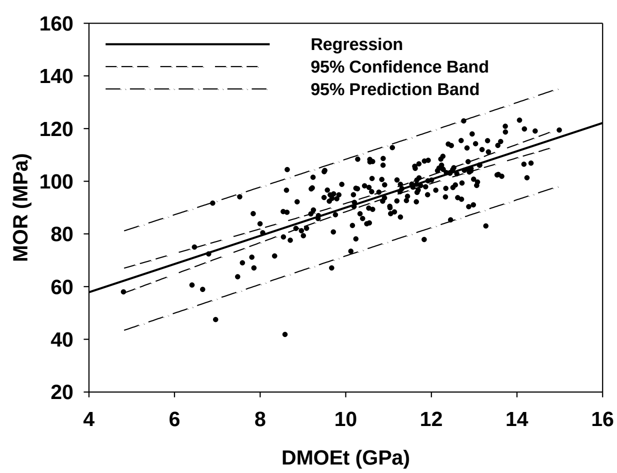

Fig. 5. Relationship between MOR and $DMOE_t$

CONCLUSIONS

1. Based on the results of these experiments, it can be concluded that the velocity values and bending properties of Taiwan incense cedar wood can be successfully evaluated by nondestructive techniques.
2. It was found the average horizontal ultrasonic wave velocities of standing trees increased as the values of DBH increased. The longitudinal ultrasonic wave velocities of logs decreased from the butt to the top of the tree, and in addition, the ultrasonic wave velocities of logs were lower than those of specimens.
3. The experimental results also indicated the values of dynamic and static MOE showed the following trend: $DMOE_u$ > $DMOE_f$ > $DMOE_t$ > MOE. The values of MOE and MOR decreased as the tree height increased.
4. After ultrasonic wave velocity was measured, it was found that the values of *r* were 0.79 for standing trees and logs and 0.70 for logs and specimens. Furthermore, not only were the velocities measured by ultrasonic wave, tap tone, and vibration methods, but the dynamic MOE was also found to be well correlated with the static bending properties of specimens, especially using the vibration method.

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