J Wood Sci (1998) 44:62–68

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Dynamic modulus of elasticity and bending properties of large beams of Taiwan-grown Japanese cedar from different plantation spacing sites*

Received: January 10, 1997 / Accepted: August 12, 1997

Abstract The effect of plantation spacings (types A–E) on the bending strength and dynamic modulus of elasticity of 41-year-old Taiwan-grown cedar (*Cryptomeria japonica* D. Don) was investigated. The results indicate that the highest values for the static bending modulus of elasticity (MOE), modulus of rupture (MOR), and dynamic modulus of elasticity ($E_{D\ell}$, E_{Dt}) occurred in trees obtained from those most densely planted (type A); there was a significant difference between type A and the other four spacing types (B, C, D, and E), but there were no significant differences among those four types. Interrelations among MOE, MOR, $E_{D\ell}$, and E_{Dt} could be represented by positive linear regression formulas, which revealed highly significant differences. The relations among the square value of stress-wave transmission velocity (V_ℓ^2 and V_t^2) and MOE, MOR, $E_{D\ell}$, and E_{Dt}, respectively, could be represented by positive linear regression formulas. The differences were highly significant.

Key words Japanese cedar · Plantation spacing · Stress wave · Bending strength · Dynamic modulus of elasticity

Introduction

It is recognized that the quality and properties of wood are generally affected by the genetic factors of the trees, environmental conditions of the site, silvicultural practices, and wood-processing variables. In general, the volume and height of stands can be controlled directly by plantation techniques, such as thinning and pruning. Better seedling propagation and suitable design of a plantation system may not only increase the biomass production of trees but also achieve an improvement in the quality of lumber/timber.

Because the trunks comprise the major part for wood utilization, the objective of the silvicultural practices should be geared to produce maximum wood volume and straight forms. Reducing the planting density (i.e., increasing the spacing), may increase the effective volume growth of a single tree, but the total volume growth per unit plantation area of stands may be decreased.

In a series of investigations on the wood quality of Japanese cedar (*Cryptomeria japonica* D, Don) trees grown at five sites with different plantation spacing, it was reported that the wood cut from type B plantation spacing (2 × 2 m, 2500 trees/ha) trees had the longest tracheid, the narrowest annual rings, the highest percentage of latewood, and the lowest percentage of heartwood.[1] Also it was reported that the values for density, bending strength (modulus of rupture, or MOR), dynamic modulus of elasticity (E_D), and compression strength of wood cut from trees obtained from the narrower plantation spacing site of type A (1 × 1 m, 10000 trees/ha) and type B were higher than for those obtained from wider plantation spacing sites of type D (4 × 4 m, 630 trees/ha) and type E (5 × 5 m, 400 trees/ha). However, there were no significant differences for shearing strength and impact bending strength among the wood cut from these five plantation spacing sites.[2] Wang and Lin[3] studied the visual grade and bending strength of lumber cut from 41-year-old Japanese cedars grown in five plantation spacing sites using the same sample trees as used in this study but different sections (odd sections of first, third, and fifth). Their results indicated that the highest frequencies of first grade log and special and first grade lumber and the highest values for specific gravity, E_D, modulus of elasticity (MOE), and MOR were seen for trees obtained from type A plantation spacing sites. The lowest values were seen in those cut from the type E site. The E_D, MOE, and MOR values for visually graded special grade lumber were significantly higher than those of second- and third-grade groups.

The purpose of this study was to investigate the effects of plantation spacing on the dynamic modulus of elasticity and bending strength of 41-year-old Taiwan-grown Japanese

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*Part of this report was presented at the International Wood Engineering Conference '96, New Orleans, LA, USA, October 1996 cedar. The interrelations between their strengths and stress-wave transmission velocity was also examined. In addition, the feasibility of using the stress wave method for assessing the quality of wood stands was explored.

Materials and methods

The experimental plantation was located in the no. 173 plot of the third branch station, Chi-Tou working station of the Experimental Forest of National Taiwan University. The area of the experimental site was 1.5 hectares (ha), and it was divided into 15 small plots, 0.1 ha each. Five types of plantation spacing were chosen for this study, and the number of trees per hectare was selected by a random method; each treatment was repeated three times. The five types of plantation spacing, similar to those selected for previous studies, were type A 1 × 1 m (10000 trees/ha), type B 2 × 2 m (2500 trees/ha), type C 3 × 3 m (1110 trees/ha), type D 4 × 4 m (630 trees/ha), and type E 5 × 5 m (400 trees/ha). A 5-m wide interval belt was established between each small plot. The seedlings were 1-year-old vegetative (cuttings) Japanese cedar. Seedlings of the same size that showed vigorous growth were selected for the plantations started in 1950. The planted trees are 41 years old to date. The experimental sites were inspected every 5 years. The number of residual trees on these five spacing plots were noted in our previous report.[1] Stands in the type A plot were thinned in 1965 to increase the growth of residual trees. Thinning intensity was 40%, and the restrained-growth and small-diameter trees were also thinned.

Preparation of specimens

The diameter and height of each tree grown on the 15 small plots were measured. The diameter breast heights (DBHs) and tree heights were noted in our previous report.[1] One mean-diameter tree was selected from each plot, and a total of 15 samples trees were cut in 1991 (41 years old), and the stem of each sample tree was cut into logs at 2.5-m intervals from the base to the top. The first, third, and fifth logs (odd sections) were used in this study, and the even sections (second, fourth, and sixth logs) were used for other experiments.[3] After the grade of each log was determined following the JAS graded standard, they were further band-sawed into lumber sequentially from the north to the south side of the stem according to the cant sawing method,[4] as shown in Fig. 1. All large-beam specimens were 210 cm long, 10 cm wide, and 6 cm thick. Most of the specimens used in this study came from the longitudinal-tangential plane. The diameter of logs varied with the planted spacings, and tree height positions changed; therefore the number of specimens obtained from the various spacings and tree height positions were different. The specimens were conditioned in a controlled-environment room: 20°C and 65% relative humidity (RH).

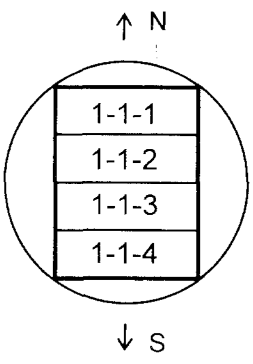

Fig. 1. Notation of large beams cut from north side to south side. *1-1-1* to *1-1-4*, large beam specimens; *N*, north side; *S*, south side

Stress-waves timer test

The stress-waves timer apparatus used in this study included the following parts: (1) temporary wave shape cut card (BE 490) (The Netherlands); (2) signal processor (American); (3) sensors (a sensor stored inside a hammer to detect stress waves, two sensors to detect transferred stress waves); and (4) FAMOS software.

The Vt and E_{Dt} values are predicted by stress-wave propagation by a hammer hitting the heads of nails driven in perpendicular to the grain. Additional experiments were conducted that hit a no. 50 nail about 1 cm into the surface of one end of the specimen, maintaining an angle of 90°. A sensor was placed on another surface. V_ℓ and $E_{D\ell}$ were predicted by stress-wave propagation by a hammer hitting the heads of nails that were driven in parallel to the grain. The set diagram for the stress-wave test is represented in Fig. 2.

Static bending test

Static bending tests were conducted in accordance with the third-point loading method; a Shimadzu model UH- 10A testing machine (Japan) was used. The span was 150 cm, and

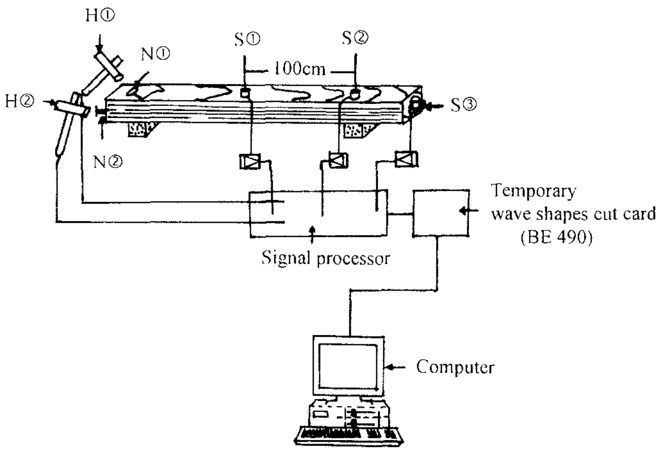

Fig. 2. Set diagram for stress-wave test. *H*, hammer; *N*, nail; *S*, sensor. V_t and E_{Dt} are predicted by hammer①, nail①, sensor①, and sensor③. V_ℓl and $E_{D\ell}$ are predicted by hammer②, nail②, and sensor③

the distance between two loading points was 50 cm. The proportional limit, ultimate load, and deflection were obtained from load-deflection curves; and the MOE and MOR were calculated. The air-dried density in this study was determined by the full size of the specimens, whereas the moisture content was determined by an oven-dried method using small specimens (5 cm long) cut from the end section after the bending test. All MOE, MOR, $E_{D\ell}$, and E_{Dt} values were adjusted to the level of 12% moisture content for easy comparison.

Results and discussions

Conditions for stress waves

A method using a hammer hitting the heads of nails being driven into specimens and another directly hitting the surface of specimens were compared. Significantly rising crests of stress waves were observed with the nail-hitting method; and the Δt values of specimens could be determined more accurately from these rising crests. Moreover, the results were reproducible for the nail-hitting method and hence the variation coefficients of the Δt values collected from each test are smaller than those with the surface-hitting method. Therefore in this study the stress-wave tests were conducted by hitting nail heads.

The effects of the nail angle with respect to the longitudinal axis and the distances between nails and sensors on the stress-wave propagation time were investigated. Results from Duncan's new multiple analysis indicated that these variables had no significant effect on the propagation velocity of stress waves.

Nanami et al.[5] studied methods to measure stress waves and indicated that marked stress wave shapes developed in the specimens hit by hammered nails. They indicated also that the results are reproducible, and so the coefficients of variation were relatively small. In addition, they investigated the effects of supporting specimens using four conditions; that is, the specimens were placed directly on reinforced concrete, PU foam, or a crosstie or were stacked. Results indicated that there are no significant differences among the Δt values obtained for these four conditions. Furthermore, the propagation velocity of stress waves was affected by the hitting power.

Gerhards[6] calculated the MOE of specimens using the damping of stress-wave amplitudes. The results indicated that there was no significant effect of sensor position – the earlywood zone or the latewood zone – on the propagation velocity of stress waves.

Effects of plantation spacing on wood density

The differences in air-dried wood density among the specimens cut from trees of type A to type E spacing were analyzed using the multiple new-range Duncan's test. The results are shown in Table 1. The air-dried wood density obtained from type A spacing trees was significantly greater than that for the other four plantation spacings; there were no significant differences among the densities for types B and D, types C and D, and types C and E. These results are similar to those reported previously by Wang and Lin,[2] who indicated that the largest air-dried wood density of Japanese cedar (in both juvenile and mature wood portions) was seen in trees cut from type A spacing, whereas the lowest density appeared in trees from a type E spacing plantation stand. They were also similar to the result observed from even sections of the same sample trees used in this study.[3] The values of air-dried wood density obtained in this study, however, were higher than those of other studies. This difference is because small clear wood specimens and boards were used in the former studies, and here we used large beams containing high-density knots. Therefore the density of large-beam specimens was slightly high as expected.

The more widely spaced trees had wider widths of earlywood; in general, the boundaries between earlywood and latewood are inconspicuous, and smaller proportions of latewood may have resulted. In contrast, the more closely spaced trees had not only narrower earlywood but also abrupt transmissions between the earlywood and latewood. As a result, they had larger percentages of latewood. Because the increments of growth were concentrated in the earlywood, the variety of latewood widths was not affected significantly by the plantation spacing.[1] Kubo and Jyodo[7] indicated that the percentage of latewood in Japanese cedar commonly was the most important factor affecting wood density, although other factors (e.g., earlywood and latewood) were related. Sumiya et al.[8] indicated that the 41-year-old Japanese cedar grown in the more widely spaced site (2500 trees/ha) had wider annual rings and more extensive growth of earlywood, although the percentage of latewood remained unchanged. Thus the wood density was less than that of lumber cut from trees from narrowly spaced sites (10000 trees/ha and 40000 trees/ha). Zobel[9] indicated that the percentage of latewood in Sitka spruce [*Picea sitchensis* (Bong.) Carr.], Norway spruce [*Picea abies* (L.) Karst], and Scotch pine (*Pinus sylvestris* L.) decreased with the increase in spacing, and they concluded that it is because the more widely spaced trees had wider widths of earlywood.

Effects of plantation spacing on mechanical properties

Modulus of rupture determined by static bending

The largest MOR values were seen for type A spacing logs followed, in order, by logs with type C, type B, type E, and type D spacing. Based on an analysis of the multiple new-range Duncan's test (Table 1), it was found that beams from trees with type A spacing had significantly larger MOR values than logs from the other four plantation spacing specimens. There were no significant differences in MORs among large-beam specimens from type C, type B, and type E, and between type E and type D, spacing. This tendency was similar to the results obtained from the even sections of

Table 1. Analysis of multiple new-range Duncan's test of wood density in air-dried condition, dynamic modulus of elasticity ($E_{D\ell}$, E_{Dt}), MOE, and MOR for the five plantation spacings

Plantation spacing	Type E	Type C	Type D	Type B	Type A
No. of specimens	56	54	69	6	33
Density in air-dried condition of specimens (g/cm^3)[a]	0.419 (0.040)	0.442 (0.039)	0.442 (0.034)	0.447 (0.039)	0.480 (0.066)
CV (%)	9.7	8.7	7.7	8.7	13.8

Plantation spacing	Type E	Type D	Type B	Type C	Type A
No. of specimens	44	47	24	51	32
MOE (kgf/cm^2)[a]	89590 (12735.9)	90150 (11546.9)	96480 (16148.2)	97750 (14134.8)	115000 (18275.1)
CV (%)	14.2	12.8	16.7	14.5	15.9

Plantation spacing	Type D	Type E	Type B	Type C	Type A
No. of specimens	47	44	24	51	32
MOR (kgf/cm^2)[a]	464 (99.2)	494 (96.1)	547 (117.3)	549 (99.8)	654 (158.8)
CV (%)	24.1	19.4	21.4	18.1	24.2

Plantation spacing	Type E	Type D	Type B	Type C	Type A
No. of specimens	45	49	24	49	32
$E_{D\ell}$ (kgf/cm^2)[a]	89150 (11015.5)	91770 (11457.3)	95490 (16285.8)	96600 (14872.4)	115580 (25137.3)
CV (%)	12.4	12.5	17.1	15.4	21.7

Plantation spacing	Type D	Type E	Type B	Type C	Type A
No. of specimens	49	45	24	49	32
E_{Dt} (kgf/cm^2)[a]	88630 (12672.7)	89910 (11252.2)	93010 (20027.2)	99110 (18704.5)	113900 (22073.1)
CV (%)	14.3	12.5	21.5	18.9	19.4

$E_{D\ell}$ and E_{Dt} were predicted by stress-wave propagation by hammer-hitting the head of nails that were driven in the direction parallel and perpendicular to the grain, respectively.

The values of parentheses represent standard deviations.

There was no significant difference in any of the parameters at the 0.01 level.

MOE, modulus of elasticity; MOR, modulues of rupture. CV, coefficient of variation.

[a] Average.

the same sample trees as reported by Wang and Lin.[3] The average MOR values for those two experiments are consistent, although the average MOR values obtained in this study were less than those obtained from small specimens cut from Japanese cedar grown at the same experimental forest site as reported by Wang and Lin.[2]

MOE determined by static bending

The average MOE values for lumber cut from trees with different plantation spacing were, in decreasing order, as follows: type A > type C > type B > type D > type E. According to the results of the multiple new-range Duncan's test (Table 1), it was found that specimens from type A spacing had a significantly larger MOE than those from the other four spacings; there were no significant differences among specimens from other plantation spacings. This tendency is consistent with the results obtained from the specimens cut from even sections of the same sample trees.[3] The average MOE values obtained in this study were 0.8%–18.7% larger than those previously reported,[3] especially those from type E spacing.

Dynamic modulus of elasticity

In regard to the average value of $E_{D\ell}$ (predicted by stress-wave propagation by hammer-hitting the heads of nails driven in parallel to the grain), and E_{Dt} (predicted by stress-wave propagation by hammer-hitting the heads of nails driven in perpendicular to the grain), a decreasing order showed as follows: type A > type C > type B > type D > type E. According to the results shown in Table 1, specimens from type A spacing had significantly larger values than those from the other four spacings, although the differences among these four groups were not significant. This tendency is consistent with the results obtained from the specimens cut from even sections of the sample trees.[3] The average values of $E_{D\ell}$ and E_{Dt} for this study were, respectively, 14.4%–25.8% and 11.4%–26.8%, larger than those previously reported.[3]

Based on the aforementioned results, MOE, MOR, $E_{D\ell}$, and E_{Dt}, values for lumber cut from type A spacing plantation stands were significantly greater than that of the type E spacing. Results reported by Wang and Chen[1] indicated that the juvenile wood zone of Japanese cedar ranged from the pith outward: 7.2–8.0 cm for type A (most densely planted spacing site) and 12.2–15.8 cm for types D and E (most widely planted spacing sites). Therefore specimens obtained from the type A spacing contain more mature wood. In addition, the type A stand was thinned with 40% intensity during the 15th growth years. Hence the thickening growth in type A trees increased with greater speed beyond the 15th growth ring, and their increments were larger than those of the type B trees beyond the 25th annual ring. The percentages of latewood in the zone from the pith to the 20th growth ring of the trees from type A trees were greater than those in type B trees, although a contrary result was observed from the 20th growth ring toward the bark. This finding suggests that the MOR values obtained from type A trees were greater than those from the more widely planted type D and type E trees. This tendency was similar to the results obtained from even sections of the same sample trees in which the greatest frequencies of first grade logs, special and first grade lumber, largest values of specific gravity in air-dried conditions, and the dynamic modulus of elasticity (E_D), MOE, and MOR occurred in trees obtained from the type A spacing. The smallest ones were in the samples cut from the type E group reported by Wang and Lin.,[3] whereas the average values of MOR for those two experiments are consistent. However, the average values of MOR obtained in this study were less than those obtained from the small specimens cut from Japanese cedar grown in the same experimental forest site as reported by Wang and Lin.[2] Our findings are also in agreement with the study reported by Sumiya et al.[8] in which they indicated that higher-density stands exhibited a trend toward increased wood density and dynamic modulus of elasticity.

Moreover, it was found that the values of $E_{D\ell}$ and E_{Dt} for this study were 20%–30% greater than those previously reported.[3] This difference might be due to the different experiment methods used. The values of $E_{D\ell}$ and E_{Dt} for this study were obtained from the sound velocity of stress waves, whereas the E_D values reported from a previous study[3] were obtained from transverse vibration under undamping of natural frequency, measured by the Metriguard model 340 transverse vibration tester. It may also be due to the higher width (b)/thickness (h) ratios for specimens from that experiment, which ranged from 4.0 to 9.5, causing the lower E_D values. Matsumoto[10] indicated that the E_D values are affected by the b/h value and reported that the E_D values decreased rapidly with increasing b/h values, ranging from 2 to 8; the E_D values then remained constant until the b/h values reached 6–8.

Effects of wood density on mechanical properties

The values of MOR, MOE, $E_{D\ell}$, and E_{Dt} for Japanese cedar increased with the increase in wood density (ϱ). Their relations can be represented by the following positive linear regression formulas:

$$\mathrm{MOR} = -178.98 + 1609.9\,\varrho,\ r = 0.596,\ F = 108^{**}$$

$$\mathrm{MOE} = -15250 + 253003\,\varrho,\ r = 0.720,\ F = 211.4^{**}$$

$$\mathrm{E_{Dl}} = -34892 + 297739\,\varrho,\ r = 0.790,\ F = 328^{**}$$

$$\mathrm{E_{Dt}} = -22124 + 267585\,\varrho,\ r = 0.676,\ F = 166^{**}$$

Although their correlation coefficients (r) were not high, significant differences (0.01 confidence level**) existed by the F-test. The r-values for specimens cut from even sections of the same sample trees reported previously[3] were in the range 0.56–0.71. Lower r-values for the above-mentioned linear regression formulas were reported earlier by Lin et al.,[11] whose data were collected from small-diameter logs of Japanese cedar and China fir. Wang and Chen[12] also reported an r-value of 0.66 for the relation between specific gravity and the MOR of China fir, suggesting that the effect of air-dried wood density of plantation timber on their strength may be negligible because there is has more juvenile wood, poor branch-knot characteristics, and heavy, irregular grain. Lin et al.[11] indicated that the specific gravity of Japanese cedar increased with an increased percentage of knots in the specimen. Sato[13] also reported that the specific gravity of wood with knots was 15–20% higher than that of wood without knots. Chow[14] studied the correlation between specific gravity and mechanical properties and indicated a significant correlation for wood speies of Lanata fir. Daiten-u, but a lower correlation coefficient for China fir. Resch and Bastendorff[15] indicated a positive relation between density and MOR and MOE in *Pinus caribea* and *Pinus oocarpa*, with their r-values being 0.79 and 0.71, respectively. Pearson and Ross[16] investigated fast-grown species of Loblolly pine and obtained higher correlation coefficients (0.95 and 0.92). Wang reported that the r-values for the relation between air-dried-based specific gravity and MOE (obtained by the resonant frequency method) and the relations between air-dried-based specific gravity and MOE and MOR were, respectively, 0.620 and 0.675–0.894.[17] Huang et al.[18] indicated that the MOR and MOE values increased with the increase in specific gravity for red oak, but its variation was large.

Correlation among various mechanical properties

Nanami et al.[5,19,20] indicated that the stress-wave method could be used to estimate the quality of standing trees of Japanese cedar. The goals of this study were to investigate the quality of standing trees grown in areas with different spacing and pruning treatment at forest sites in Taiwan. The stress-wave-propagated velocity must be obtained from impacts on the lateral sections of standing trees; it could not be obtained from impacts on the end section of the trunk. Therefore if the correlation between stress-wave-propagated velocity obtained from these two methods could be recognized, the correlations among the stress-wave-propagated velocity and static bending properties (MOE, MOR) could be established. It is expected that the

Table 2. Coefficients of linear regression formulas ($y = a + bx$) for the correlation among mechanical properties and stress-wave-propagated speed

Coefficients				r	F
y	x	a	b		
MOR	MOE	−48.56	59.1×10^{-4}	0.76	294.0**
MOE	$E_{D\ell}$	25338.5	69×10^{-5}	0.79	333.9**
MOE	E_{Dt}	36941.7	58×10^{-5}	0.70	185.9**
MOR	$E_{D\ell}$	74.6	43×10^{-4}	0.66	147.0**
MOR	E_{Dt}	124.1	39×10^{-4}	0.61	118.0**
MOR	V_ℓ^2	−37.25	3×10^{-5}	0.50	62.0**
MOR	V_t^2	167.95	2×10^{-5}	0.38	33.1**
MOE	V_ℓ^2	367.78	45×10^{-4}	0.65	142.3**
MOE	V_t^2	411.19	26×10^{-4}	0.46	50.6**
$E_{D\ell}$	V_ℓ^2	−35008	65×10^{-4}	0.66	148.7**
E_{Dt}	V_t^2	−15264	56×10^{-4}	0.81	369.6**
V_ℓ	V_t	0.549	2070.798	0.68	163.9**

** Highly significant (0.01 confidence level) by F-test.

wood quality of standing trees can be estimated from impacts on the lateral sections.

The correlation among mechanical properties and stress-wave-propagated velocity could be represented by linear regression formulas, summarized in Table 2. Although the correlation coefficients (r) were slightly lower, ranging from 0.38 to 0.81, they were highly significant at the 0.01 confidence level (**), as indicated by the F-test.

Huang et al.[18] reported a high correlation ($r = 0.93$) between sound velocity and the dynamic MOE for red oak, which they obtained using the hammer-hitting method. Chen[21] indicated a highly negative correlation ($r = -0.94$ to -1.00) between propagation times and the dynamic MOE for particleboard measured using stress-transmission velocity. Their correlation coefficients were higher than those obtained in the present study. This difference may be because small, clear specimens were used by Huang et al. and particleboard by Chen; moreover, their specimens had more uniform quality and so were more homogeneous than the large-beam specimens used in this study. Tanaka[22] reported that the correlation coefficient for the linear regression formula between the dynamic MOE and the MOE was 0.6, but the value for the linear regression formula between propagation velocity of ultrasound and MOE was only 0.35 using the ultrasonic method. Therefore the density of specimens could not be ignored when calculating the MOE value. Sandoz[23] studied spruce quality using the ultrasonic method and indicated a high correlation between the sound velocity squared and MOE. Nanami et al.[5] studied the regressions between the values of the square of stress transmission velocity and the dynamic modulus of elasticity, and indicated that the correlation coefficients were high for the wood cut from each forest site. This finding suggests that the variation of timber density at each forest site is small, and so it could be considered constant. A similar tendency was found for the dynamic modulus of elasticity and transmission wave velocity in this study. Therefore the transmission wave velocity may be used as an indicator to assess the of quality of timber.

Conclusions

Based on the results in this study the following conclusions may be drawn.

1. Lumber cut from trees with type A plantation spacing had the highest values for air-dried-based density, bending MOR and MOE, and dynamic MOE ($E_{D\ell}$ and E_{Dt}). A significant difference existed between type A and the other four spacing types (B, C, D, E), but there were no significant differences among those four types.
2. Interrelations among MOE, MOR, $E_{D\ell}$, and E_{Dt} can be represented by positive linear regression formulas. The differences were highly significant.
3. The relations among the squared value of stress-wave-transmission velocity (V_ℓ^2 and V_t^2) and MOE, MOR, $E_{D\ell}$, and E_{Dt}, respectively, can be represented by positive linear regression formulas, with highly significant differences. Therefore transmission-wave velocity may be considered an indicator for assessing the quality of standing trees.

Acknowledgment The investigation reported in this paper was supported financially by the National Science Council of the Republic of China (NSC-86-2313-B-002-097).

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