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Relationships among selected wood properties of 20-year-old Taiwania (*Taiwania cryptomerioides*) trees

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Abstract The relationships between bending properties, compressive strength, tracheid length, microfibril angle, and ring characteristics of 20-year-old Taiwania (*Taiwania cryptomerioides* Hay.) trees were examined. The trees came from different thinning and pruning treatments, but the practices showed no significant effect on the investigated properties. The results showed that based on comparison with the literature, plantation-grown immature Taiwania have noticeably lower average strength properties than mature trees of the same species. Wood density and bending and compressive strengths were not related to either tracheid length or microfibril angle in young Taiwania. There were positive relationships between bending strength and compressive strength. The wood density, ring width, earlywood width, earlywood density, and latewood percentage were the most important predictors of strength by simple linear regressions. The wood density and ring width/earlywood width may be considered as indicators for assessing the bending strength, while wood density and latewood percentage were the best predictors of compressive strength by multiple linear regressions.

Key words Taiwania · Bending strength · Compressive strength

Introduction

In general, the goal of most forest tree silvicultural programs concentrate on increasing height, diameter growth, and stem straightness at young ages. When trees grow older, inclusion of wood properties into silvicultural programs should be a required consideration. The indexes of wood property evaluation include wood density, ring characteristics, bending properties, compressive strength, tracheid length, and microfibril angle among others.

Taiwania is becoming increasingly important as a plantation tree in Taiwan. The major focus of plantations has been as a resource for lumber production. It is well known that the wood quality may vary with genetic factors of the trees, environmental conditions of the site, silvicultural practices, and other considerations. The forest industry in Taiwan is moving toward intensive silviculture. As a result of different intensive silvicultural treatments carried out before rotation, wood properties of plantations have changed. Therefore, there is also considerable interest in young trees for solid wood products.

Concerning research into the wood properties of Taiwania, Chou[1] reported the strength properties of Taiwania trees of different ages, Tang[2] and Wang et al.[3] reported the mechanical properties of Taiwania grown with different planting densities, and Chiu et al.[4] reported the lumber quality of Taiwania grown with different pruning treatments. In addition, Tang[5] reported the within-tree variation in the strength properties of Taiwania, and Chiu et al.[6] showed that the tracheid length dimensions of Taiwania increase outward from the pith and that radial variation in microfibril angle changes from a high value in the rings near the pith and gradually declines toward the cambium. However, little research has been performed to investigate relationships among important wood properties of juvenile Taiwania.

Several studies in the literature are cited here that were concerned with relationships between different wood properties. Deresse et al.[7] reported that the correlation between both the flexural strength and stiffness of juvenile wood and microfibril angle was negative, with bending modulus of elasticity more sensitive than flexural strength. Bendtsen and Senft[8] reported that the correlation between mechanical properties and specific gravity, cell length, and fiber angle ranged from 0.50 for cell length versus modulus of rupture in cottonwood to 0.80 for specific gravity versus

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Fig. 1. The sampled Taiwania stand. ***a***, no thinning; ***b***, after thinning

compressive strength in pine. Kaya and Smith[9] reported that the best combination of two independent variables for predicting maximum compressive strength is relative density and tracheid length. Koga and Zhang[10] reported that wood density is not significantly correlated with annual growth rate (ring width) in either juvenile wood or mature wood, and the relationship between wood density and annual growth rate in balsam fir may vary with cambial age. Zhang[11] reported that variation and correlations of various ring width and ring density features were analyzed in 18 European oak trees and found the correlation coefficient between ring width and latewood width is as high as 0.97. Zhang et al.[12] reported that no significant relationship or even a weak positive relationship between wood density and growth can be found in some families. Karenlampi and Riekkinen[13] reported that the basic density is independent of growth rate, even if it is negatively correlated with annual ring width. Koga et al.[14] reported that there was no significant relationship between annual ring width and basic density in mature wood. Taylor and Burton[15] reported that specific gravity was not significantly influenced by growth rate differences in any growth zone. Zhang[16] reported that the relationships of specific gravity and the mechanical properties with growth rate vary remarkably with both the wood property and the wood category.

In a series of investigations on the wood quality of young Taiwania trees grown with different and pruning treatments, effects were reported on annual ring characteristics,[17] bending properties,[18] tracheid length, microfibril angle,[6] and compressive strength.[19] The strength properties of these trees in the thinning treatments showed the following trend: no thinning > medium thinning > heavy thinning, and in the pruning treatments the following trend was observed: medium > no pruning > heavy pruning. However, most results showed no statistically significant difference among thinning, pruning, and thinning and pruning treatments. Moreover, information on the relationships among these various wood properties is somewhat scarce.

Therefore, there is interest in examining relationships among selected wood properties to understand the wood quality of young Taiwania. The objective of this work was to investigate and understand the relationships between bending properties, compressive strength, tracheid length, microfibril angle, and ring characteristics. A statistical regression was applied to deduce the most appropriate regression equations for the basic wood properties to provide a better understanding of their interrelationships.

Materials and methods

The study plantation was planted at a rate of 1750 trees/ha (initial spacing) in 1980. Thinning (811–1528 trees/ha) and pruning (3.6–4.5 m) treatments were implemented in 1990. The study site is located in the no. 12 compartment of the Liukuei Experimental Forest of the Taiwan Forestry Research Institute (TFRI), Kaohsiung Country, southern Taiwan.

The diameter and height of each tree on the 27 small plots were investigated and measured. A mean diameter from the trees was selected from each plot. In total, 27 mean diameter trees from the stands were selected and cut for testing. The average diameter at breast height (DBH) of test sampled trees ranged from 23.53 to 28.03 cm. The average tree heights varied from 15.2 m to 15.8 m. (Fig. 1) These trees were harvested on February 14 and 15, 2001, and were about 20 years old.

One 50-cm-long log was cut from each tree where its DBH was about 80–130 cm above the ground. One cross-sectional disk (10 cm thick) was cut from each sample log. A diametrical strip (passing through the pith) was sawn from each disk in the same direction. The strip was cut from the disk for drilling resistance, tracheid length, and microfibril angle measurements.

In addition, a piece of cant (passing through pith) was sawn from each log (40 cm long) in an east–west direction. Then, they were further band-sawn into specimens by the cant sawing method, as shown in Fig. 2.

Only the nine outermost growth rings (about 3 specimens and diametrical strips) near the bark of the trees were taken and used to assess the selected wood properties. This is because the trees were sampled 9 years after thinning and pruning treatments. The cambium age of the sample specimens was 12–20 years old (from different silvicultural regimes). All small clear specimens [32 (long) × 1.5 (wide) ×

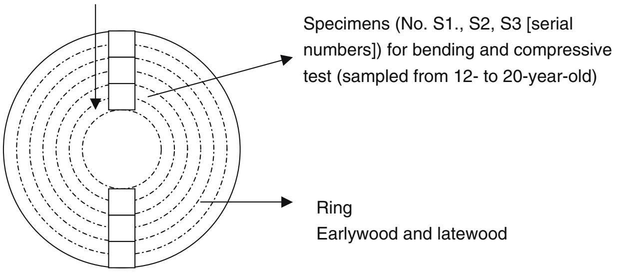

Fig. 2. Notation of specimen logs cut from one side to the other. S1, S2, and S3 specimens are the number of small clear specimens

1.5 cm (thick) and 3 (long) × 1.5 (wide) × 1.5 cm (thick)] were cut from the 40-cm-long cant for the bending and compressive tests. Thus, more than a total of 324 specimens were measured (27 trees × more than 6 specimens × 2 tests) for two strength tests. All specimens were conditioned in a controlled environment room at 20°C and 65% relative humidity such that the wood had a moisture content of 12%.

A commercially available ultrasonic testing tool was used to evaluate the ultrasonic wave velocity and dynamic modulus of elasticity. Then, specimens [32 (long) × 1.5 (wide) × 1.5 cm (thick)] were also measured using an ultrasonic wave technique for longitudinal transmission; the ultrasonic wave apparatus (Sylvatest-duo, 22 kHz; Swiss Products) included a transmitting transducer and receiving transducer. The ultrasonic wave velocity (*V*) and the dynamic modulus of elasticity (DMOE) were calculated in this experiment.

All diametric strips of Taiwania were subjected to the drilling resistance test, tracheid length, and microfibril angle measurement. These strips were chosen from same product lot and experimental methods were taken from the same techniques used in previous studies.[6,17]

Resistograph measurements were made on specimens (strips, at ca. 12% moisture content) in the radial direction. The annual ring contours were marked on a chart for tree ring and control parameters, including the average tree-ring width (*RW*), earlywood width (*EW*), latewood width (*LW*), tree-ring density (*RD*), earlywood density (*EWD*), latewood density (*LWD*), highest density (*HD*), lowest density (*LD*), and latewood percentage (*LWP*) in a ring.

Bending and compressive methods for wood strength determination were in accordance with CNS 454[20] and CNS 453,[21] respectively. Static bending tests were conducted in accordance with the center-loading method for specimens using a universal test machine (UH-10A; Shimadzu, Kyoto, Japan). All specimens were loaded flatwise, and the span was 26 cm in the bending tests. The proportional limit, ultimate load, and deflection were obtained from the load–deflection curves, and the modulus of elasticity (*MOE*) and modulus of rupture (*MOR*) were calculated. Moreover, the compressive strength in the longitudinal direction to the grain of a test specimen was evaluated.

Table 1. Average wood properties of Taiwania plantation trees

Wood property	Average	Number of samples
RD (kg/m^3)	394.9 (54.0)	27 trees × ≥6 specimens
V (m/s)	5318.6 (819.4)	
DMOE (MPa)	11661.0 (3351.1)	
MOE (MPa)	4680.3 (1438.5)	
MOR (MPa)	55.6 (11.0)	
*MOR*c (MPa)	25.3 (4.7)	
FL (mm)	3.14 (0.42)	27 trees × ≥9 rings
MFA (degree)	17.9 (2.6)	
RW (mm)	5.10 (1.61)	
EWW (mm)	4.39 (1.51)	
LWW (mm)	0.72 (0.35)	
EWD (kg/m^3)	390.6 (64.2)	
LWD (kg/m^3)	509.0 (71.1)	
HD (kg/m^3)	552.7 (84.2)	
LD (kg/m^3)	272.6 (50.7)	
LWP (%)	14.4 (7.7)	

Numbers in parentheses are standard deviations
RD, density; *V*, ultrasonic wave velocity; *DMOE*, dynamic modulus of elasticity; *MOE*, modulus of elasticity; *MOR*, modulus of rupture; *MOR*c, compressive strength; *FL*, fiber length; *MFA*, microfibril angle; *RW*, ring width; *EWW*, earlywood width; *LWW*, latewood width; *EWD*, earlywood density; *LWD*, latewood density; *HD*, highest density; *LD*, lowest density; *LWP*, latewood percentage

Results and discussion

The effects of various thinning and pruning methods on the bending properties, compressive strength, tracheid length, microfibril angle, and annual ring characteristics of 20-year-old Taiwania trees were investigated. However, most results showed no statistically significant difference among treatments. Therefore, all measurements were collected and analyzed together.

Results for the mean density (*RD*), ultrasonic wave velocity (*V*), dynamic modulus of elasticity (*DMOE*), modulus of elasticity (*MOE*), modulus of rupture (*MOR*), compressive strength (*MOR*c), fiber length (*FL*), microfibril angle (*MFA*), ring width (*RW*), earlywood width (*EWW*), latewood width (*LWW*), earlywood density (*EWD*), latewood density (*LWD*), highest density (*HD*), lowest density (*LD*), and latewood percentage (*LWP*) of young Taiwania materials are summarized in Table 1. The mean values of the mechanical properties in this study were similar to the results of Chou[1] for this species of four age groups and those of Tang[2] for different plantation spacing.

Chou[1] indicated that compressive and bending strength of Taiwania trees of different ages and tree heights, and intratree variations were about 16.1–28.5 MPa and 39.1–51.7 MPa, respectively. Wang et al.[18] reported that the mean *RD*, *DMOE*, and *MOR* values of different planting density were 411–420 kg/m^3, 10600–11300 MPa, and 47.9–50.6 MPa, respectively. In this study, the wood density and *MOR* values of 20-year-old Taiwania were lower than those for the materials examined by Wang et al.[3] Chiu et al.[6] and Tang[5] This result is plausible because the specimens used in the respective studies were 35-, 24-, and 50-year-old Taiwania. As is well known, juvenile wood varies in terms of tree ages, and is undesirable for some forest products because of low strength.[8,22] Chiu et al.[23] reported that the position of demarcation between juvenile and mature wood occurred at an approximate distance of 10.8–13.2 cm from the pith that was about 18–20 years of cambium age. Therefore, 20-year-old Taiwania materials have a large proportion of juvenile wood. Juvenile wood has substantially less mechanical strength compared with mature wood of the same specific gravity and a large amount of juvenile wood has a negative effect on solid wood products. Chou[1] indicated that strength properties increased with increasing age.

A cause for the variation in results (intertree, within tree, interring, and within ring) may have been that juvenile wood has various degrees of impact on the wood properties. Chiu et al.[23] indicated that intratree variations in compressive strength were greater than intertree variations. Zobel and van Buijtenan[24] stated that more variability in wood characteristics existed within a single tree than among trees growing on the same site. In general, within-tree variations in wood properties are greater than between-tree variations.[25]

Values of the *MOR* (bending strength) and *MOR*c (compressive strength) increased with an increase in wood density, and the relationship was represented by positive linear regression formulas (Table 2). Values of the compressive strength (*MOR*c) increased with increases in bending properties (*MOR*, *RD*, and *MOE*). Their relationships can be represented by positive linear regression formulas (Table 2). Although their determination coefficients (R^2) were not high, significant differences ($P < 0.01$) were found by the *F*-test. These results are in agreement with many previous studies.[26–28]

Values of tracheid length (*TL*) increased with a decrease in microfibril angle (*MFA*), and the relationship could be expressed by the following linear regression:

$$MFA = -2.46TL + 26.0 \quad R^2 = 0.13 \quad F = 12.6^{**}$$

There was a significant difference ($P < 0.01$) by the *F*-test; however, the determination coefficient (R^2) was low.

All specimens (disks) were sampled from each tree at breast height. It is known that cambial ages affect both tracheid length and *MFA*. Hsieh[29] indicated that the largest *MFA* of both *sugi* and Taiwania occurs near the pith and tends to decrease in the radial direction. *MFA* was the largest at the base of *sugi* and Taiwania trees and decreased with increasing height. Fukunaga et al.[30] reported that the stable value of *MFA* is reached earlier with increasing height above the ground. However, there was little difference between stable values at different heights in *hinoki*. Hirakawa and Fujisawa[31] indicated that the *MFA* commonly declined with height in *sugi*, but the variation patterns and the height at which constant values occur were a little different among cultivars and between clones. Yamashita et al.[32] reported that the *MFA* angle values and their pattern of variation within a *sugi* stem varied widely among cultivars, but these variations were small among individuals within each cultivar. Moreover, tracheid length has the same radial variation without regard to the height.

Table 2. Coefficients of linear regression formulas ($Y = AX + B$) for the relationships among mechanical properties and ultrasonic wave velocity

Y	*X*	*A*	*B*	R^2	*F* value
MOR	*RD*	0.18	–13.8	0.42	57.5**
*MOR*c	*RD*	0.063	0.35	0.33	38.4**
MOR	*V*	0.003	7.1	0.29	32.3**
MOR	*DMOE*	0.001	15.8	0.43	60.6**
MOR	*MOE*	0.002	16.4	0.45	64.9**
MOE	*V*	1.42	–2898.6	0.66	156.4**
*MOR*c	*V*	0.004	4.69	0.46	69.4**
*MOR*c	*DMOE*	0.001	14.1	0.47	72.4**
*MOR*c	*MOE*	0.002	14.8	0.47	73.1**
MOR	*MOR*c	1.72	12.1	0.53	91.7**

R^2, Coefficient of determination
** Significant at the 1% level

There was no significant relationship between the tracheid length/microfibril angle and strength properties (bending strength $R^2 = -0.02, -0.03$ and compressive strength $R^2 = -0.03, -0.01$, respectively) for Taiwania by linear regression analysis. This may have been because there was less variation in the properties of small logs as a result of it being juvenile wood.

Using segmented regression analysis for compressive strength parallel to the grain, Lin et al.[33] reported that the juvenile wood region of Taiwania extended up to about 10–15 cm from the pith and was approximately 18–23 years old. Thus, the materials used in this study consisted of the juvenile wood with a gradual transition in wood properties (*TL* and *MFA*). In other words, there was no sharp demarcation between juvenile and mature wood. Moreover, all specimens were taken from the 9 outermost growth rings near the bark of the trees (from about annual ring 12 to 20, i.e., transition zone) and used to assess wood properties. Groom et al.[34] reported from mechanical properties of individual earlywood and latewood loblolly pine fibers were various locations within a tree (i.e., classified into juvenile, transition, and mature zones). Mott et al.[35] reported that fibers of comparable microfibril angle showed large variations in fiber properties, and attributed these to the presence of fiber defects such as crimps, kinks, and microcompressions. Therefore, these factors may be the reason behind the lack of significant relationships between the tracheid length/microfibril angle and wood strength in the transition zone of Taiwania in this study.

There was no significant relationship between the tracheid length and wood density or between microfibril angle and wood density ($R^2 = -0.05$ and -0.01, respectively) for young Taiwania by linear regression analysis.

Zobel and Sprague[22] indicated that specific gravity was not related to either tracheid length or fiber angle for loblolly pine, and there was no relationship between the basic density and tracheid length in *Pinus caribaea*. Hannrup et al.[36] reported that the earlywood radial lumen diameter and latewood proportion were the two most important predictors of wood density by multiple regression analyses.

Values of *MOR* (bending strength) increased with a decrease in *RW* and *EW*; however, there was an increase in the *RD* and *EWD*. Their relationships can be represented by

Table 3. Coefficients of linear regression formulas ($Y = AX + B$) for the relationships between ring traits and strength

Y	X	A	B	R^2	F value
MOR	*RW*	–2.87	70.9	0.21	20.8**
MOR	*EWW*	–3.19	70.3	0.23	23.8**
MOR	*RD*	0.06	32.1	0.18	18.1**
MOR	*EWD*	0.10	17.9	0.27	28.7**
*MOR*c	*RW*	–9.4	309.2	0.13	11.3**
*MOR*c	*EWW*	–11.8	313.2	0.18	17.0**
*MOR*c	*LWP*	2.60	223.3	0.18	16.8**
*MOR*c	*RD*	0.46	79.6	0.24	25.6**
*MOR*c	*EWD*	0.41	97.3	0.27	29.9**

** Significant at the 1% level

linear regression formulas (Table 3). Their determination coefficients (R^2) were low, and significant differences ($P < 0.01$) were found by the F-test. These results indicated that *RW*, *EW*, *RD*, and *EWD* were the most important predictors of wood bending strength.

Moreover, values of *MOR*c (compressive strength) increased with decreases in *RW* and *EW*, although there were increases in the *LWP*, *RD*, and *EWD*. Their relationships can be represented by linear regression formulas (Table 3). Their determination coefficients (R^2) were low, and significant differences ($P < 0.01$) existed by the F-test. These results indicated that *RW*, *EW*, *LWP*, *RD*, and *EWD* were the most important predictors of wood compressive strength.

Values of *MOR* and *MOR*c obtained from specimens were investigated for relationships between strength and other properties. Several ring characteristics affecting strength properties, such as wood density (*D*), ring width (*RW*), earlywood width (*EW*), earlywood density (*EWD*), latewood percentage (*LWP*), were included.

Judging from the coefficient of determination, highly significant relationships among the wood properties do exist. This suggests that *MOR* is affected greatly by the four wood properties of *D*, *RW*, *EW*, and *EWD*. There were positive relationships in *MOR* with *D* and *EWD*, but negative ones with *RW* and *EW*. However, *MOR*c was greatly affected by the five wood properties of *D*, *RW*, *EW*, *EWD*, and *LWP*. There were positive relationships in *MOR*c with *D*, *EWD*, and *EWP*, but negative ones with *RW* and *EW*.

Furthermore, for a better understanding of the relationships among these ring characteristics and the wood strengths (bending and compressive), the resulting data were fitted to a curve by multivariable models. Then a stepwise regression procedure was used to acquire the most suitable multiple linear regression to predict various mechanical properties. The following linear regression equations were obtained by the F-value test:

$$MOR = 0.17D - 1.52RW - 5.82, \quad R^2 = 0.59, F = 55.9^{**},$$

$$MOR = 0.17D - 1.69EW - 5.09, \quad R^2 = 0.59, F = 56.9^{**}, \text{ and}$$

$$MOR\text{c} = 0.72D + 1.83LWP - 44.2, \quad R^2 = 0.54, F = 45.1^{**}$$

The coefficients of correlation were significant at the 1% level (**). These results show that *D* and *RW*/*EW* values are the best to predict *MOR*; however, *D* and *LWP* are the best to predict *MOR*c by multiple linear regression.

Conclusions

The bending properties, compressive strength, tracheid length, microfibril angle, and ring characteristics of 20-year-old Taiwania (*Taiwania cryptomerioides* Hay.) trees grown with different thinning and pruning treatments were explored. However, the treatments showed no significant effect on the properties investigated. The relationships between the selected properties were investigated. The results are summarized as follows:

1. The trees investigated in this study exhibited noticeably lower average bending and compressive strengths than are reported in the literature for wood from mature Taiwania.
2. There was no significant relationship between the tracheid length and wood density or between microfibril angle and wood density, indicating that wood density is not related to either trait in young Taiwania.
3. There was no significant relationship between the tracheid length or microfibril angle and the two wood strengths (bending and compressive).
4. There were positive relationships between bending and compressive strength.
5. The *RD*, *RW*, *EW*, and *EWD* were the most important predictors of bending strength, while the *RD*, *RW*, *EW*, *EWD*, and *LWP* were the most important predictors for compression strength by simple linear regression.
6. The *RD* and *RW*/*EW* were the best predictors of *MOR*, while the *RD* and *LWP* were the best predictors of *MOR*c by multiple linear regression.

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