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Application of the fractometer for crushing strength: juvenile–mature wood demarcation in Taiwania (*Taiwania cryptomerioids*)

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Abstract The fractometer is a device that breaks a radial increment core along the fiber for the measurement of crushing strength, which is a direct wood quality indicator for structural lumber. In this study, the crushing strength of Taiwania (*Taiwania cryptomerioides* Hay) trees using the fractometer was investigated and the data were used to determine the position of demarcation between juvenile and mature wood. Segmented regression and variance component analysis were used to estimate the demarcation position. With increasing cambium age, the core wood improves the crushing strength in the outer wood area. Within-tree variations in wood properties were greater than between-tree variations. In this experiment, the position of demarcation between juvenile and mature wood occurred at an approximate distance of 10.8 cm to 13.2 cm from the pith at about 18–20 years of cambium age.

Key words Taiwania (*Taiwania cryptomerioides* Hay) · Crushing strength · Juvenile–mature wood demarcation · Fractometer

Introduction

During the past 20 years, wood scientists and the forest products industry have developed and used nondestructive testing (NDT) tools for a wide range of applications, ranging from the grading of structural lumber to the evaluation of standing trees. These NDT tools include ultrasonic waves, stress waves, tap tones, the drilling resistance method, soft X-ray, and increment core sampling.[1–5]

Currently, there is an increasing interest in developing and using cost-effective technologies to evaluate the strength of standing trees. The fractometer is a device that breaks a radial increment core (5 mm in diameter) along the fiber for the measurement of fracture strength. The advantages of the fractometer are that it is relatively fast, easy to use, causes minimal damage to the specimen (tree), and it can perform direct strength measurements using small-diameter cores. In some studies, the device is applied to evaluate the compressive strength and to monitor tree quality.[6–8]

The largest overall cause of wood variation among conifers is the presence of juvenile wood and its relative proportion to mature wood. Juvenile wood is a cause of great concern, and emphasizes the quality of the wood produced.[9] Lee and Wang,[10] and Chiu and Lee[11] indicated the negative effect of the presence of a large amount of juvenile wood on solid wood products. The most accepted concept is that it is directly related to the age of the cambium (growth ring from the pith). Nearly, all wood properties, both physical and chemical, are highly varied within the juvenile zone, but tend to be near uniform within the mature zone.[12–15] For example, the specific gravity, cell length, strength, cell wall thickness, transverse shrinkage, and the percent latewood gradually increase while S2 fibril angle, longitudinal shrinkage, and moisture content decrease from the pith outward for a number of years before becoming approximately constant in conifers.[16] One of the wood properties, the crushing strength (compressive strength parallel to the grain), is the best direct wood quality indicator and is used to evaluate wood. However, it has not yet been used to determine the juvenile–mature wood demarcation.

Forest managers and wood industries would benefit from knowing the demarcation point between the juvenile and mature wood. Therefore, many studies have been conducted to determine the point of demarcation between the juvenile and mature wood in different species. Researchers generally agree that juvenile wood predominates in the first 5–20 growth rings.[15,16] However, the age between juvenile

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wood and mature wood varies according to species, genetic factors of the trees, environmental conditions (site), silvicultural practices, wood properties (indicators), measurement methods, and others.

Researchers have also used various methods to determine the age of demarcation between the two wood zones. For example, visual interpretation of graphically plotted wood properties against the individual growth ring positions:[17,18] segmented modeling where the intersection point of the two regressions is considered as the point of demarcation between juvenile and mature wood;[15,19,20] statistical analysis with nonlinear regression (this analysis utilizes nonlinear data for the estimation of the juvenile wood area coupled with linear trend estimation for mature wood areas);[21] Tasissa and Burkhart[22] reported that segmented modeling, iterative solutions, and constrained solution approaches were used to estimate the age. The variance component technique for the determination of the boundary between the two wood zones was mostly done based on specific gravity and tracheid length (wood quality indicators).[10,11] This cited that the age of the juvenile–mature wood transition was set at a point where the variance component due to the effect of ring position reached 0%. In these articles, the tracheid length, specific gravity, the specific compressive strength, the specific modulus of elasticity, modulus of rupture, modulus of elasticity, maximum crushing strength, cell length, and fibril angle are used as the quality indicators of the juvenile–mature wood demarcation.[5–9,12,15]

Taiwania (*Taiwania cryptomerioides* Hay), a tree indigenous to Taiwan, was selected to test and analyze the crushing strength because it is an important timber species in Taiwan and the trees harvested for commercial applications are composed entirely of juvenile wood.

A series of investigations on the wood quality of Taiwania trees grown with different thinning and pruning treatments, including density, ring trait, bending properties, ultrasonic characteristics, and knot trait have been conducted.[2–4,23] However, the wood produced in Taiwania plantations tends to have a large proportion of juvenile wood. With the properties of juvenile wood being markedly different from those of mature wood, problems arise in processing and wood quality is affected. We are therefore interested in the formation of position (or age) demarcation between juvenile and mature wood.

In this study, the crushing strength of Taiwania was investigated using a fractometer. The study explored two methods (i.e., variance component and segmented regression analysis) for determining the demarcation position on the assessment of radial variation patterns of crushing strength. The demarcation position can provide information on wood utilization and processing.

Materials and methods

Taiwania was selected to test the validity of the variance component and segmented regression analysis for crushing strength. The experimental plantation was located in compartment 3, Liukuei Experimental Forest of the Taiwan Forestry Research Institute (TFRI). The mean annual temperature, relative humidity, and precipitation were 18.6°C, 81%, and 1150mm, respectively. The weather can be divided into a dry season and a rainy season. No silvicultural treatment was performed on trees sampled from this plot. The test samples were taken as each of the 19 trees in a study plantation established with a 2×2 m spacing and 2500 trees/ha in 1972.

We took different diameter at breast height (DBH) classes in order to understand the effect of different DBH on juvenile–mature wood demarcation (position). However, the data of suppressed trees are not ideal for strength analysis.[5] Therefore, the samples can only be classified into two types on the basis of DBH, namely, mean 33.6cm (type A: 8 trees) and 26.4cm (type B: 11 trees) (i.e., dominant trees and intermediate trees, respectively). The two DBH classes are suitable to be used as structural lumber.

An increment borer was used to cut cores 5mm in diameter from Taiwania trees. From the eastern aspect of each sample tree, we extracted a pith-to-bark increment core specimen at DBH (same direction) in December 2003, when the specimens were about 32 years old. The increment cores were conditioned in a controlled environment (20°C and 65% relative humidity). The measurements were performed on treated core (12% moisture, conditioned for 2 months).

Assessment of the crushing strength of Taiwania was investigated by using a fractometer. The fractometer (Type II; IML, Germany) is a device that breaks a radial increment core for the measurement of fracture strength along the fiber. The commercially available fractometer was used to evaluate the crushing strength of increment cores from pith to bark every 12mm. The schematic of the testing apparatus is shown in Fig. 1. The cylindrical specimen is inserted into the jaws so that the fibers are parallel to the direction of the load.

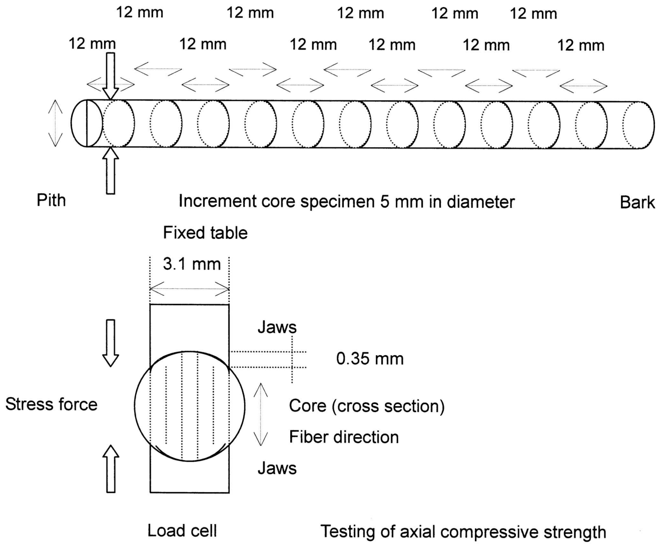

Fig. 1. Schematic diagram of measurements performed with fractometer

A total of 14 samples from each tree (core of type A) were studied (numbered 1.2cm, 2.4cm, 3.6cm, and so on, up to 16.8cm outward from the pith to the bark) and a total of 11 samples from each tree (core of type B) were studied (numbered 1.2cm, 2.4cm, 3.6cm, and so on, up to 13.2cm outward from the pith to the bark) for crushing strength.

Results and discussion

Transverse variation in crushing strength

Wood variation among conifers is due to the presence of juvenile wood and its relative proportion to mature wood. Wood characteristics within the juvenile zone are not uniform but rapidly change from the pith outward, while the characteristics are nearly constant in mature wood. The undefined zone in between is often referred to as the transition zone.

Pith-to-bark radial variation patterns of crushing strength for type A and type B Taiwania are presented in Figs. 2 and 3, respectively. Taiwania crushing strength data follow a distinctive three-stage variation pattern. Although similar results have been reported elsewhere (for *Cryptomeria japonica* and *Chamaecyparis formosensis*),[10,11] different results for red pine (*Pinus resinosa*) specific gravity are also available in the literature.[11] As a whole, the radial variation pattern in crushing strength in type A shows little variation for 6 age rings, followed by a faster increase from 6 to 16 age rings, after which the variation pattern showed a constant fluctuation to bark. However, the transverse variations of the mean crushing strength increased from pith outwardly to 18 age rings, and then showed little decrease or change toward the bark for type B. In this experiment, with increasing cambium age, the core wood improves the crushing strength in the outer wood area. This result is similar to those previously reported by Lin et al.,[5] who indicated that the transverse variation of the crushing strength increased from pith outwardly to 10–12cm and then became irregular toward the bark. Chiu et al.[24] indicated that the tracheid length dimensions increased outward from the pith and radial variation in microfibril angle gradually declined from a high value in the rings near the pith while moving toward the cambium.

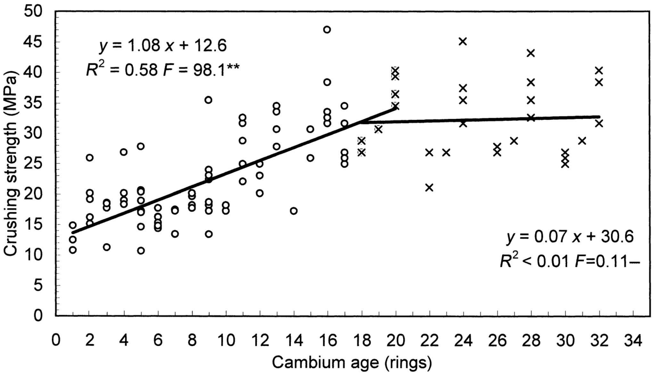

Fig. 2. The region of juvenile wood determined by segmented regression analysis for crushing strength in type A specimens

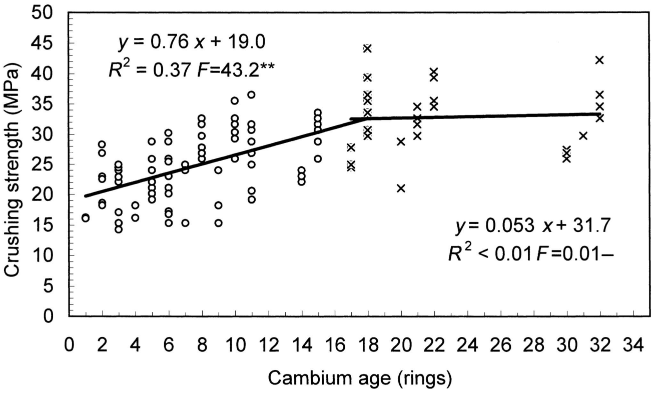

Fig. 3. The region of juvenile wood determined by segmented regression analysis for crushing strength in type B specimens

In this study, this was the case with Taiwania wood crushing strength. The mean crushing strengths of type A among the 14 test groups (radial) ranged from 16.3 to 34.9MPa, a difference of 114.3%; while the tree-to-tree variation ranged from 21.5 to 28.7MPa, a difference of 33.8%. The mean crushing strengths of type B among the 11 test groups ranged from 21.8 to 35.1MPa, a difference of 61.1%; while the tree-to-tree variation ranged from 24.6 to 30.3MPa, a difference of 23.5%.

This trend was also supported by an analysis of variance. As shown in Table 1, the radial variation component contributed 58.6%, while the between-tree variance component made a much lower contribution (4.2%) to the total variation in type A. Similarly, the radial variation component contributed 38.5%, while the between-tree variance component made a much smaller contribution (1.6%) to the total variation in type B (Table 2). Therefore, the within-tree variance component contributed more to the total variation than did the between-tree variance component in this study. Also, type A trees showed greater variation (within-tree/between-tree) than type B trees. The results indicated that the faster grown trees had not only bigger DBH but also larger variation than the slower grown trees. On the contrary, the smaller the DBH value, the smaller the variation.

Different DBH trees (growth rates) may have different variation components and they can also have different wood properties, even though the trees are of the same age and grown at the same site. Yang et al.[25] indicated that such discrepancies caused by differences in tree genetics and environmental influences are common among biological materials such as trees.

The average crushing strengths for specimens of type A and type B are 27.8 (±1.6) MPa and 32.6 (±4.4) MPa, respectively (Table 3). According to statistical analysis, significant differences ($P < 0.01$) existed for the crushing strength between type A and type B. Lin et al.[5] and Wang et al.[3]

Table 1. Sampling efficiency affected by the distance from pith in the working sample from type A Taiwania

No. sampled	Position (cm)	Age (rings)	*F* values	Variance components (%)		
				Position	Trees	Error
14	1.2–16.8	2–32	13.58**	58.6	4.2	37.2
13	2.4–16.8	3–32	12.90**	56.9	4.9	38.2
12	3.6–16.8	5–32	12.56**	55.7	5.8	38.5
11	4.8–16.8	6–32	12.43**	53.9	8.5	37.7
10	6.0–16.8	8–32	8.63**	42.8	12.3	44.9
9	7.2–16.8	9–32	4.80**	26.4	18.2	55.5
8	8.4–16.8	11–32	3.43**	16.5	29.2	54.3
7	9.6–16.8	13–32	1.66	5.4	29.0	65.7
6	10.8–16.8	16–32	1.03	0.2	30.1	69.7
5	12.0–16.8	17–32	1.66	5.1	33.7	61.3
4	13.2–16.8	20–32	0.53	0	24.0	76.0
3	14.4–16.8	24–32	0.36	0	26.2	73.8
2	15.6–16.8	28–32	0.59	0	0.9	99.1

** Significant at the 1% level

Table 2. Sampling efficiency affected by the distance from pith in the working sample from type B Taiwania

NO. sampled	Position (cm)	Age (rings)	*F* values	Variance components (%)		
				Position	Trees	Error
11	1.2–13.2	2–32	7.42**	38.5	1.6	60.0
10	2.4–13.2	3–32	8.48**	39.6	7.5	52.9
9	3.6–13.2	5–32	7.93**	35.8	12.4	51.7
8	4.8–13.2	6–32	6.02**	27.7	17.1	55.2
7	6.0–13.2	8–32	3.90**	17.0	24.6	58.5
6	7.2–13.2	10–32	3.62**	15.2	26.6	58.2
5	8.4–13.2	11–32	4.53**	18.0	31.1	50.9
4	9.6–13.2	15–32	3.93*	15.8	30.4	53.8
3	10.8–13.2	18–32	0.26	0	34.4	65.6
2	12.0–13.2	22–32	0.47	0	24.2	75.9

** Significant at the 1% level; * significant at the 5% level

Table 3. Average ring width (RW), bulk density (BD), and crushing strength (σc) of increment core

Parameter	Type A	Type B
RW (mm)	5.25 (0.61)	4.13 (0.25)
BD (kg/m^3)	377.5 (43.8)	388.7 (23.3)
σc (MPa)	24.1 (2.8)	26.7 (1.6)

The values in parentheses represent the standard deviation

indicated that there is a significant negative relationship between the crushing strength/bulk density and DBH. In other words, the crushing strength values decreased with increasing DBH. The type A trees had bigger DBH than type B trees, but type A trees showed lower strength than type B, and vice versa. In even-aged stands, the superior rapid growth trees had a large DBH and wide annual rings, so they had lower bulk densities, moduli of elasticity, and strengths.[26,27]

Relationships between ring width, bulk density, and crushing strength

The mean values of ring width (RW), bulk density (BD), and crushing strength (σc) of the incrsement cores are shown in Table 3. Their relationships can be represented by the following linear regression formulas:

$$\sigma c = -0.918\mathrm{RW} + 30.3, \quad R^2 = 0.13, \quad F = 11.3^{**}$$

$$\sigma c = 0.0453\mathrm{BD} + 7.80, \quad R^2 = 0.24, \quad F = 25.6^{**}$$

$$\mathrm{RW} = -0.01\mathrm{BD} + 10.9, \quad R^2 = 0.17, \quad F = 16.6^{**}$$

where ** indicates a confidence level of 0.01. Although their determination coefficients (R^2) were low, significant differences were found by the *F* test. This is similar to the results reported earlier by Wang et al.[2,26–38]

Variance component analysis

Thirteen sets of crushing strength data were created by varying the number of tests from 14 (positions 16.8 cm through 1.2 cm analyzed) to 2 (positions 16.8 cm through

15.6 cm analyzed) for inclusion in the working type A sample (Table 1). Furthermore, ten sets of crushing strength data were created by varying the number of tests from 11 (positions 13.2 cm through 1.2 cm analyzed) to 2 (positions 13.2 cm through 12.0 cm analyzed) for inclusion in the working type B sample (Table 2).

According to the technique, the age (or position) of transition from juvenile to mature wood is set at a point where the variance component attributable to the effect of distance from pith position becomes 0% (Tables 1 and 2). In this study, the point occurred at a distance of 13.2 cm (type A, 20 age rings) and 10.8 cm (type B, 18 age rings) from pith for crushing strength. In summary, the juvenile wood region of Taiwania was around 10.8–13.2 cm away from the pith in 18–20-year-old trees.

Segmented regression analysis

We sought an objective method to determine the age (or position) at which a change is "significant" and can be interpreted as the point of demarcation between juvenile and mature wood. In the segmented regression analysis, the intersection point of the regression is considered as the point of demarcation between juvenile and mature wood.[10,17]

The evaluation of juvenile and mature wood demarcation by segmented regression analysis is shown in Figs. 2 and 3. The results indicate that the juvenile wood region of Taiwania is about 18–20 and 20 years old (Types A and B) by segmented regression analysis using crushing strength.

The result of juvenile and mature wood demarcation by segmented regression analysis was similar to that of the variance component analysis. In other words, the position or age of demarcation may be determined by using the above two methods.

The result of this study (i.e., the juvenile wood region was 18–20 years old) is consistent with that of Wang and Chen[26] which indicated that the boundary between the juvenile and mature wood was at about the 17th to the 22nd annual rings from the pith for Japanese cedar (plantation). Yang[13] and Haygreen and Bowyer[16] also indicated that juvenile wood predominated in the first 5–20 growth rings, with the duration of its formation primarily dependent upon species. Zhu et al.[19] indicated that the radial variation of tracheid length of Japanese larch (*Larix kaempferi* Carriere) with ring number could be described by a logarithmic formula, and plantations reached the demarcation of juvenile and mature wood at the age of 18 years. With the segmented regression method, they also analyzed the radial variation of average density and found that the demarcation of juvenile and mature wood occurred between the ages of 15 and 21 years.

Type A trees (DBH ca. 33.6 cm: 13.2 cm, 18–20 years old) showed greater distance between the pith and the point of demarcation between juvenile and mature wood than type B trees (DBH ca. 26.4 cm: 10.8 cm, 18 years old). The results indicated that the faster grown trees not only had bigger DBH and wider ring width, but also showed that the position of demarcation was farther from the pith than for slower grown trees. On the contrary, the smaller the DBH value, the nearer the position of demarcation.

Furthermore, the juvenile wood position of this study was around 18–20 rings from the pith based on the measurement of crushing strength. Thus, the age of demarcation between the two wood zones of type A trees is similar to that of type B trees.

Conclusions

The wood quality of Taiwania specimens was investigated using a fractometer. The fractometer provides a relatively fast, easy method for obtaining direct crushing strength measurements using increment core while causing minimal damage to the sample. This study examined two methods (i.e., variance component and segmented regression analysis) for determining the demarcation position of juvenile and mature wood based on the assessment of radial variation patterns of the crushing strength in Taiwania. The results indicate that with increasing cambium (or distance from pith), the core wood improves the crushing strength into the outer wood area. Within-tree variations in wood properties are greater than between-tree variations. The type A trees (DBH ca. 33.6 cm) had bigger DBH and variation than type B trees (DBH ca. 26.4 cm), but the type A trees had lower strength than type B trees.

In this experiment, the juvenile wood region of Taiwania was around 10.8 to 13.2 cm away from the pith by variance components and segmented regression analysis using crushing strength. It was about 18–20 rings from the pith. Type A trees showed the position of demarcation between juvenile and mature wood to be farther from the pith than the demarcations for the Type B trees. Two analyses were proposed to determine the position of demarcation between juvenile and mature wood.

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References

1. Kasal B (2003) Semi-destructive method for in-situ evaluation of compressive strength of wood structural members. Forest Prod J 53:55–58
2. Wang SY, Chiu CM, Lin CJ (2003) Application of the drilling resistance method for annual ring characteristics evaluation of Taiwania (*Taiwania cryptomerioides* Hay.) trees grown in different thinning and pruning treatments. J Wood Sci 49:116–124
3. Wang SY, Lin CJ, Chiu CM (2005) Evaluation of wood quality of Taiwania trees grown with different thinning and pruning treatments using the ultrasonic-wave method. Wood Fiber Sci 37: 192–200
4. Wang SY, Lin CJ, Chiu CM, Chen JH, Yang TH (2005) Dynamic modulus of elasticity and bending properties of Taiwania young trees grown with different thinning and pruning treatments. J Wood Sci 51:1–6

5. Lin CJ, Wang SY, Chiu CM (2004) Assessment of crushing strength in Taiwania using the Fractormeter. Taiwan Forest Prod Indus 23:23–31
6. Matheny NP, Clark JR, Attewell D, Hillery K, Graham AW, Posner G (1999) Assessment of fracture moment and fracture angle in 25 tree species in the United States using the Fractometer. J Arboriculture 25:18–23
7. Dolwin JA (1996) Evaluation of internal defects in trees and the legal implications. Arboricultural J 20:173–178
8. Mattheck CG, Breloer H, Bethge KA, Albrecht WA, Zipse AW (1995) Use of the Fractormeter to determine the strength of wood with uncipient decay. J Arboriculture 21:105–112
9. Zobel BJ, Sprague JR (1998) Juvenile wood in forest trees. Springer, Berlin Heidelberg New York pp 26–38
10. Lee CH, Wang SY (1996) A new technique for the demarcation between juvenile and mature wood in *Cryptomeria japonica*. IAWA J 17:125–131
11. Chiu CM, Lee CH (1997) The validity of a new technique differentiating between juvenile and mature wood in conifers. Taiwan J Forest Sci 12:387–392
12. Zobel BJ, van Buijtenen JP (1989) Wood variation its cause and control. Springer, Berlin Heidelberg, New York, pp 21–22, 26–38, 88–89
13. Yang KC (1987) Wood properties, wood qualities and silvicultural treatments. Q J Chinese Forestry 20:7–28
14. Bao FC, Jiang ZH, Jiang XM, Lu XX, Luo XQ, Zhang SY (2001) Differences in wood properties between juvenile wood and mature wood in 10 species grown China. Wood Sci Tech 35:363–375
15. Watanabe H, Tsutsumi J, Matsumoto T, Ohta S (1964) Studies on juvenile wood. II. On distribution of specific compressive strength and specific modulus of elasticity in stem of Sugi tree. Mokuzai Gakkaishi 10:125–130
16. Haygreen JG, Bowyer JL (1982) Forest products and wood science – an introduction. Iowa State University Press, Ames, pp 109–110
17. Bendtsen BA, Senft J (1986) Mechanical and anatomical properties in individual growth rings of plantation-grown eastern cottonwood and loblolly pine. Wood Fiber Sci 18:23–38
18. Zhu J, Nakano T, Tokumoto M, Takeda T (2000) Variation of tensile strength with annual rings for lumber from the Japanese larch. J Wood Sci 46:284–288
19. Zhu J, Nakano T, Hirakawa Y (2000) Effects of radial growth rate on selected indices for juvenile and mature wood of Japanese larch. J Wood Sci 46:417–422
20. Bhat KM, Priya PB, Rugmini P (2001) Characterization of juvenile wood in Teak. Wood Sci Technol 34:517–532
21. Evans JW, Senft JF, Green DW (2000) Juvenile wood effect in red alder: analysis of physical and mechanical data to delineate juvenile and mature wood zones. Forest Prod J 50:75–87
22. Tasissa G, Burkhart HE (1998) Juvenile–mature wood demarcation in loblolly pine trees. Wood Fiber Sci 30:119–127
23. Wang SY, Lin CJ, Chiu CM (2003) Effects of thinning and pruning on knots and lumber recovery of Taiwania (*Taiwania cryptomerioides* Hay.) planted in the Alu-Kuei area. J Wood Sci 49:444–449
24. Chiu CM, Lin CJ, Wang SY (2005) Tracheid length and microfibril angle of immature Taiwania grown with different thinning and pruning treatments. Wood Fiber Sci (in press)
25. Yang JC, Lee CH, Chiu CM (1998) Precision of estimating Luanta fir specific gravity by a few outer growth rings. Taiwan J Forest Sci 13:251–257
26. Wang SY, Chen KN (1992) Effects of plantation spacing on tracheid lengths, annual-ring widths, and percentages of latewood and heartwood of Taiwan-grown Japanese cedar. Mokuzai Gakkaishi 38:645–656
27. Chuang ST, Wang SY (2001) Evaluation of standing tree quality of Japanese cedar grown with different spacing using stress-wave and ultrasonic-wave methods. J Wood Sci 47:245–253
28. Wang SY, Chiu CM (1993) Wood properties of Japanese cedar originated by seed and vegetative reproduction in Taiwan VI. Compression and bending properties. Mokuzai Gakkaishi 39: 1128–1139