# CRUSHING STRENGTH SAMPLING WITH MINIMAL DAMAGE TO TAIWANIA (*TAIWANIA CRYPTOMERIOIDES*) USING A FRACTOMETER


*Cheng-Jung Lin*

Adjunct Assistant Professor
Division of Forest Utilization
Taiwan Forestry Research Institute

*Song-Yung Wang*†

Professor
School of Forestry and Resource Conservation
National Taiwan University, Taiwan

and

*Chih-Ming Chiu*

Senior Scientist
Division of Forest Management
Taiwan Forestry Research Institute, Taiwan
53 Nanhai Rd.
Taipei 100, Taiwan
cmchiu@tfri.gov.tw



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ABSTRACT

The Fractometer is a device that stresses radial increment cores in the direction of the fiber to measure crushing strength, which can provide a direct wood quality indicator for structural lumber. This study analyzes the pattern of the radial variation in Taiwania (*Taiwania cryptomerioides* Hay.) trunk wood crushing strength to explore its effect on the precision and efficiency of the sampling procedure in the outer increment core zone as an alternate nondestructive sampling method. A pith-to-bark 0.5-cm caliber core was extracted at breast height (1.3 m above the ground) from each tree and was separated into individual section groups. Then individual crushing strengths were determined using the Fractometer.

In this study, the variation in crushing strength in the transverse direction increased from the pith outward to the bark side. An analysis of variance and correlation analysis were used to evaluate the data. The magnitude of the radial variation in crushing strength was smaller than the tree-to-tree variation. Including samples of at least 7.2 cm, 5.4 cm, and 2.4 cm near the bark side was found to be acceptable for the assessment of wood crushing strength for trees of Type A (DBH > 27 cm), Type B (DBH = 23~27 cm), and Type C (DBH > 23 cm), respectively.



*Keywords:* Taiwania (*Taiwania cryptomerioides* Hay.), crushing strength, sampling efficiency, analysis of variance, partial core sample, Fractometer.


## INTRODUCTION

There is large tree-to-tree (inter-tree) and within-tree (radial; inter-ring/within-ring) variation in wood properties in a species, even if the trees are of the same age and have been grown under the same conditions (Zobel and Sprague 1998; Zobel and van Buijtenen 1989). Owing to this large variation, a sufficient number of sample specimens are needed to represent the properties of a group. Without enough sample trees and specimens, the tree-to-tree and within-tree differences might overshadow any differences due to the genetic factors, environmental

† Member of SWST

condition, and silvicultural practices. In general, for the assessment of tree quality, sample trees are felled, and the samples are bucked into sections of a given length. The wood qualities are measured from considerable quantities of wood volumes. This destructive sampling method necessitates the handling of a large volume of wood specimens, and so short-cut methods have been developed using increment cores or disk samples extracted at a specified position along the stem.

Increment boring helps minimize the damaging effects on study trees, and the degree of injury can be further minimized by using only a portion of the increment core extracted, preferably near the bark. This is because increment boring of only the portion near the bark not only helps minimize damaging effects on study trees, but also provides enough data for the evaluation of wood quality. This method has been tested by the conventional indirect indicators (e.g., tracheid length and specific gravity) (Lee and Wahlgren 1979; Chiu and Lee 1997; Yang et al. 1998), but its effectiveness and applicability have not been determined by crushing strength. The effect of different diameters at breast height (DBH) on sampling efficiency is also not understood for the same age and site. These data are vital to the interpretation and comparison of study results and must be given careful consideration in the course of wood sampling.

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. However, the drawbacks of these methods are that the correlation between nondestructive and destructive parameters may be weak and may be affected by other factors. Moreover, the NDT methods cannot be used for direct strength measurements. Therefore, the drawback of NDT is the relatively inaccurate information generated from the strength properties (Kasal 2003).

Currently, there is strong 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 direction of fiber for the measurement of fracture strength. The advantages of the Fractometer are that it is relatively fast, easy to use, inflicts less damage on trees, and can conduct direct strength measurements using small-diameter cores. Its crushing strength is a good direct wood quality indicator that can be used to evaluate lumber. In some studies, this device has been employed to evaluate compressive strength and monitor tree quality (Lin et al. 2004; Matheny et al. 1999; Dolwin 1996; Mattheck et al. 1995).

This paper analyzes the magnitude of radial variation patterns in trunk wood crushing strength and examines the effect on the precision and efficiency of the sampling procedure in three DBH classes of Taiwania (*Taiwania cryptomerioides* Hay).

## MATERIAL AND METHODS

Taiwania, a tree indigenous to Taiwan, was selected to test and analyze the sampling efficiency for crushing strength because it is an important timber species in Taiwan. Crushing strength was chosen to explore the sampling efficiency because it is a good direct indicator of lumber quality in softwoods. Moreover, Wu (1972) reported that the growth rings of natural Taiwania are conspicuous, and the transition from earlywood to latewood is gradual. Tracheids usually have one row of bordered pits and are rarely paired in the radial walls. The longitudinal parenchyma cells are present in diffuse and zonate arrangement. Rays are uniseriate, ranging from 1 to 25 cells in height. The average fiber length and width are 3.488 mm and 44.5 μ, respectively.

Assessment of the crushing strength of Taiwania was investigated using a Fractometer. The Fractometer (Type II, IML, Germany) is a device that breaks a radial increment core (5 mm in diameter) for the measurement of compressive strength parallel to the grain.

The test samples were taken from each of the 57 trees (total) in a study plantation with stand density of 2,500 trees/ha, in 1980. The experimental plantation was located in compartment No.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 is divided into a dry season and a rainy season. In 1990, this plantation was thinned to a basal area of about 33 $m^2$/ha (1150 trees/ha), and trees were pruned from the root base upward to 3.6 m of their height.

We took different DBH classes in order to understand the effect of different DBH on the efficiency of the sampling with minimal damage. The samples can be classified into three types on the basis of DBH, namely, mean 28.8 cm (Type A greater than 27 cm, 18 trees), 25.2 cm (Type B from 23 to 27 cm, 24 trees), and 21.6 cm (Type C less than 23 cm, 15 trees) (i.e. dominant trees, intermediate trees, and overtopped trees, respectively). From the eastern aspect of each sample tree, we extracted a pith-to-bark increment core specimen (5 mm in diameter) at DBH (same direction) in July 2004, when they were about 24 years old. The specimens (increment cores) were conditioned in a controlled-environment room (20°C and 65% relative humidity). The measurements were done on conditioned cores (12% moisture), and a commercially available Fractormeter was used to evaluate the crushing strength of increment cores from pith to bark per 0.6 cm (section). 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 load.

In this study, 18, 24, and 15 replications of Type A, Type B, and Type C were considered in all statistical analyses, respectively. The increment core sample of Type A was then separated into 24 individual test groups (DBH ca. 28.8 cm, i.e. radius = 14.4 cm, 0.6 cm × 24 = 14.4 cm), and they were numbered 1, 2, 3 to 23, 24 from pith to bark. The increment core sample of Type B was then separated into 21 individual test groups (DBH ca. 25.2 cm, i.e. radius = 12.6 cm, 0.6 cm × 21 = 12.6 cm), and they were numbered 1, 2, 3 to 20, 21 from pith to bark. The increment core sample of Type C was then separated into 18 individual test groups (DBH ca. 21.6 cm, i.e. radius = 10.8 cm, 0.6 cm × 18 = 10.8 cm), and they were numbered 1, 2, 3 to 17, 18 from pith to bark.

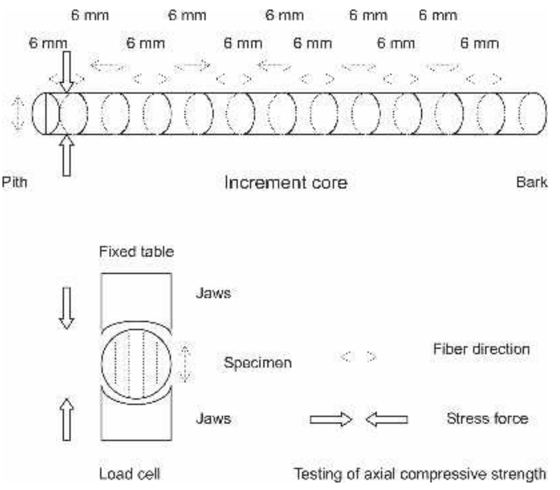


FIG. 1 Schematic diagram of measuring the fracture strength.

Parts of the increment core near the pith and bark were discarded because of their tendency to contain compressed wood, resulting in an undesirable compression problem during the extraction process under the dissecting microscope. The sampled trees were planted on a mountain slope, and the sampled cores were conditioned ranging from green to 12% moisture content. Therefore, parts of cores may be damaged by growth stress and dry defects, and so faulty sampled cores from increment corer were discarded in this experiment.

An analysis of variance was conducted, and variance components were calculated according to the following tabulation:

TABLE 1. *Analysis of variance.*

| Source of variation | d.f. | MS | F | Expected MS |
|---|---|---|---|---|
| Between test groups | r – 1 | $M_1$ | $M_1/M_3$ | $\sigma^2 + t\sigma_R^2$ |
| Between trees | t – 1 | $M_2$ | $M_2/M_3$ | $\sigma^2 + r\sigma_T^2$ |
| Error | (r – 1)(t – 1) | $M_3$ | | $\sigma$ |

r = no. of sampled trees, t = no. of compressive test groups.

All analyses were carried out according to the randomized complete block design. Mean crushing strengths were used as items in the correlation analysis.

## RESULTS AND DISCUSSION

The between-position (section) differences in crushing strength were statistically significant at the 1% level for Types A, B, and C (Tables 1 to 3). All 18, 24, and 15 sample trees are pooled together, and their mean crushing strength and 95% confidence interval are presented in Fig. 2. As a whole, Taiwania shows a gradual but steady increase in crushing strength outward from the pith. Taiwania crushing strength data do not follow a distinctive three-stage variation pattern, as reported elsewhere (*Cryptomeria japonica* and *Chamaecyparis formosensis*) (Lee and Wang 1996; Chiu and Lee 1997). However, similar results have been reported on the specific gravity of red pine (*Pinus resinosa*) (Chiu and Lee 1997; Yang et al. 1998).

The general radial variation pattern is that strength continues to increase outward from the pith and is characterized by an initial period of rapid increase in strength, followed by a gradual increase on the second stage. During the third stage, strength shows little increase or change (Haygreen and Bowyer 1982). That is to say, wood variation among conifers occurs due to the presence of juvenile wood and its relative proportion to mature wood. Wood characteristics within the juvenile zone are not uniform but

TABLE 2. *Test of significance as affected by sampling the different number of specimens (increment core) in the analysis of variance (DBH = 28.8 cm).*

| No. of specimens used | Position (from pith-to-bark) | Mean crushing strength | *F* value | Variance component (%) | | |
|---|---|---|---|---|---|---|
| | | | | Positions | Trees | Error |
| 24 | 1–24 (0–14.4 cm) | 281.8 | 7.46** | 19.1 | 27.9 | 53.1 |
| 23 | 2–24 (0.6–14.4 cm) | 283.5 | 7.25** | 18.7 | 27.5 | 53.8 |
| 22 | 3–24 (1.2–14.4 cm) | 283.9 | 7.58** | 19.5 | 27.1 | 53.4 |
| 21 | 4–24 (1.8–14.4 cm) | 286.2 | 7.29** | 18.6 | 28.1 | 53.3 |
| 20 | 5–24 (2.4–14.4 cm) | 287.8 | 7.93** | 19.9 | 28.6 | 51.5 |
| 19 | 6–24 (3.0–14.4 cm) | 289.9 | 7.70** | 19.2 | 29.3 | 51.5 |
| 18 | 7–24 (3.6–14.4 cm) | 291.9 | 8.35** | 20.2 | 30.4 | 49.4 |
| 17 | 8–24 (4.2–14.4 cm) | 294.7 | 7.89** | 18.9 | 31.9 | 49.3 |
| 16 | 9–24 (4.8–14.4 cm) | 298.5 | 6.70** | 16.5 | 31.6 | 51.9 |
| 15 | 10–24 (5.4–14.4 cm) | 301.5 | 5.95** | 14.6 | 32.2 | 53.2 |
| 14 | 11–24 (6.0–14.4 cm) | 306.1 | 3.92** | 9.1 | 35.1 | 55.8 |
| 13 | 12–24 (6.6–14.4 cm) | 309.7 | 2.89** | 5.9 | 38.3 | 55.8 |
| 12 | 13–24 (7.2 – 14.4 cm) | 310.0 | 3.24** | 1.5 | 86.3 | 12.2 |
| 11 | 14–24 (7.8–14.4 cm) | 313.7 | 1.95* | 3.1 | 37.9 | 59.0 |
| 10 | 15–24 (8.4–14.4 cm) | 315.7 | 1.70– | 2.3 | 37.4 | 60.3 |
| 9 | 16–24 (9.0–14.4 cm) | 318.2 | 1.14– | 0.5 | 34.1 | 65.4 |
| 8 | 17–24 (9.6–14.4 cm) | 319.7 | 1.13– | 0.5 | 33.6 | 66.0 |
| 7 | 18–24 (10.2–14.4 cm) | 321.7 | 0.95– | 0 | 36.1 | 63.9 |
| 6 | 18–23 (10.2–13.8 cm) | 322.6 | 1.04– | 0.2 | 35.0 | 64.8 |
| 6 | 19–24 (10.8–14.4 cm) | 324.5 | 1.17– | 0.6 | 36.8 | 62.7 |
| 5 | 19–23 (10.8–13.8 cm) | 322.9 | 1.28– | 1.0 | 33.4 | 65.6 |
| 5 | 20–24 (11.4–14.4 cm) | 324.5 | 0.97– | 0 | 41.0 | 59.0 |
| 4 | 20–23 (11.4–13.8 cm) | 326.5 | 0.90– | 0 | 35.5 | 64.6 |
| 4 | 21–24 (12.0–14.4 cm) | 326.7 | 1.26– | 0.7 | 50.6 | 48.7 |
| 3 | 21–23 (12.0–13.8 cm) | 330.1 | 0.90– | 0 | 48.0 | 52.0 |
| 2 | 21–22 (12.0–13.2 cm) | 330.5 | 3.70– | 3.8 | 71.2 | 25.1 |
| 3 | 22–24 (12.6–14.4 cm) | 322.5 | 0.43– | 0 | 42.4 | 57.6 |
| 2 | 22–23 (12.6–13.8 cm) | 325.6 | 0.24– | 0 | 35.7 | 64.3 |
| 2 | 23–24 (13.2–14.4 cm) | 322.9 | 0.75– | 0 | 29.5 | 70.5 |

* Significant at the 5 percent level; **Significant at the 1 percent level; – not significant.

TABLE 3. *Test of significance as affected by sampling the different number of specimens (increment core) in the analysis of variance (DBH = 25.2 cm).*

| No. of specimens used | Position (from pith-to-bark) | Mean crushing strength | *F* value | Variance component (%) | | |
|---|---|---|---|---|---|---|
| | | | | Positions | Trees | Error |
| 21 | 1–21 (0–12.6 cm) | 281.6 | 7.07** | 14.4 | 28.5 | 57.1 |
| 20 | 2–21 (0.6–12.6 cm) | 282.4 | 7.47** | 15.2 | 28.4 | 56.4 |
| 19 | 3–21 (1.2–12.6 cm) | 282.5 | 7.98** | 16.2 | 28.3 | 55.6 |
| 18 | 4–21 (1.8–12.6 cm) | 283.5 | 8.50** | 17.2 | 27.8 | 55.1 |
| 17 | 5–21 (2.4–12.6 cm) | 285.3 | 8.52** | 17.4 | 27.2 | 55.4 |
| 16 | 6–21 (3.0–12.6 cm) | 286.3 | 9.09** | 18.1 | 28.4 | 53.6 |
| 15 | 7–21 (3.6–12.6 cm) | 289.2 | 8.75** | 17.5 | 28.5 | 54.1 |
| 14 | 8–21 (4.2–12.6 cm) | 291.8 | 8.43** | 16.5 | 30.2 | 53.3 |
| 13 | 9–21 (4.8–12.6 cm) | 295.9 | 7.36** | 13.9 | 33.6 | 52.5 |
| 12 | 10–21 (5.4–12.6 cm) | 299.1 | 6.83** | 12.5 | 36.1 | 51.4 |
| 11 | 11–21 (6.0–12.6 cm) | 302.4 | 6.18** | 11.5 | 35.3 | 53.2 |
| 10 | 12–21 (6.6–12.6 cm) | 307.0 | 4.37** | 7.4 | 40.2 | 52.4 |
| 9 | 13–21 (7.2 – 12.6 cm) | 310.4 | 3.84** | 6.0 | 43.6 | 50.4 |
| 8 | 14–21 (7.8–12.6 cm) | 313.6 | 3.12** | 4.4 | 46.0 | 49.7 |
| 7 | 15–21 (8.4–12.6 cm) | 317.5 | 1.70– | 1.5 | 47.6 | 50.9 |
| 6 | 15–20 (8.4–12.0 cm) | 317.2 | 2.07– | 2.2 | 48.9 | 49.0 |
| 6 | 16–21 (9.0–12.6 cm) | 318.2 | 2.05– | 2.1 | 48.2 | 49.5 |
| 5 | 16–20 (9.0–12.0 cm) | 317.9 | 2.61– | 3.1 | 49.3 | 47.4 |
| 4 | 16–19 (9.0–11.4 cm) | 313.2 | 1.37– | 0.8 | 50.1 | 49.1 |
| 5 | 17–21 (9.6–12.6 cm) | 318.3 | 2.40– | 2.9 | 47.3 | 49.8 |
| 4 | 17–20 (9.6–12.0 cm) | 318.0 | 3.22* | 4.4 | 48.2 | 47.4 |
| 3 | 17–19 (9.6–11.4 cm) | 311.7 | 1.77* | 1.5 | 51.2 | 47.3 |
| 4 | 18–21 (10.2–12.6 cm) | 323.4 | 1.09– | 0.2 | 48.2 | 51.6 |
| 3 | 18–20 (10.2–12.0 cm) | 324.8 | 1.58– | 1.2 | 51.3 | 47.5 |
| 2 | 18–19 (10.2–11.4 cm) | 318.7 | 0.03– | 0 | 55.9 | 44.1 |
| 3 | 19–21 (10.8–12.6 cm) | 324.6 | 1.91– | 1.8 | 50.0 | 48.2 |
| 2 | 19–20 (10.8–12.0 cm) | 327.3 | 3.71– | 4.8 | 52.7 | 42.6 |
| 2 | 20–21 (11.4–12.6 cm) | 328.1 | 2.16– | 2.6 | 44.0 | 53.5 |

* Significant at the 5 percent level; **Significant at the 1 percent level.

change rapidly from the pith outward. The area of rapid change is juvenile wood, while the mature wood is much more constant. The undefined zone in between is often referred to as the transition zone.

Nearly all wood properties, both physical and chemical, are highly varied within the juvenile zone but tend to remain unchanged within the mature zone (Zobel and van Buijtenen 1989; Yang 1987; Bao et al. 2001; Watanabe et al. 1964). In other words, the rate of change in most properties is very rapid in the first few rings, while the subsequent rings gradually assume the character of mature wood.

In this experiment, with increasing distance from the pith, the core (juvenile) wood has better crushing strength toward the outer (mature) wood area (Fig. 2). This result is similar to that previously reported by Lin et al. (2004), who indicated that the transversal variation in crushing strength increased from pith outwardly to 10–12 cm and then irregularly toward the bark. Chiu et al. (2005) indicated that the tracheid length dimensions increase outwards from the pith and radial variation in microfibril angle from a high value in the rings near the pith, and decline gradually towards the cambium. Furthermore, the values for the ring width decrease with the cambium age (rings).

In general, within-tree (radial) variations in wood properties are greater than between-tree variations (Lee and Wahlgren 1979). However, this was not the case with Taiwania wood crushing strength. This trend was supported by analysis of variance. As shown in Table 2, the radial variation component contributed 19.1%, while

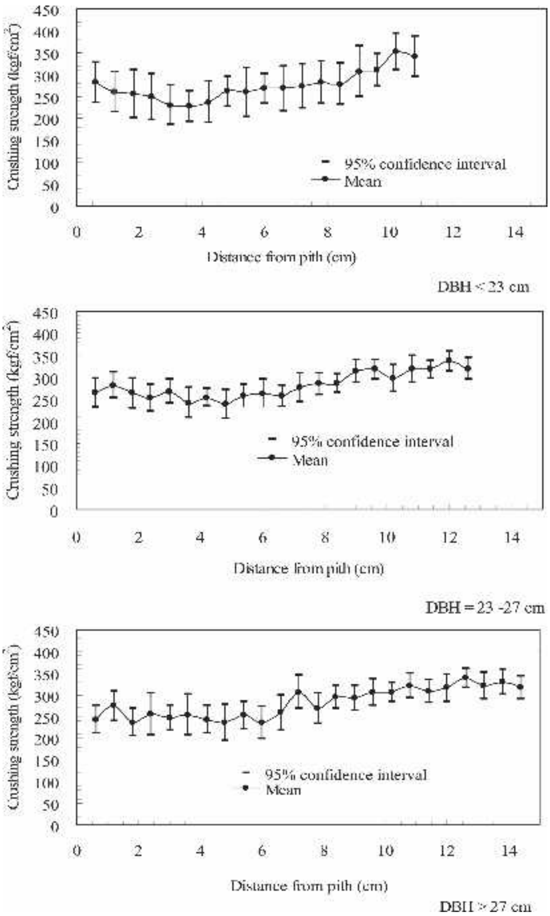


FIG. 2 Taiwania mean crushing strength and its 95% confidence interval.

the between-tree variance component made a much higher contribution (27.9%) to the total variation in Type A. However, the radial variation component contributed 14.4% and 14.8%, while the between-tree variance component made a much higher contribution (28.5% and 37.7%) to the total variation in Types B and C (Tables 3 and 4), respectively. Therefore, the between-tree (inter-tree) variance component contributed more to the total variation than did the within-tree (intra-tree) variance component in this study. Moreover, Type B trees (intermediate) caused smaller variation (intra-tree) than Type A and Type C trees (dominant and overtopped). However, Type A trees (dominant) caused smaller inter-tree variation than Type B and Type C trees (intermediate and overtopped).

The ranges of the crushing strength values were observed, with the following results: Mean crushing strength of Type A among the 24 test groups ranged from 235.2 to 339.2 kgf/cm$^2$, a difference of 44.2%; while the tree-to-tree variation ranged from 222.1 to 351.6 kgf/cm$^2$, a difference of 58.3%. Mean crushing strength of Type B among the 21 test groups ranged from 238.5 to 336.9 kgf/cm$^2$, a difference of 41.3%; while the tree-to-tree variation ranged from 200.7 to 355.1 kgf/cm$^2$, a difference of 76.9%. Mean crushing strength of Type C among the 18 test groups ranged from 227.9 to 352.0 kgf/cm$^2$, a difference of 54.5%; while the tree-to-tree variation ranged from 207.4 to 377.3 kgf/cm$^2$, a difference of 81.9%.

These results indicated that different DBH trees (growth rates) may have differing variation components, and they may also have differing crushing strengths; even though the trees are of the same age and grown at the same site. Yang et al. (1998) indicated that such discrepancies are likely caused by differences in tree genetics and environmental influences, and are common among biological material such as trees.

The presence of statistically significant radial variation differences in strength is an important factor affecting the sampling efficiency of the specimens. In general, there is a close relationship between the sample size and the consistency of the study material. The general radial variation is that crushing strength continues to increase outward from the pith. This was also found in our study (see Fig. 2).

The average crushing strength for specimens of Types A, B, and C is 281.8 (±34.5) kgf/cm$^2$, 281.6 (±29.3) kgf/cm$^2$, and 274.5 (±34.5) kgf/cm$^2$, respectively. According to the result of statistical analysis shown, no significant differences ($P > 0.05$) existed, which may be due to many causes. For one, the thinning treatment helps increase volume growth (DBH) and tree form without adversely affecting wood properties. Some investigators have found that wood

TABLE 4. *Test of significance as affected by sampling the different number of specimens (increment core) in the analysis of variance (DBH = 21.6 cm).*

| No. of specimens used | Position (from pith-to-bark) | Mean crushing strength (kgf/cm$^2$) | $F$ value | Variance component (%) | | |
|---|---|---|---|---|---|---|
| | | | | Positions | Trees | Error |
| 18 | 1–18 (0–10.8 cm) | 274.5 | 4.75** | 14.8 | 37.7 | 47.5 |
| 17 | 2–18 (0.6–10.8 cm) | 274.1 | 5.30** | 15.9 | 39.7 | 44.4 |
| 16 | 3–18 (1.2–10.8 cm) | 275.0 | 5.52** | 16.7 | 38.9 | 44.4 |
| 15 | 4–18 (1.8–10.8 cm) | 276.3 | 5.94** | 18 | 38.3 | 43.7 |
| 14 | 5–18 (2.4–10.8 cm) | 278.1 | 6.74** | 19.2 | 40.6 | 40.2 |
| 13 | 6–18 (3.0–10.8 cm) | 281.8 | 6.71** | 18.3 | 43.4 | 38.4 |
| 12 | 7–18 (3.6–10.8 cm) | 286.3 | 5.92** | 15.6 | 46.2 | 38.2 |
| 11 | 8–18 (4.2–10.8 cm) | 290.9 | 5.06** | 13.5 | 46.6 | 39.9 |
| 10 | 9–18 (4.8–10.8 cm) | 293.8 | 5.51** | 13.7 | 49.8 | 36.5 |
| 9 | 10–18 (5.4–10.8 cm) | 297.7 | 5.68** | 13.4 | 52.1 | 34.5 |
| 8 | 11–18 (6.0–10.8 cm) | 301.5 | 5.95** | 12.9 | 55.9 | 31.2 |
| 7 | 12–18 (6.6–10.8 cm) | 306.3 | 6.60** | 12.8 | 59.8 | 27.4 |
| 6 | 12–17 (6.6 – 10.2 cm) | 300.4 | 6.11** | 11.5 | 61.7 | 26.9 |
| 6 | 13–18 (7.2–10.8 cm) | 311.8 | 6.59** | 12.3 | 61.4 | 26.4 |
| 5 | 13–17 (7.2–10.2 cm) | 305.9 | 6.77** | 11.8 | 63.7 | 24.5 |
| 5 | 14–18 (7.8–10.8 cm) | 317.7 | 7.16** | 12.1 | 64.2 | 23.7 |
| 4 | 14–17 (7.8–10.2 cm) | 311.8 | 8.05** | 13.0 | 65.0 | 22.1 |
| 4 | 15–18 (8.4–10.8 cm) | 327.5 | 4.68** | 7.0 | 70.0 | 23.0 |
| 3 | 15–17 (8.4–10.2 cm) | 322.9 | 6.38** | 9.2 | 70.3 | 20.5 |
| 3 | 16–18 (9.0–10.8 cm) | 334.6 | 4.15* | 7.6 | 63.6 | 28.8 |
| 2 | 16–17 (9.0–10.2 cm) | 331.2 | 11.45** | 16.9 | 63.6 | 19.4 |
| 2 | 17–18 (9.6–10.8 cm) | 346.7 | 0.45– | 0 | 68.8 | 31.2 |

* Significant at the 5 percent level; **Significant at the 1 percent level.

properties remain unchanged despite siivicutural manipulations (Zobel and van Buijtenen 1989). In addition, there is large variation between species and within the same species, due to tree-to-tree, within-tree, ring-to-ring, and within-ring variations in wood properties (Zobel and van Buijtenen 1989; Zobel and Sprague 1998; Bendtsen and Senft 1986). Given these causes, researchers may adopt any process that suits their study purpose with an understanding of tree conditions.

In order to assess the validity of using portions of an increment core to be included in the working sample, we divided the entire core sample from each tree into various sections near the bark. This is because increment boring of only the portions of the section samples near the bark not only helps minimize damaging effects on a study tree, but also provides enough data for the assessment of genetic, environmental, and silvicultural information on wood properties.

The within-tree differences in crushing strength were statistically significant at the 1% level for the core wood specimens within test groups (Tables 2 to 4). It was found that at least twelve (from 7.2 to 14.4 cm), eight (from 7.8 to 12.6 cm), and four outer sections (from 8.4 to 10.8 cm) should be sampled in the evaluation of wood crushing strength for Types A, B, and C, respectively. These results led us to believe that an acceptable wood sample could be obtained from growth increments situated in the outer section of the increment core.

In order to further establish the sufficiency and validity of sampling portions of the core sample located near the bark side, mean crushing strengths of 1, 2, 3 to all 24 (Type A), 21 (Type B), and 18 (Type C) section groups were calculated, and the simple correlations between them were examined. These results indicated that mean values of various section groups sampled from the bark side were significantly correlated with the entire core (from pith to bark) means (Tables 5 to 7). These results imply that tree means can be effectively predicted us-

TABLE 5. *Correlation coefficients comparing the effect of sampling different numbers of specimens on crushing strength prediction (DBH = 28.8 cm).*

| No. of specimens used | Position (from pith-to-bark) | $R^2$ | $F$ value |
|---|---|---|---|
| 24 vs 1 | 24 (13.8–14.4 cm) | 0.36 | 8.48* |
| 24 vs 2 | 23–24 (13.2–14.4 cm) | 0.35 | 8.01* |
| 24 vs 3 | 22–24 (12.6–14.4 cm) | 0.38 | 9.24** |
| 24 vs 4 | 21–24 (12.0–14.4 cm) | 0.43 | 11.35** |
| 24 vs 5 | 20–24 (11.4–14.4 cm) | 0.63 | 25.66** |
| 24 vs 6 | 19–24 (10.8–14.4 cm) | 0.67 | 29.76** |
| 24 vs 7 | 18–24 (10.2–14.4 cm) | 0.70 | 35.42** |
| 24 vs 8 | 17–24 (9.6–14.4 cm) | 0.71 | 37.07** |
| 24 vs 9 | 16–24 (9.0–14.4 cm) | 0.77 | 50.58** |
| 24 vs 10 | 15–24 (8.4–14.4 cm) | 0.76 | 48.14** |
| 24 vs 11 | 14–24 (7.8–14.4 cm) | 0.81 | 61.68** |
| 24 vs 12 | 13–24 (7.2–14.4 cm) | 0.84 | 79.54** |
| 24 vs 13 | 12–24 (6.6–14.4 cm) | 0.89 | 119.19** |
| 24 vs 14 | 11–24 (6.0–14.4 cm) | 0.93 | 203.72** |
| 24 vs 15 | 10–24 (5.4–14.4 cm) | 0.94 | 251.33** |
| 24 vs 16 | 9–24 (4.8–14.4 cm) | 0.96 | 356.98** |
| 24 vs 17 | 8–24 (4.2–14.4 cm) | 0.97 | 416.74** |
| 24 vs 18 | 7–24 (3.6–14.4 cm) | 0.96 | 362.85** |
| 24 vs 19 | 6–24 (3.0–14.4 cm) | 0.98 | 693.80** |
| 24 vs 20 | 5–24 (2.4–14.4 cm) | 0.98 | 708.82** |
| 24 vs 21 | 4–24 (1.8–14.4 cm) | 0.99 | 1388.70** |
| 24 vs 22 | 3–24 (1.2–14.4 cm) | 0.996 | 3771.44** |
| 24 vs 23 | 2–24 (0.6–14.4 cm) | 0.998 | 8205.13** |

TABLE 6. *Correlation coefficients comparing the effect of sampling different numbers of specimens on crushing strength prediction (DBH = 25.2 cm).*

| No. of specimens used | Position (from pith-to-bark) | $R^2$ | $F$ value |
|---|---|---|---|
| 21 vs 1 | 21 (12.0–12.6 cm) | 0.51 | 22.07** |
| 21 vs 2 | 20–21 (11.4–12.6 cm) | 0.56 | 26.44** |
| 21 vs 3 | 19–21 (10.8–12.6 cm) | 0.65 | 39.34** |
| 21 vs 4 | 18–21 (10.2–12.6 cm) | 0.68 | 44.03** |
| 21 vs 5 | 17–21 (9.6–12.6 cm) | 0.75 | 63.46** |
| 21 vs 6 | 16–21 (9.0–12.6 cm) | 0.76 | 65.36** |
| 21 vs 7 | 15–21 (8.4–12.6 cm) | 0.79 | 81.11** |
| 21 vs 8 | 14–21 (7.8–12.6 cm) | 0.79 | 80.69** |
| 21 vs 9 | 13–21 (7.2–12.6 cm) | 0.81 | 87.62** |
| 21 vs 10 | 12–21 (6.6–12.6 cm) | 0.81 | 86.98** |
| 21 vs 11 | 11–21 (6.0–12.6 cm) | 0.85 | 119.22** |
| 21 vs 12 | 10–21 (5.4–12.6 cm) | 0.88 | 152.95** |
| 21 vs 13 | 9–21 (4.8–12.6 cm) | 0.90 | 194.68** |
| 21 vs 14 | 8–21 (4.2–12.6 cm) | 0.93 | 296.49** |
| 21 vs 15 | 7–21 (3.6–12.6 cm) | 0.95 | 370.24** |
| 21 vs 16 | 6–21 (3.0–12.6 cm) | 0.96 | 516.91** |
| 21 vs 17 | 5–21 (2.4–12.6 cm) | 0.98 | 837.73** |
| 21 vs 18 | 4–21 (1.8–12.6 cm) | 0.98 | 1171.50** |
| 21 vs 19 | 3–21 (1.2–12.6 cm) | 0.99 | 1912.67** |
| 21 vs 20 | 2–21 (0.6–12.6 cm) | 0.99 | 3863.17** |
| 21 vs 18 | 3–20 (1.2–12.0 cm) | 0.98 | 1038.16** |
| 21 vs 19 | 2–20 (0.6–12.0 cm) | 0.99 | 1743.16** |
| 21 vs 20 | 1–20 (0–12.0 cm) | 0.998 | 8675.78** |

ing the sampling of only a few of the outmost section groups.

To account for 81% or more of the variation in tree means (corresponding to an $R^2 = 0.81$), it is necessary to sample at least enough sections of the parts of core. It was found that at least eleven ($R^2 = 0.81$, from 7.8 to 14.4 cm), nine ($R^2 = 0.81$, from 7.2 to 12.6 cm), and three outer sections ($R^2 = 0.81$, from 9.0 to 10.8 cm) should be sampled to evaluate wood crushing strength for Types A, B, and C, respectively.

According to the analysis of variance (significant at the 1% level) and simple correlation ($R^2 \geqq 0.81$) on Taiwania, we would recommend that at least twelve (7.2 cm near the bark), nine (5.4 cm near the bark), and four outer sections (2.4 cm near the bark) should be sampled to assess wood crushing strength in Types A, B, and C, respectively. The results indicated that the faster grown trees not only had bigger DBH, but also more outer sections that needed to be sampled for the evaluation of crushing strength. On the contrary, trees with smaller DBH required fewer outer sections to evaluate crushing strength, with less damage to the Taiwania.

## CONCLUSIONS

A pith-to-bark increment core of 0.5-cm caliber was extracted at 1.3 m above the ground from each of 57 Taiwania trees. The study analyzed the extent of the radial variation pattern in crushing strengths and explored the sampling efficiency affected by the use of several sections extracted from the outer core sample.

In this experiment, with increasing distance from pith, the core wood showed better crushing strength toward the outer wood area. Several sets of data were made by sampling different numbers of section groups along the core sample, and they were subjected to an analysis of variance and simple correlation to evaluate

TABLE 7. *Correlation coefficients comparing the effect of sampling different numbers of specimens on crushing strength prediction (DBH = 21.6 cm).*

| No. of specimens used | Position (from pith-to-bark) | $R^2$ | $F$ value |
|---|---|---|---|
| 18 vs 1 | 18 (10.2–10.8 cm) | 0.50 | 9.09* |
| 18 vs 2 | 17–18 (9.6–10.8 cm) | 0.74 | 25.25** |
| 18 vs 3 | 16–18 (9.0–10.8 cm) | 0.82 | 39.75** |
| 18 vs 4 | 15–18 (8.4–10.8 cm) | 0.81 | 38.26** |
| 18 vs 5 | 14–18 (7.8–10.8 cm) | 0.89 | 70.94** |
| 18 vs 6 | 13–18 (7.2–10.8 cm) | 0.89 | 71.88** |
| 18 vs 7 | 12–18 (6.6–10.8 cm) | 0.91 | 93.03** |
| 18 vs 8 | 11–18 (7.8–10.8 cm) | 0.93 | 121.70** |
| 18 vs 9 | 10–18 (5.4–10.8 cm) | 0.95 | 176.11** |
| 18 vs 10 | 9–18 (4.8–10.8 cm) | 0.97 | 339.81** |
| 18 vs 11 | 8–18 (4.2–10.8 cm) | 0.98 | 348.55** |
| 18 vs 12 | 7–18 (3.6–10.8 cm) | 0.98 | 512.24** |
| 18 vs 13 | 6–18 (3.0–10.8 cm) | 0.97 | 336.67** |
| 18 vs 14 | 5–18 (2.4–10.8 cm) | 0.98 | 524.57** |
| 18 vs 15 | 4–18 (1.8–10.8 cm) | 0.99 | 665.12** |
| 18 vs 16 | 3–18 (1.2–10.8 cm) | 0.992 | 1103.58** |
| 18 vs 17 | 2–18 (0.6–10.8 cm) | 0.994 | 1597.83** |

the amount of information. At least 7.2 cm, 5.4 cm, and 2.4 cm near the bark side should be sampled to evaluate wood crushing strength for Types A (DBH < 23 cm), B (DBH from 23 to 27 cm), and C (DBH > 27 cm), respectively.

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