REAL-TIME MEASUREMENT OF THE VISCOELASTICITY OF GREEN JUVENILE WOOD OF JAPANESE CEDAR AT HIGH TEMPERATURE

*Yoshitaka Kubojima**
Researcher

Youki Suzuki
Researcher

Mario Tonosaki
Researcher
Forestry and Forest Products Research Institute
1 Matsunosato, Tsukuba, Ibaraki 305-8687, Japan

(Received January 2010)

Abstract. Changes in the viscoelasticity of green juvenile and mature wood during high-temperature drying were measured in real time. For each measurement, a 180-mm-long specimen of Japanese cedar (*Cryptomeria japonica*), its supporting system, a magnetic driver, and a deflection sensor were placed in an electric oven and a free–free flexural vibration test was performed. The temperature was fixed at 120°C. The resonance frequency decreased and the loss tangent increased during heating of the juvenile vs mature wood. These tendencies apparently occurred because the initial moisture content of the juvenile wood was higher than mature wood and because the juvenile wood had the larger number of intercellular layers.

Keywords: High temperature, juvenile wood, real-time measurement, vibration test, viscoelasticity.

INTRODUCTION

An increasing number of conifer plantations in Japan are being left without thinning (Chiba 1999). The reason may be that thinned timber has inferior qualities and that suitable uses for it have not been developed. Because the ratio of juvenile wood is high for small-diameter thinned timber, qualities such as tensile strength, specific compressive strength, specific compressive Young's modulus, and dynamic flexural Young's modulus are lower than mature wood and variations in wood properties in the juvenile portion are large (Panshin et al 1964; Ohta et al 1968a, 1968b; Ohta 1972). Properties of juvenile wood can be related to the microfibril angle (Ohta et al 1968a, 1968b; Ohta 1972; Iizuka et al 2007). The boundary between juvenile and mature wood has been assumed to be 10-15 yr from the pith based on the average ring density, length of tracheids, and microfibril angle (Watanabe et al 1963, 1964; Fukazawa 1967; Ohta et al 1968a, 1968b; Ohta 1972; Shiokura and Watanabe 1972, 1973). Conversely, there have been studies that show that the boundary between juvenile and mature wood depends on tree height (Jozsa and Middleton 1994; Jozsa et al 1998). Shiokura (1982) applied a variation distribution of the average tracheid length with a logarithmical relationship to distinguish between juvenile and mature wood.

To use more small-diameter timber, laminates for glued laminated timber have been developed from thinnings. Adequate compression, bending, and shear strength were obtained by using laminates with higher strength properties in the outer laminates and lower for inner layers, respectively (Ido et al 2007; Tansho et al 2007).

However, serious defects such as warp and checking can occur in kiln-drying juvenile wood

---

* Corresponding author: kubojima@ffpri.affrc.go.jp

Wood and Fiber Science, 42(3), 2010, pp. 328-334

(Nara et al 1977). It is therefore important to know the basic properties of the juvenile wood for processing. However, there has been a serious lack of information about the changes in the properties of juvenile wood during drying.

To understand the changes in properties that occur during wood processing, especially drying, a system for testing at high temperature has been developed and real-time measurements have been made under various temperature and RH conditions (Kubojima et al 2001, 2002, 2003, 2004, 2005, 2009). In the present study, specimens were made containing pith from Japanese cedar, and the relationship between the temporal change in viscoelasticity and the distance from the pith during heating was investigated.

MATERIALS AND METHODS

Specimens

Green Japanese cedar (*Cryptomeria japonica* D. Don) was used. The specimens were 180 mm long (longitudinal direction [L]), 20 mm wide (radial direction [R]), and 10 mm thick (tangential direction [T]). Specimens were cut from planks containing pith and directions 1 and 2 from the pith were designated (Fig 1). Longitudinally matched specimens were used to measure temperature, weight, dimensions, and vibrational properties.

Tracheid Length

After performing vibration tests, small chips cut from the latewood of the specimens were macerated in a solution of acetic acid and hydrogen peroxide at 70°C (Franklin 1945). The lengths of 50 tracheids per annual ring were measured, and their mean was calculated as the tracheid length for each annual ring. The tracheid length of the specimens for the vibration test was obtained by averaging the tracheid length of all annual rings in each specimen.

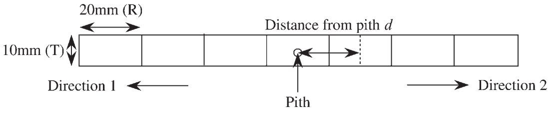

Figure 1. Schematic diagram of specimens used for measurements of temperature, weight, and viscoelasticity.

Vibration Test

To obtain resonance frequency and loss tangent, a free–free flexural vibration test was conducted. In this test, each end of a specimen is regarded as a free end, ie both bending moment and shear force are zero at each end. The high-temperature apparatus from a previous study was used (Kubojima et al 2001; Fig 2). The test beam was suspended by two wires 0.12 mm in diameter at the nodal position of the free–free vibration corresponding to its first resonance mode. It was excited in the direction of thickness at one end by a magnetic driver and the motion of the beam was detected by a deflection sensor at the other end. The signal was processed through a fast-Fourier transform digital signal analyzer.

The resonance frequency f was obtained and loss tangent tanδ was calculated from the width at –6 dB from the peak of the resonance curve Δf:

$$\tan\delta = \frac{\Delta f}{\sqrt{3}f}.$$

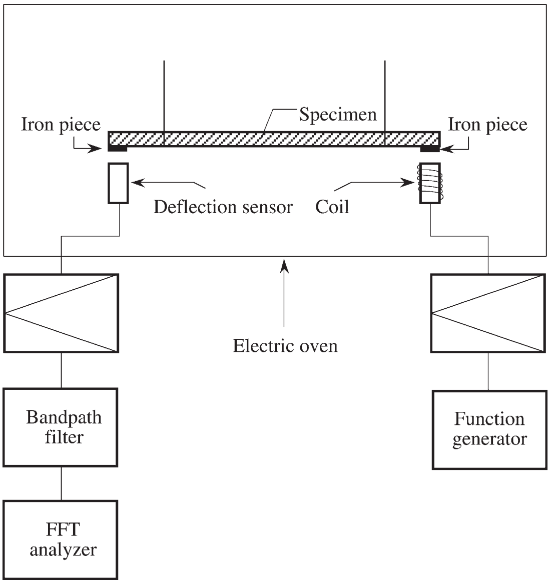

Figure 2. Apparatus for the vibration test.

The dimensions of specimens were regarded as constant during the heating. It took 100 s to create a resonance curve.

Measurement of Wood Properties During Heating

A type-T thermocouple was inserted in the L direction at a distance of 30 mm from the central point of the RT plane. Specimens were removed from the oven at 20-min intervals to measure dimensions and weight.

In the vibration tests, a specimen, its supporting system, a magnetic driver, and a deflection sensor were placed in the electric oven as shown in Fig 2. After a vibration test at room temperature (about 20°C), the temperature was raised to 120°C. The vibration tests were conducted at the beginning of heating and were continued at intervals of 5-10 min. After heating, the specimens were oven-dried at 105°C, and vibration tests were repeated at room temperature.

Because there were small openings for cables of the magnetic driver and the deflection sensor, the measuring system was not sealed and the RH in the oven was uncontrolled.

RESULTS AND DISCUSSION

Tracheid Length

Figure 3 shows the radial distribution of the tracheid length. Because tracheid length was constant, the mature wood was in the range of 88 mm $\leq d$ (distance from pith) and $\leq$110 mm for directions 1 and 2. Conversely, juvenile wood was in the range of $d \leq 66$ mm for directions 1 and 2 because tracheid length increased with an increase in d.

Temperature and Moisture Content

The changes in the temperature in a specimen with time (Fig 4) can be roughly divided into four regions like in our previous results for some cases (Kubojima et al 2002). The temperature rose in Range I and increased more slowly in Range II. It then rose faster in Range III. In Range IV, it was constant near the set point temperature. For example, in the case of $d = 0$, the boundaries between Ranges I and II, II and III, and III and IV were about 60, 160, and 210 min, respectively. When the temperature of the specimen for $d = 0$ started to increase in each region, the temperature increase ratios were 2.00, 0.18, and 0.37°C/min for ranges I, II, and III, respectively.

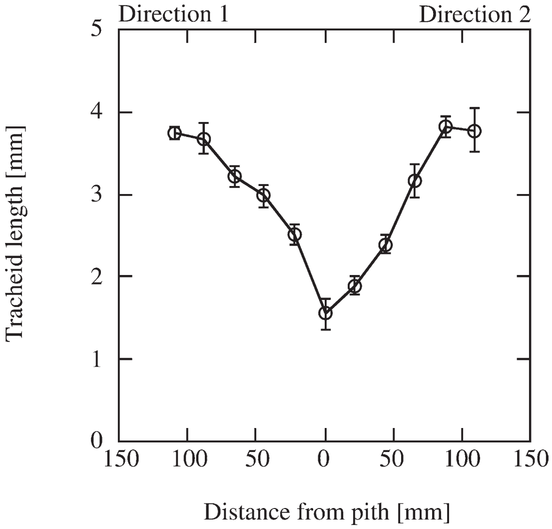

Figure 3. Radial variation of tracheid length of the specimens for the vibration test. Juvenile wood: $d \leq 66$ mm for directions 1 and 2. Mature wood: 88 mm $\leq d \leq$ 110 mm for directions 1 and 2. d, distance from pith.

However, the temporal change in temperature did not show this trend, presumably because of the nonuniformity of initial moisture content in the specimen. Because the initial moisture content was not as high as the maximum moisture content shown in Fig 6, it caused the nonuniformity.

The boundary between regions III and IV increased with an increase in the initial moisture content shown in Fig 6.

Viscoelasticity

Figure 5 shows the changes in viscoelasticity with time during heating. The resonance frequency can be expressed by:

$$f = \frac{ik^2}{2\pi l^2}\sqrt{\frac{E}{\rho}},$$

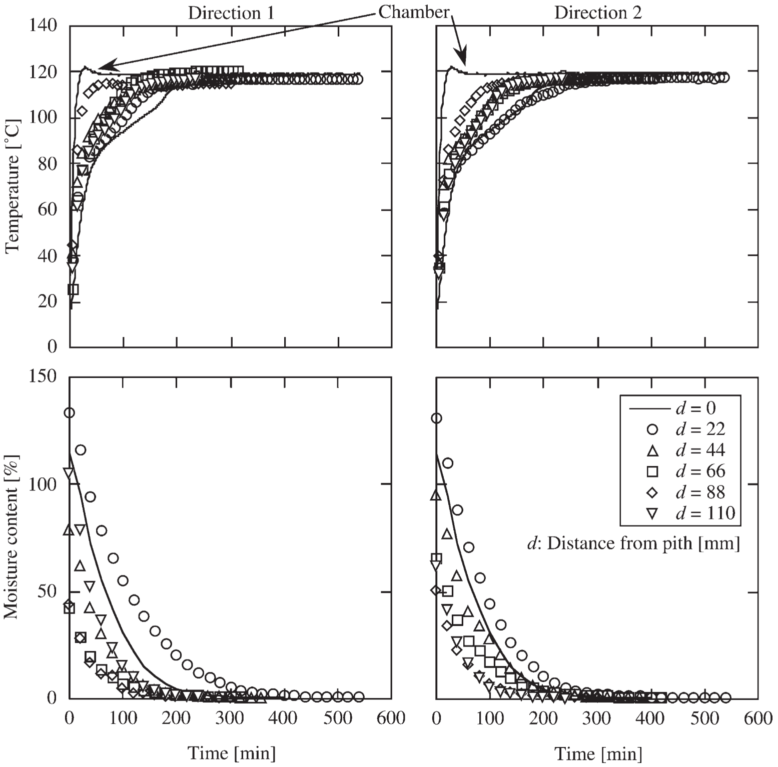

Figure 4. Changes in temperature and moisture content with time.

where i = radius of gyration of a cross-section, k = a constant, E = Young's modulus, l = length, and ρ = density. Because shrinkage of the specimen during heating was small, changes in i and l were also slight. Hence, the change in the resonance frequency corresponded to that in the specific Young's modulus.

The changes in the resonance frequency and loss tangent with time showed similar tendencies with our previous results (Kubojima et al 2002, 2005). The temporal change in the resonance frequency corresponded to that in the loss tangent; the resonance frequency and loss tangent were minima and maxima at the earlier stage of heating, respectively. They became stable when the temperature in the specimen was near the set point temperature.

Comparing the results of Figs 5 and 6, the heated green specimens had a large variation in viscoelasticity. The resonance frequency and loss tangent were 963-1529 Hz and 6.7-12.9 × 10^{-3}, respectively, under room temperature and oven-dried conditions, while the resonance frequency and loss tangent during heating were 584-1476 Hz and 5.6-49.0 × 10^{-3}, respectively. The radial variation of the initial moisture content is related to this variation. According to Ohsaki et al (2007), resonance frequency decreases and the loss tangent increases for specimens with higher initial moisture content.

However, changes in the resonance frequency and loss tangent of juvenile wood were larger than those of the mature wood when their initial moisture contents were similar as shown in Table 1. Thus, it appears that not only the initial moisture content, but also characteristics of the juvenile wood may account for the

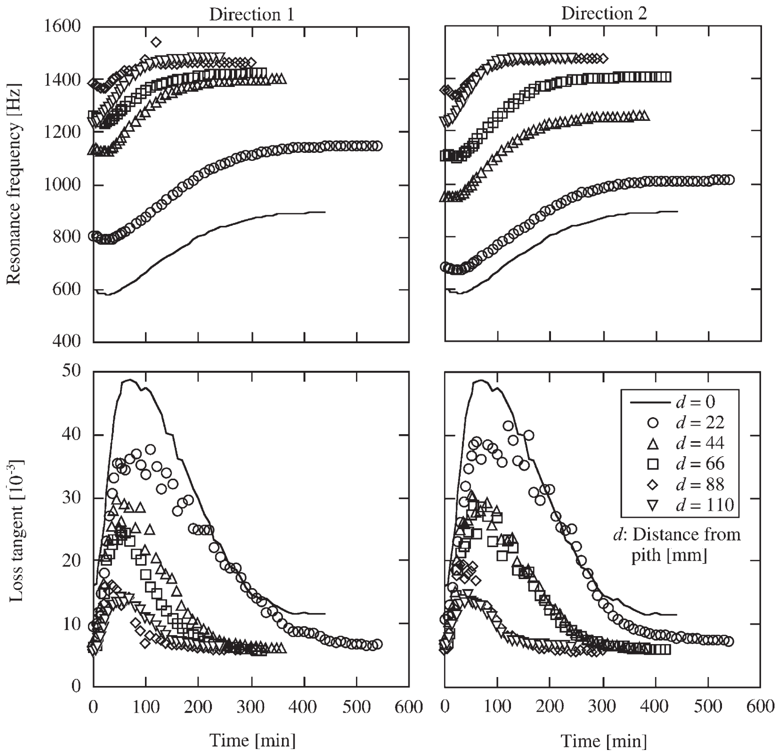

Figure 5. Changes in viscoelasticity with time.

large variations in the temporal changes in viscoelasticity.

Tracheid length in juvenile wood was shorter than that in mature wood (Fig 3). As a result, the number of tracheids, eg the number of intercellular layers in the juvenile wood, was larger than that in the mature wood.

Because most of the compound middle lamella consists of amorphous material (Saiki et al 1958), it can cause a decrease in resonance frequency and an increase in loss tangent. Hence, it is reasonable that juvenile wood had a lower specific Young's modulus and higher loss tangent under room temperature and oven-dried conditions as shown in Fig 6. The larger microfibril angle of juvenile wood can be an additional cause.

The softening temperature of cellulose is not strongly influenced by moisture content, whereas the softening temperatures of hemicellulose and lignin are significantly lowered by water. For example, the softening temperatures for spruce periodate lignin are 195°C (dry), 159°C (3.9% MC), 115°C (12.6% MC), and 90°C (27.1% MC) (Goring 1963; Takamura 1968). According to Furuta et al (2008), storage elastic moduli of wood and bamboo from 20 to 100°C decreases remarkably with decreases in lignin content. These results mean that the degree of thermal softening at about 60-80°C largely depends on lignin content. Hence, the intercellular layer will cause a further decrease in resonance frequency and a further increase in loss tangent under high temperature and high moisture content conditions of green wood specimens.

Thus, it is possible that the resonance frequency decreased and the loss tangent increased in juvenile rather than mature wood during heating because of the greater number of intercellular layers of the juvenile wood. Therefore, the

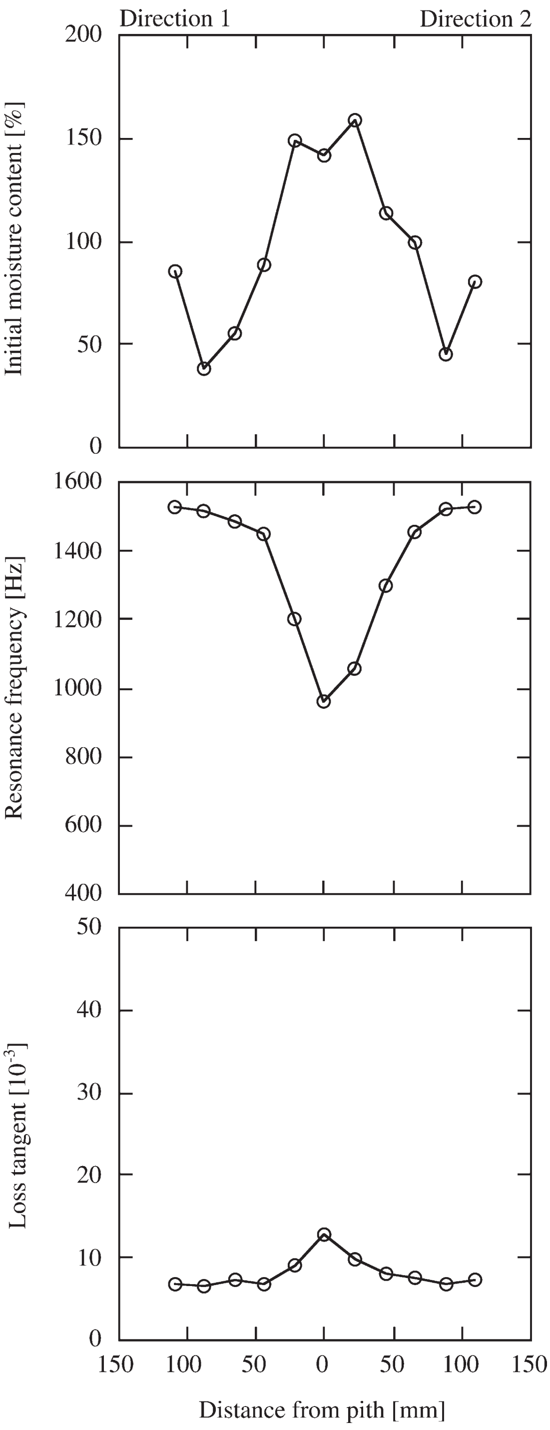

Figure 6. Radial variations of initial moisture content and viscoelasticity under room temperature and oven-dried conditions.

Table 1. Change in viscoelasticity during heating of the specimens with similar initial moisture content.

	d (mm)	MC_i (%)	Resonance frequency (Hz) Maximum	Resonance frequency (Hz) Minimum	Loss tangent (10^{-3}) Maximum	Loss tangent (10^{-3}) Minimum
Direction 1	44	88	1399	1122	29.8	6.0
	110	85	1478	1232	14.0	5.5
Direction 2	66	100	1407	1103	29.0	6.0
	110	80	1476	1231	14.6	6.4

d, distance from pith; MC_i, initial moisture content.

larger variation in the viscoelasticity of juvenile vs mature wood can be attributed to the properties of the juvenile wood as well as the radial variation in initial moisture content.

CONCLUSIONS

Changes in viscoelasticity of green juvenile and mature wood during high-temperature drying were measured in real time with the following results:

1. Changes in resonance frequency and loss tangent with time showed similar tendencies as our previous results.
2. Heating green specimens led to extremely large variations in viscoelasticity.
3. Resonance frequency decreased and loss tangent increased during heating of the juvenile vs mature wood. It is assumed that this occurred because the initial moisture content of juvenile wood was higher than mature wood and that juvenile wood had the larger number of intercellular layers. As a result, viscoelasticity was affected.

ACKNOWLEDGMENTS

We thank Ms. Emiko Okada of the Forestry and Forest Products Research Institute for her help in conducting the experiments.

REFERENCES

Chiba Y (1999) Utilization of thinnings. Pages 58-59 *in* the Committee of The Encyclopedia of Wood Industry, ed. The encyclopedia of wood industry. Wood Technological Association of Japan, Tokyo, Japan.

Franklin GL (1945) Preparation of thin section of synthetic resins and wood–resin composites, and a new maceration method for wood. Nature 3924:51.

Fukazawa K (1967) The variation of wood quality within a tree of Cryptomeria japonica D. Don.—Characteristics of juvenile and adult wood resulting from various growth condition and genetic factors. Research Bulletin of the Faculty of Agriculture Gifu University 25:47-127.

Furuta Y, Nakajima M, Nakatani T, Kojiro K, Ishimaru Y (2008) Effects of the lignin on the thermal-softening properties of the water-swollen wood. J Soc Mat Sci Jpn 57:344-349.

Goring DAI (1963) Thermal softening of lignin, hemicellulose and cellulose. Pulp Paper Mag Can 64:T517-T527.

Ido H, Nagao H, Kato H, Yoshida N (2007) Abstract of the 57th Annual Meeting of the Japan Wood Research Society, Hiroshima, Japan. PD017.

Iizuka K, Okazaki K, Eizawa J, Saito Y, Ishiguri F, Mustafa AKA, Yokota S, Yoshizawa N (2007) Wood structure and static bending properties in juvenile wood of 26-year-old sugi from seedlings. Wood Ind 62:22-27.

Jozsa LA, Middleton GR (1994) A discussion on wood quality attributes and their practical implications. Forintek Canada Corp Special Publication SP-34.

Jozsa LA, Munro BD, Gordon JR (1998) Basic wood properties of second-growth western hemlock. Forintek Canada Corp Special Publication SP-38.

Kubojima Y, Kobayashi I, Tonosaki M, Suzuki Y (2009) Equilibrium moisture content of Japanese cedar (*Cryptomeria japonica*) green wood for columns in a high-temperature water vapor environment. J Jpn Wood Res Soc 55:279-284.

Kubojima Y, Suzuki Y, Tonosaki M (2002) Real-time measurement of vibrational properties of green wood at high temperatures. Wood Fiber Sci 34:643-650.

Kubojima Y, Suzuki Y, Tonosaki M (2004) Real-time vibration testing method of wood in superheated water vapor. Bull For For Prod Res Inst 393:335-339.

Kubojima Y, Suzuki Y, Tonosaki M (2005) Vibrational properties of green wood in high temperature water vapor. Holzforschung 59:446-450.

Kubojima Y, Suzuki Y, Tonosaki M, Ishikawa A (2003) Moisture content of green wood in high temperature water vapor. Holzforschung 57:634-638.

Kubojima Y, Wada M, Suzuki Y, Tonosaki M (2001) Real-time measurement of vibrational properties and fine structural properties of wood at high temperature. Wood Sci Technol 35:503-515.

Nara N, Chiba M, Oyama Y (1977) Prevention of defect-occurrence in todomatsu squares during kiln-drying. J Hokkaido For Prod Res Inst 309:1-4.

Ohsaki H, Kubojima Y, Tonosaki M, Ohta M (2007) Changes in vibrational properties of wetwood of Japanese fir (*Abies Sachalinensis* Mast) with time during drying. Wood Fiber Sci 39:232-240.

Ohta S (1972) Studies on mechanical properties of juvenile wood, especially of sugi-wood and hinoki-wood. Bulletin Kyusyu Univ For 45:1-80.

Ohta S, Watanabe H, Matsumoto T, Tsutsumi J (1968a) Studies on mechanical properties of juvenile wood. I. Fibril angle and dynamic modulus of elasticity of juvenile wood in stem of sugi-trees. Reports Kyusyu Univ For 22:105-116.

Ohta S, Watanabe H, Matsumoto T, Tsutsumi J (1968b) Studies on mechanical properties of juvenile wood. II. Variation of fundamental structural factors and mechanical properties of hinoki trees (*Camaecyparis obtusa* Sieb. et Zucc.). J Jpn Wood Res Soc 14:261-268.

Panshin AJ, De Zeeuw C, Brown HP (1964) Textbook of wood technology. Volume I—Structure, identification, uses, and properties of the commercial woods of the United States Second Edition. McGraw-Hill Book Company, New York, NY.

Saiki H, Miyazaki Y, Wakashima T (1958) Electronmicroscopic investigation on the cell wall structure of wood. Bull Gov For Exper Sta 104:1-115.

Shiokura T (1982) Extent and differentiation of the juvenile wood zone in coniferous tree trunks. J Jpn Wood Res Soc 28:85-90.

Shiokura T, Watanabe H (1972) Fundamental studies on wood quality of larch tree (*Larix leptolepis* Gord.). (Part 3) Variation of tracheid length and fibril angle within a tree trunk. J Agric Sci Tokyo 17:81-86 (Nogyo Daigaku).

Shiokura T, Watanabe H (1973) Studies on juvenile wood (Part 5). The influence exerted by the early growth hastening on the variation in average tracheid length in the radial direction across tree trunks of sugi (*Crypotomeria japonca* D. Don). J Agric Sci Tokyo 18:139-144 (Nogyo Daigaku).

Takamura N (1968) Studies on hot pressing and drying process in the production of fibreboard. III. Softening of fibre components in hot pressing of fibre mat. J Jpn Wood Res Soc 4:75-79.

Tansho T, Noda Y, Matusmoto K, Maeda N (2007) Abstract of the 57th Annual Meeting of the Japan Wood Research Society, Hiroshima, Japan. D10-0930.

Watanabe H, Tsutsumi J, Kojima K (1963) Studies on juvenile wood. I. Experiments on stems of sugi trees (*Cryptomeria japonica* D. Don). J Jpn Wood Res Soc 9:225-230.

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 trees (*Cryptomeria japonica* D. Don). J Jpn Wood Res Soc 10:125-130.