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Growth and wood quality of sugi (*Cryptomeria japonica*) planted in Akita prefecture (II). Juvenile/mature wood determination of aged trees

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Abstract Variations of certain anatomical and mechanical indices within tree stems of aged sugi (*Cryptomeria japonica*) trees planted in Akita prefecture were studied. The determination of the juvenile/mature wood boundary was also discussed, and the effects of wood structure on mechanical properties were investigated. On the basis of radial and vertical variation of the anatomical and mechanical indices, modulus of elasticity (MOE)/ shear modulus (G) was chosen as the index for determining the juvenile/ mature wood boundary. The increase rates of MOE/G at the points of 1%, 2%, and 3% were discussed. It was found that for aged trees, all three points were thought to be effective for dividing juvenile and mature wood. However, for younger trees, the point of 2% was recommended, which was mostly consistent with the result obtained by the increase rate of 1% for tracheid length (TL). Among mechanical properties, the MOE showed more significant juvenile/mature wood differences than did modulus of rupture (MOR) and σ. By correlation analysis, it was suggested that microfibril angle largely contributed to the indices of MOE and G, and specific gravity largely contributed to the indices of MOR and σ.

Key words Akita sugi · Mechanical property · Juvenile/ mature wood · Microfibril angle · Tracheid length

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Introduction

Japanese cedar (*Cryptomeria japonica* D. Don) is historically one of the most common species used for reforestation and as timber in Japan. Recently, the long rotation management for plantation forests of Japanese cedar has received attention because of the undesirable quality of juvenile wood in young trees and the inactivity of the forestry and wooden material industries.

In Akita prefecture, located in the northern part of Japan, there exists many natural and plantation forests of Japanese cedar. Their age distribution is comparatively inclined toward an aged class, and some of these forests are over 300 years old. Such a situation would be quite suitable for the application of long rotation management.

In a previous article,[1] we reported the basic wood properties such as the log Young's modulus, tracheid length, shrinkage indices, and bending strength using samples from plantations aged between 40 and 60 years old. Herein we describe the variation of microfibril angle, tracheid length, and various mechanical properties across tree radii and with height above ground using aged sample trees. The demarcation of juvenile and mature wood determined by means of these indices is also discussed.

Materials and methods

Materials

The plantation that was assayed for this study came from the Lake Tazawa area, in the northern part of Akita prefecture. The forest is situated at an elevation of about 350 m on a moderate slope facing west. Four representative trees were harvested from this 78-year-old plantation. The mean height and diameter at breast height of the sample trees were 28 m and 41 cm, respectively. All trees harvested were straight with uniform crowns, and free of lean and visible defects. After felling, 50-cm-long logs were taken at breast height every 2 m along the trunk of each tree. Seven logs were cut from each of three trees and four logs were cut from one, to give a total number of 25 logs. Because the samples used in this study were cut from breast height to 13.2 m above the ground, the following statements on vertical direction referred only to this part of the trunks. The logs were divided into two parts: a 10-cm thick disk for measuring microfibril angle of S_2 layers of latewood tracheids (MFA) and tracheid length of latewood (TL), and short logs that were 40 cm in length. The short logs were sawed into straight strain lumbers, and small clear specimens with section sizes of 2 (radial) ×2 cm (tangential) were continuously obtained from both bark sides to pith. In total, 300 small clear specimens were prepared for testing torsional, bending, compressive, and shearing properties.

Measurement

For each sample disk, the TL and MFA were measured at the 3rd, 6th, 9th, 12th, 15th, and 20th annual rings and every 10 years after the 20th annual rings from the pith. The latewood slice of each annual ring was macerated in Schulze solution for 2–3 days and the lengths of the split tracheid were measured using a universal projector. Forty tracheids per annual ring were measured and their mean value was calculated. Images of the slit-like pit aperture in the tangential direction of the latewood were obtained using a scanning electron microscope (SEM), and the angle between the cell longitudinal axis and the slit-like pit aperture was determined as the MFA value.[2] Thirty sound tracheids per tree ring were selected for MFA measurement and their mean value was calculated.

The small clear specimens were first used for torsional tests in order to obtain the shear modulus (G) and then used for measuring specific gravity (SG), modulus of elasticity in bending (MOE), modulus of rupture (MOR), compressive strength parallel to grain (σ), and shearing strength (τ) according to JIS-Z2101.[3] The annual ring number from the pith for each specimen was determined in reference to the annual ring at the center of the end section. The average moisture content of the small clear specimens was 13.1%.

Results

Tracheid length and microfibril angle

For all sample trees, similar radial variations of TL and MFA were observed at all heights. Figure 1 provides an example of the radial variations at breast height and 9.2 m above the ground. As shown in Fig. 1, both the TL and MFA showed pronounced trends with annual ring number. The TL was at a minimum in the earliest annual rings, showed marked improvement for a number of years, and then exhibited stability or only gradual improvement thereafter. The MFA was at a maximum in the first-formed rings, decreased with age for some years, and then remained constant. These results were consistent with previous reports.[4–8]

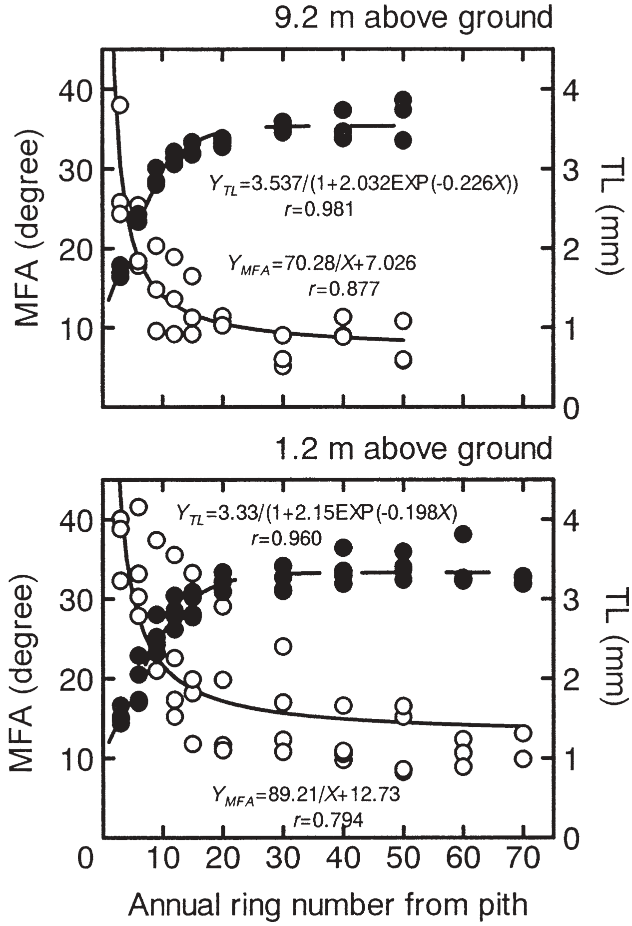

Fig. 1. Radial variations of microfibril angle (MFA) and tracheid length (TL). *Open circles*, MFA; *filled circles*, TL; *solid lines*, fraction curve of MFA; *broken lines*, logistic curve of TL

Furthermore, the radial variations in TL were tentatively fitted with the logarithm and logistic curve, with the results showing that the logistic curve fit well with the higher correlation coefficient. Then the annual rates increase of TL for different heights were calculated by using a logistic curve, with the points at which the annual rate increase decreased to 1%, 2%, and 3% as shown in Table 1. Shiokura[9] used a logarithmic formula to describe the radial variation in TL in association with ring number, and he also suggested that for dividing juvenile and mature wood, 1% of the increasing rate for TL was desirable. In this study, a logistic curve was found to be more suitable than a logarithmic curve. Also, we thought that it should be necessary to choose more demarcation points to observe the fittest one as well as to evaluate the variation of wood quality in juvenile/mature wood. Therefore, the points of 1%, 2%, and 3% were used for TL, MFA, and MOE/G appeared in the following results.

In the same way, logarithm, power, and fraction equations were used to determine a relationship between MFA and annual ring number from the pith. It was found that

Table 1. The boundary between juvenile and mature wood at different heights determined by decreasing MFA rates and increasing TL rates

Heights (m)	Decreasing MFA rates			Increasing TL rates		
	1%	2%	3%	1%	2%	3%
1.2	24	16	13	19	15	13
3.2	30	20	15	19	15	13
5.2	31	21	16	19	15	13
7.2	23	16	12	16	14	12
9.2	27	18	14	17	14	12
11.2	22	15	12	16	13	12
13.2	24	16	13	17	13	11

Values in the table refer to the annual ring numbers from pith
MFA, microfibril angle; TL, tracheid length

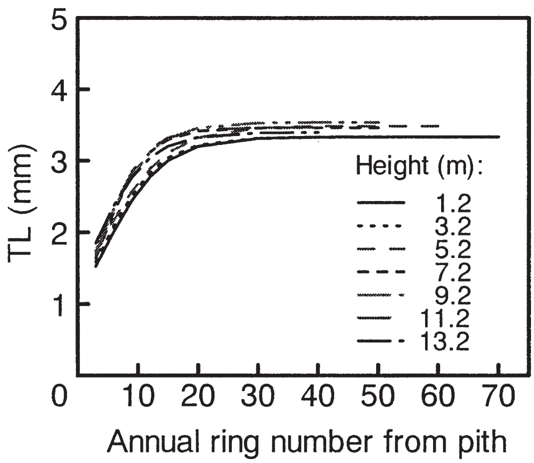

Fig. 2. Regression curves for different heights with TL

among these functions, the fraction equation provided a very satisfactory regression. Therefore, the fraction equation was used to calculate the decrease rate of MFA. Table 1 shows the assumed boundary (annual ring numbers from pith) of juvenile and mature wood based on the various decrease rates at different heights.

To show the general variations in the TL and MFA in the stem, the data of four sample trees at the same height were pooled, and the regression curves for all heights were fitted (Figs. 2, 3). For the TL, from the pith to about the 15th annual ring, no significant differences were observed among differing heights, but after the 15th annual ring, the TL increased with increasing heights from 1.2 m to 5.2 m, and above 5.2 m the TL was larger but there were no differences among various heights. For the MFA, the value at breast height was always larger compared with those of the upper logs. Above 3.2 m, there was a slight variation with height. Megraw et al.[10] reported that for *Pinus taeda*, the MFA decreased with increases in height. Moreover, a report[4] on young sample trees of Japanese cedar pointed out that the MFA diminished as height increased until a certain tree height. Thus, it was concluded that the lower part of the trunk had a large MFA that coincided with those of the aged trees examined in this study.

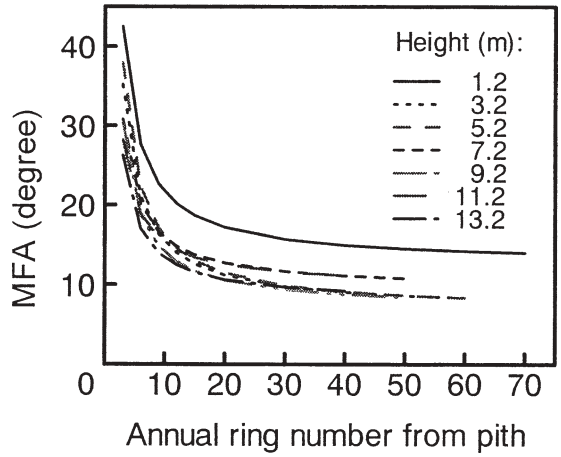

Fig. 3. Regression curves for different heights with MFA

The mechanical properties of small clear specimens

The results of mechanical tests for all sample trees are shown in Table 2. The mean values of the indices were somewhat higher compared with the values reported previously.[11,12] It could be explained that the sample trees used in this study were relatively aged trees. From the average values, no regular trends were found in the vertical direction. By investigating the radial variations of every mechanical index, it was found that the MOE was small near the pith and increased abruptly after that, and reached a constant at about the 15th annual ring. This trend was well described using a logarithmic curve. MOR and σ were small near the pith, and increased gradually with annual ring numbers, but their variation in the radial direction was small in comparison with MOE. τ and SG showed a similar trend, and both of them were large near the pith, and decreased in the following several annual rings, and then increased at about the 15th annual ring. G showed a reverse variation trend with MOE. The negative correlation between G and annual ring number was well fitted using a fraction equation. As an example, the radial variation of MOE, G, and SG at a height of 9.2 m for all sample trees is shown in Fig. 4.

In order to estimate the age of transition from juvenile to mature wood from the viewpoint of mechanical properties, the relations between annual ring number from the pith with MOE, G, MOE/G, and SG, respectively, were fitted by using suitable functions, and the annual change rate of each index was calculated. The point at which the change rate exceeded a certain threshold was defined as the age of demarcation between juvenile and mature wood. MOE/G is an important index that reflects both elasticity and rigidity of wood.[13] In this study, MOE/G showed more significant variation than either of MOE or G near the pith. Also, the correlation coefficient of the regression curve between MOE/G and age was the highest among the mechanical properties. It follows that the ratio of MOE/G was used to estimate the demarcation point between juvenile and mature wood. Figure 5 shows an example of logarithmic curve of MOE/G, its increase rate curve, as well as the method for

Table 2. Mean values of strength properties at different heights for all sample trees

	1.2 m	3.2 m	5.2 m	7.2 m	9.2 m	11.2 m	13.2 m
MOE (GPa)							
Mean	8.43	8.70	8.55	8.26	8.67	8.16	8.58
CV(%)	17.0	19.6	21.3	23.5	22.2	23.1	18.2
MOR (MPa)							
Mean	66.0	69.0	66.9	66.9	69.7	68.0	69.0
CV(%)	12.0	13.0	13.5	15.8	16.3	13.4	12.5
G (MPa)							
Mean	807	772	765	789	786	807	805
CV(%)	17.3	21.4	17.2	17.2	13.6	14.0	11.4
SG							
Mean	0.371	0.380	0.378	0.381	0.381	0.384	0.390
CV(%)	8.2	7.4	8.8	9.5	10.1	9.5	8.2
σ (MPa)							
Mean	38.0	39.9	38.9	39.1	39.7	39.9	40.3
CV(%)	10.1	10.4	14.0	13.4	13.3	12.7	10.9
τ (MPa)							
Mean	6.47	6.65	6.89	6.91	6.87	6.86	7.01
CV(%)	15.1	14.7	19.0	15.7	18.5	15.4	13.7

MOE, Young's modulus in bending; MOR, modulus of rupture; *G*, shear modulus; SG, specific gravity; σ, compressive strength parallel to grain; τ, shearing strength; CV, coefficient of variation

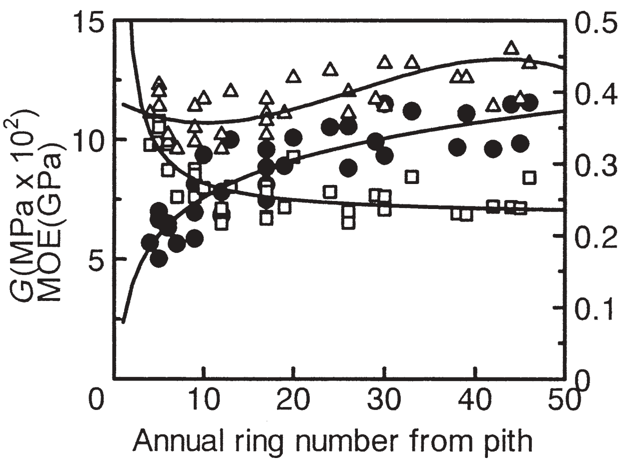

Fig. 4. Radial variations of modulus of elasticity (MOE), shear modulus (*G*), and specific gravity (SG) with annual ring number from the pith. Data shown is for 9.2 m above ground for all sample trees. Regression equations: MOE = 2.263ln(x) + 2.369 (r = 0.870); G = 13.948/x + 6.791 (r = 0.753), SG = $-0.000005x^3 + 0.0004x^2 - 0.0066x + 0.3882$ (r = 0.664). *Filled circles*, MOE; *open squares*, *G*; *open triangles*, SG

Table 3. Demarcation determined by the increase rate of MOE/*G*

Heights (m)	1%	2%	3%
1.2	31	19	15
3.2	33	20	16
5.2	32	19	15
7.2	30	18	14
9.2	29	18	14
11.2	27	16	13
13.2	27	16	12

Values in the table refer to the annual ring numbers from pith

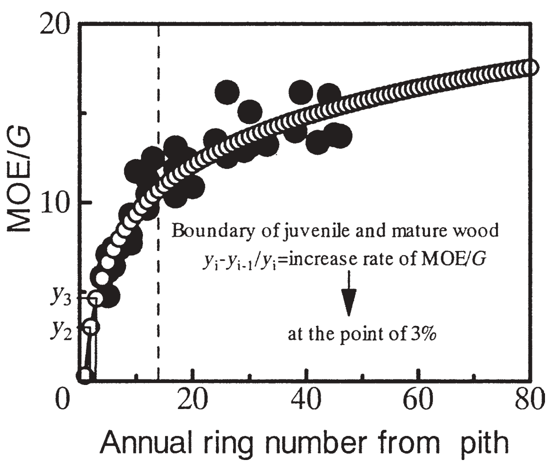

Fig. 5. Determination of the juvenile zone by using MOE/*G*. Data shown is for 9.2 m above ground. *Filled circles*, MOE/*G*; *open circles*, logarithmic curve

dividing juvenile and mature wood based on the increase rate of 3%. By the same method, boundaries of different heights were estimated at the points of 1%, 2%, and 3% of the increase rate of MOE/*G*, with the results being shown in Table 3. With increasing height there was a slight decrease in annual ring numbers. This result was almost the same as that of TL.

The logarithm curve for MOE, and the fraction curve for *G* at different heights are shown in Figs. 6 and 7. Few differences were observed among heights from pith to about the 10th annual rings for MOE, and after that MOE varied greatly, and at breast height was the lowest. For *G*, it showed an adverse trend. From the pith to about the 10th annual ring, the differences between heights were large, and

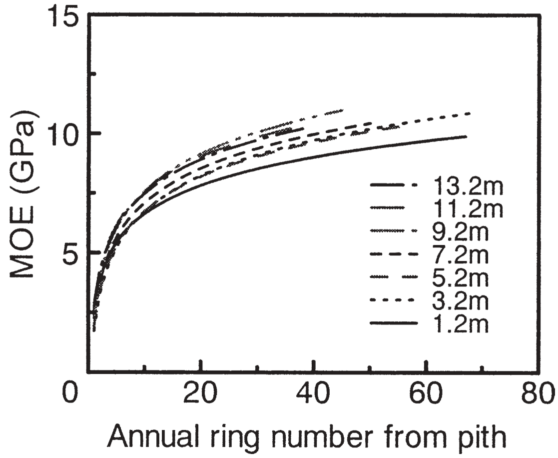

Fig. 6. Regression curves for MOE at different heights

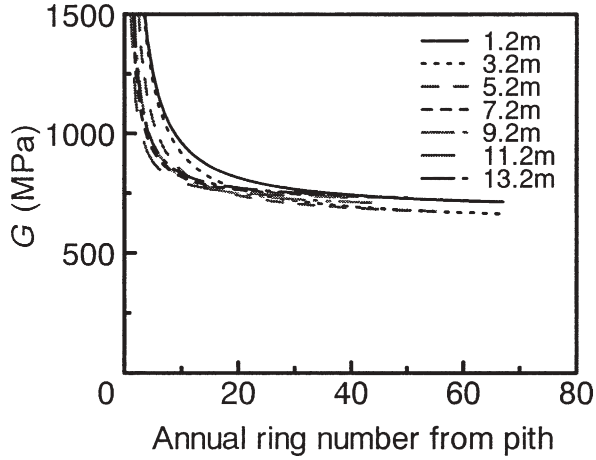

Fig. 7. Regression curves for *G* at different heights

after that they became small, however, the *G* at breast height was always large from pith to bark.

Discussion

Juvenile/mature wood determination

Because the properties of wood change gradually with tree growth, the determination of the boundary between juvenile and mature wood is extremely difficult. This issue is further complicated by the fact that the point varies with the property index used for investigation. However, it is necessary to establish a definite demarcation point for comparing juvenile and mature wood properties for the sake of managing forests and for processing wood. Up to now, TL,[7] MFA,[14] wood density,[15] and mechanical indices[14] have been used to determine the transition point from juvenile to mature wood, and for all of them, the point when the rate of change became constant was assumed to be the boundary separating juvenile and mature wood. In fact, TL was the basic index for determining the boundary between juvenile and mature wood, and in this research the demarcation that was based on TL showed almost the same points at all heights (Table 1). However, the annual ring number at which the decrease rate of MFA became constant showed irregular results in relation to height, so MFA did not appear to be appropriate for demarcating juvenile wood from mature wood. The demarcation based on the MOE/*G* showed results similar to those of TL (Table 3), and, with the increasing height, showed a reduction of boundary ages. Watanabe et al.[16] reported the same result by studying the distribution of specific compressive strength and specific modulus of elasticity within the stem.

For practical purposes, we think that uniform wood quality should be important, and we are more concerned with the mechanical properties of wood that are closely related to end-product quality. Therefore, MOE/*G* was thought an effective index for determining the boundary between juvenile and mature wood. The results based on MOE/*G* are shown in Table 3.

Properties of juvenile and mature wood

Table 4 presents the mean values of each index examined in both juvenile and mature wood determined by 1%, 2%, and 3% of the increase rate of MOE/*G*. In regard to anatomical properties, the average value of the MFA in mature wood was about 50% less compared with that in juvenile wood. However, the average TL in mature wood was 30%–40% longer than that in the juvenile wood. No significant difference was found between juvenile and mature wood for SG. In regard to mechanical properties, MOE showed the most significant difference between juvenile and mature wood, with a 31%–38% increase from juvenile to mature wood. MOR and σ showed a 12%–16% increment from juvenile to mature wood and 6%–13% for τ. *G* decreased by about 12%–18% from juvenile to mature wood.

Theoretically, demarcation determined by a low increase rate leads to uniform wood quality. From Table 4 we find an improvement in coefficients of variation (CV) and an average value from the point of 3% to 1%, especially in mature wood. However, both the average value and the CV showed an insignificant difference among these three points, so we thought that each of them is applicable as a point for determining the boundary between juvenile and mature wood. However, the conclusion here is only appropriate for aged trees. For younger trees, for example, those less than 40 years old, the differences among the boundaries obtained from 1%, 2%, and 3% may cause significant variations of wood quality in either juvenile or mature wood. In this situation, the 2% of the increase rate of MOE/*G* was thought a reasonable index for determining the juvenile/mature wood boundary. The wood quality in mature wood determined by these means was relatively stable, and almost the same result was obtained by using 1% of TL.

Table 4. Average juvenile and mature wood properties

Indices	Increase rate of MOE/*G*	Juvenile wood	Mature wood	Mature/Juvenile
MFA (degrees)	1%	19.4 (47.2)	9.7 (36.3)	0.50
	2%	20.7 (44.4)	10.4 (39.8)	0.50
	3%	22.3 (41.3)	11.2 (42.3)	0.50
TL (mm)	1%	2.66 (22.6)	3.43 (5.3)	1.29
	2%	2.54 (23.0)	3.39 (5.5)	1.34
	3%	2.39 (23.4)	3.34 (6.3)	1.40
SG	1%	0.37 (8.9)	0.40 (7.2)	1.07
	2%	0.37 (9.0)	0.39 (8.1)	1.06
	3%	0.37 (9.4)	0.39 (8.2)	1.06
MOE (GPa)	1%	7.55 (20.6)	9.91 (10.4)	1.31
	2%	6.99 (20.5)	9.46 (12.9)	1.35
	3%	6.70 (20.1)	9.27 (14.1)	1.38
MOR (MPa)	1%	63.8 (13.2)	74.1 (9.9)	1.16
	2%	62.2 (12.9)	71.5 (11.8)	1.15
	3%	61.5 (13.0)	70.6 (12.2)	1.15
G (MPa)	1%	827 (18.6)	730 (9.6)	0.88
	2%	868 (19.0)	735 (9.9)	0.85
	3%	898 (18.8)	739 (10.4)	0.82
σ (MPa)	1%	37.5 (11.9)	42.1 (9.4)	1.12
	2%	36.5 (10.8)	41.2 (10.8)	1.13
	3%	36.0 (10.3)	40.8 (11.1)	1.13
τ (MPa)	1%	6.47 (15.2)	7.3 (14.7)	1.13
	2%	6.47 (14.4)	7.00 (16.4)	1.08
	3%	6.50 (14.6)	6.91 (16.6)	1.06

The data used here includes all tree heights for all sample trees. Coefficients of variation are shown in parentheses

Table 5. Correlation coefficients for mechanical versus anatomical properties

Mechanical property	Anatomical property		
	SG	MFA	TL
MOE	0.668*	−0.657*	0.726*
MOR	0.837*	−0.481*	0.440*
σ	0.906*	−0.453*	0.399*
G	0.079	0.611*	−0.719*
τ	0.754*	0.174	0.045

* $P < 0.01$

Correlation between anatomical and mechanical properties

It was known that the differences of properties between juvenile and mature wood were caused by the differences in anatomical structures. In order to examine this statement, regression analyses between anatomical and mechanical indices were performed (Table 5). The results showed that SG correlated with all mechanical properties except for *G*, and correlated significantly with strength indices such as MOR and σ.

From Fig.4, curve changes for *G* seemed to relate with MOE. In fact, the correlation of these results existed only in juvenile wood, where MFA significantly affected both *G* and MOE. On the other hand, the correlation between SG and MOE was mainly in mature wood, so the relationship between SG and *G* was not found.

From the correlation coefficients, it was also found that MFA and TL correlated with all mechanical properties except for τ, and they related significantly with indices of modulus such as MOE and *G*. This could be explained by the variations of MFA and TL within the stem, which exactly paralleled those of MOE and *G*. Anatomically, it was thought that TL related with mechanical properties, and MFA had a close relationship with MOE and *G*, as well as other mechanical properties. Hirakawa et al.[17] reported that about 90% of variation of MOE resulted from the variation of SG and MFA.

Conclusions

Variations of certain anatomical and mechanical indices within tree stems of aged sugi trees in Akita prefecture were studied. The determination of juvenile and mature wood was also discussed, and the effects of wood structure on its mechanical properties were investigated. The following conclusions were obtained.

In the radial direction, MOE increased abruptly in juvenile wood and then increased gradually in mature wood. *G* decreased sharply in juvenile wood and became almost constant in mature wood.

In the vertical direction (from breast height to about 13.2 m), the values at breast height for TL were small, and those for MFA were big compared with the upper parts of the stem. For MOE and *G*, the variation with tree height varied between juvenile and mature wood. In juvenile wood, there were little vertical difference for MOE, but *G* decreased with increasing height. In mature wood, MOE showed an increasing trend as heights increased, but few differences were found among tree heights for *G*.

For dividing juvenile and mature wood, the relations between annual ring number and MOE/*G* were regressed with a logarithmic curve, and the increase rates of MOE/*G* at the points of 1%, 2%, and 3% were discussed. For aged trees, when the three points were used to determine and juvenile/mature wood boundary, few differences existed in wood quality between juvenile and mature wood, so all three points were thought to be effective for dividing juvenile and mature wood. However, for younger trees, the point of 2% was recommended, and was mostly consistent with the result obtained by the increase rate of 1% for TL.

Among the mechanical properties, the MOE showed more significant juvenile/mature wood differences than did MOR and σ. By correlation analysis, it was suggested that MFA contributed largely to the indices of MOE and *G*, and SG contributed largely to the indices of MOR and σ.

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