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ORIGINAL ARTICLE

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Longitudinal shrinkage variations within trees of sugi (*Cryptomeria japonica*) cultivars

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Abstract The longitudinal shrinkage variations within trees and the relationship with density, microfibril angle, and modulus of elasticity were examined for five sugi cultivars selected for different within-tree distributions of density, microfibril angle, and modulus of elasticity. The cultivars showed significant differences in longitudinal shrinkage and in its within-tree distribution. The within-tree distributions were categorized into two types: (1) large values of longitudinal shrinkage near the pith that decreased with height and from pith to bark, (2) small values of longitudinal shrinkage near the pith that increased slightly from pith to bark. There were strong relationships between longitudinal shrinkage and microfibril angle, and modulus of elasticity, with large values of longitudinal shrinkage associated with large microfibril angle and low modulus of elasticity. Sugi exhibited large variation in longitudinal shrinkage within stem and among cultivars, with the variation strongly affected by microfibril angle.

Key words Longitudinal shrinkage · Microfibril angle · Modulus of elasticity · *Cryptomeria japonica*

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Introduction

A major need of manufacturers of forest products is wood uniformity, and juvenile wood is a major cause of nonuniformity.[1] While longitudinal shrinkage is much smaller than transverse shrinkage, excessive longitudinal shrinkage can cause a noticeable shortening in the long dimension of lumber. Longitudinal shrinkage is appreciably higher in juvenile wood and compression wood in which the microfibrils are oriented at a significant angle from the cell axis.[2] Crook and bow often occur in lumber, and waviness occurs in veneer that has such wood on one edge or face. If the lumber is sorted by shrinkage properties before drying and an appropriate drying method is applied, there should be an increase in the drying yield and quality of lumber.[3]

The amount of shrinkage is generally proportional to the amount of cell wall material, and thus shrinkage increases in proportion to wood density.[4] Wood shrinkage occurs by the removal of water bound to the cellulose and hemicellulose molecules. The region consisting of noncrystalline cellulose and hemicellulose shrinks in the direction that is orthogonal to the crystalline cellulose microfibrils. Therefore, longitudinal shrinkage increases and transverse shrinkage decreases with an increase in the microfibril angle, which is the angle at which cellulose microfibrils are oriented. This anisotropic behavior has been explained by the reinforced-matrix hypothesis.[5] Recently, the contribution of noncrystalline cellulose to longitudinal shrinkage behavior has been investigated.[6]

Sugi (*Cryptomeria japonica* D. Don) is a major plantation species in Japan. However, there is little information about the variation of shrinkage properties in sugi. The microfibril angle (MFA) is large in the core of sugi stem and its within-tree distributions are different among cultivars.[7–9] Therefore, longitudinal shrinkage is expected to be large at the core with different distributions among cultivars.

To clarify the differences in longitudinal shrinkage and its within-tree distributions among cultivars, we examined the radial and height trends of longitudinal shrinkage, density, MFA, and modulus of elasticity in stems of five

Table 1. Stand locations, tree ages, numbers of trees and means of diameter at breast height (DBH) of five sugi cultivars

Cultivar	Stand location	Tree age (years)	Number of trees	Mean of DBH (cm)
Boka-sugi	Takaoka, Toyama	36	42	25.4
Yabukuguri	Kahoku, Kumamoto	42	10	29.8
Aya-sugi	Kahoku, Kumamoto	49	30	31.7
Ryuunohige	Kikuchi, Kumamoto	52	30	24.1
Kumotooshi	Kikuchi, Kumamoto	55	10	27.0

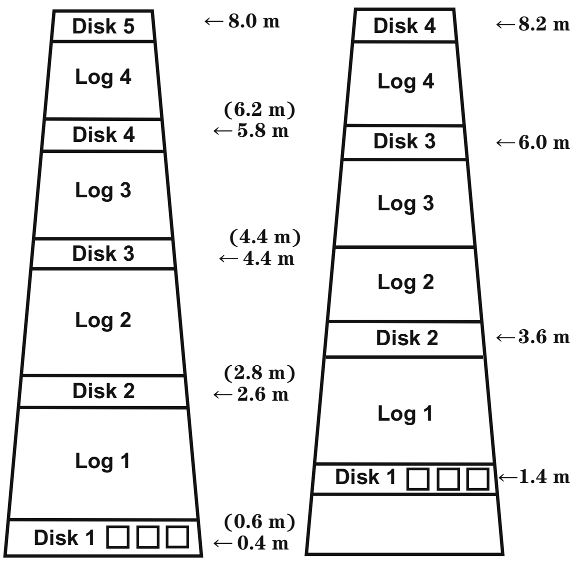

Fig. 1. Sampling heights of aya-sugi, ryuunohige, and boka-sugi (*left*) and yabukuguri and kumotooshi (*right*). The sampling heights of boka-sugi are shown in parentheses. The first disk of ryuunohige was taken at 0.6 m height

cultivars. The relationships between the trends are discussed in terms of sorting lumber with high longitudinal shrinkage.

Materials and methods

Materials

The five sugi cultivars used in this study were: boka-sugi, yabukuguri, aya-sugi, ryuunohige, and kumotooshi (Table 1). The trees of boka-sugi were sampled from two stands in Toyama Prefecture, and the trees of yabukuguri, aya-sugi, ryuunohige, and kumotooshi were sampled from stands in Kumamoto Prefecture, Japan. The two stands of boka-sugi were 20 km apart, but were managed in the same way.

Disks of 200-mm thickness were cut at different heights between the logs above the ground (Fig. 1). The disks were used to measure longitudinal shrinkage, density, and MFA, and the logs were used to test for modulus of elasticity.

Longitudinal shrinkage and basic density

Longitudinal shrinkage and basic densities were measured at different radial and height positions within the stem using JIS-Z-2101:1994.[10] The longitudinal shrinkage specimens with dimensions of 5 (T) × 30 (R) × 60 (L) mm were taken at two, three, or four radial positions from pith to bark. The innermost specimens were taken from more than 20 mm from the pith to avoid knots. The surfaces of the transverse planes were finished with a hand planer. A centerline parallel to the longitudinal axis was marked for length measurement on the surface of the radial plane. All these procedures were completed without drying.

The longitudinal dimension was measured in the green and oven-dried condition using a Sony digital gauge (DG-100S) to a precision of 0.002 mm. The shrinkage specimens were oven-dried for one night at 60°C and for two nights at 103°C. The longitudinal shrinkage from green to oven-dry (α_L) was obtained as a percentage of the green dimension. The basic density (BD) was obtained as oven-dry weight per green volume. The ring number from the pith (RingNo) was recorded for the shrinkage specimens.

Microfibril angles

The MFA of the S_2 layer was measured at different radial and height positions within the stem using the shrinkage specimens from five trees in each cultivar. A thin tangential section was cut from the last-formed latewood of the growth ring that was used for the shrinkage measurement. Using images enlarged by an optical microscope, the angles between tangential slit-like pit apertures and the axis of tracheids were measured for 30 tracheids and then the mean value was obtained as the MFA.[11]

Modulus of elasticity

The dynamic modulus of elasticity (E_{fr}) of log was measured by tapping the logs in the green condition.[12,13] The fundamental frequency of longitudinal vibration was obtained with a fast Fourier transform digital signal analyzer (Ryon SA-71). The E_{fr} was calculated using Eq. 1

$$E_{fr} = 4L^2f^2\rho \quad (1)$$

where L is the length, f is the fundamental frequency of longitudinal vibration, and ρ is the green density.

Statistical analysis

The variation in wood properties within stem and among cultivars was evaluated using the JMP5.01 software package (SAS Institute). About 8% of the specimens were not analyzed because they included knots. The differences among the radial and height positions within stem were examined by *t*-tests and correlation analysis between RingNo and α_L at each height. The differences among cultivars were examined by one-way analysis of variance (ANOVA) and Tukey-Kramer HSD test at two heights for α_L (1.4–1.7 m and 5.8–6.2 m) and E_{fr} of logs (2.5–2.8 m and 6.9–7.1 m). The α_L of the first and second disks and the E_{fr} of the first and second logs were averaged for boka-sugi, aya-sugi, and ryuunohige, because they were sampled at heights that were different from those for yabukuguri and kumotooshi (Fig. 1).

The relationships between α_L and BD, MFA, and E_{fr} of logs were evaluated using correlation analysis for each cultivar and for the combined five cultivars. The relationship between α_L and E_{fr} of logs was examined using α_L averaged from both ends of each log.

Results

Longitudinal shrinkage

There were large within-tree differences in longitudinal shrinkage (α_L) (Fig. 2, Table 2). The within-tree patterns of α_L of the cultivars were categorized into two types: (1) large α_L near the pith at the base of the stem that decreased with height and from pith to bark, and (2) small α_L near the

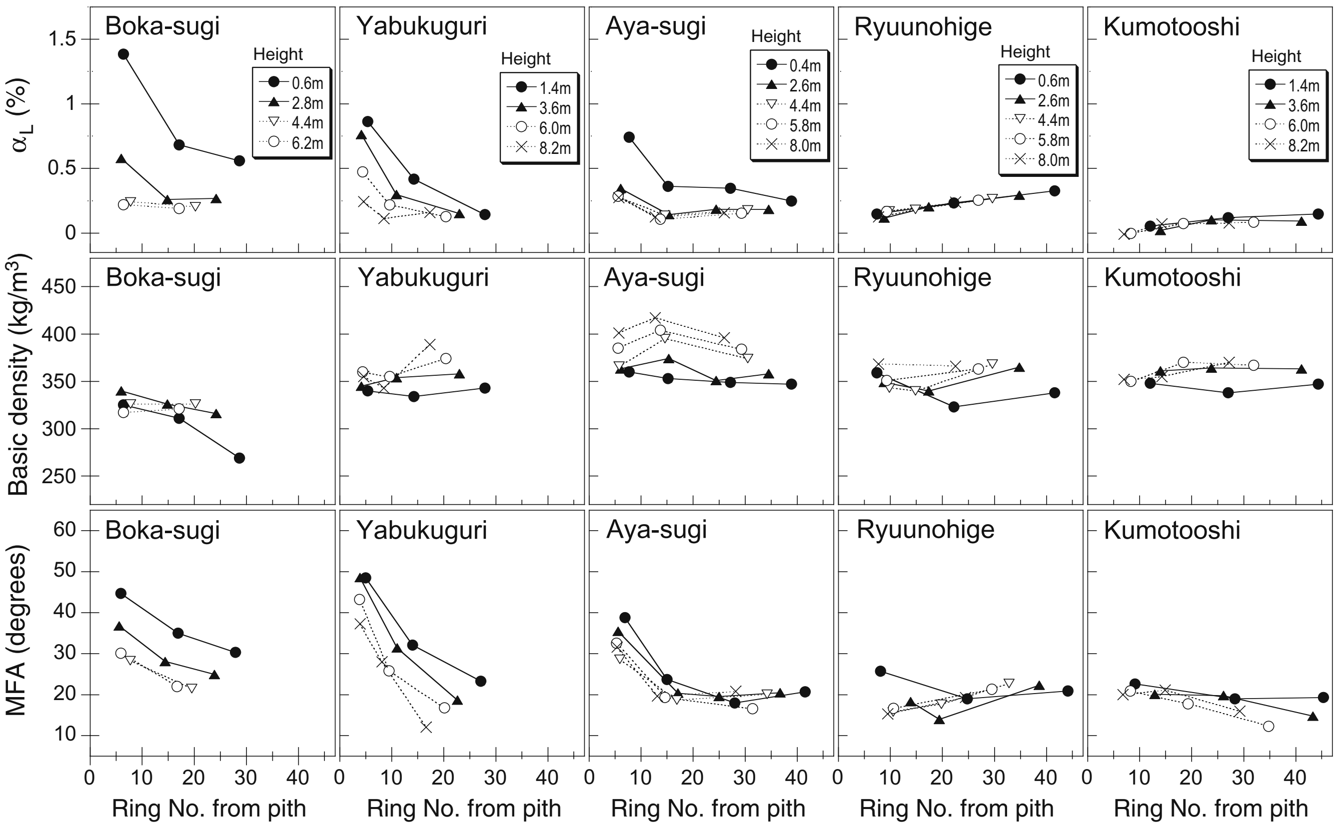

Fig. 2. Radial profiles of longitudinal shrinkage (α_L), basic density, and microfibril angle (*MFA*) at different heights for the five sugi cultivars

Table 2. Longitudinal shrinkage from green to oven-dry (α_L) of the sugi cultivars at two heights

Cultivar	Height 1.4–1.7 m			Height 5.8–6.2 m		
	Disk	IP	OP	Disk	IP	OP
Boka-sugi	0.613 a	0.942 a	0.414 a	0.206 b	0.220 bc	0.189 b
Yabukuguri	0.534 a	0.863 a	0.142 c	0.273 a	0.473 a	0.128 cd
Aya-sugi	0.320 b	0.540 b	0.216 bc	0.187 b	0.285 b	0.158 c
Ryuuohige	0.227 bc	0.133 c	0.310 b	0.214 b	0.167 c	0.256 a
Kumotooshi	0.117 c	0.055 c	0.148 c	0.057 c	–0.003 d	0.084 d

There was significant difference among the cultivars by ANOVA in each position at each height ($P < 0.001$). Values in same column with different letters were significantly different by Tukey-Kramer HSD test ($P < 0.05$)

Disk, mean of the radial positions from pith to bark; IP, the inner part of the stem near the pith; OP, the outer part of the stem near the bark pith that was unchanged with height and increased slightly from pith to bark. Boka-sugi, yabukuguri, and aya-sugi showed the type 1 pattern, and there were significant negative correlations between RingNo and α_L for the different heights (P < 0.01). Ryuunohige and kumotooshi showed the type 2 pattern, and there were significant positive correlations between RingNo and α_L for the different heights (P < 0.01).

The α_L was significantly different among the five cultivars (Table 2). The α_L was the largest in boka-sugi and yabukuguri, and the smallest in ryuunohige and kumotooshi. The differences between the cultivars were larger in the inner stem and at lower heights.

Basic density

The differences in BD among the radial and height positions were generally small. The within-tree patterns of BD showed no similarities with those of α_L (Fig. 2). Among the cultivars, BD was significantly higher in aya-sugi and lower in boka-sugi compared with the other three cultivars (P < 0.01). The order of BD by cultivar did not coincide with the order of α_L.

Microfibril angles

There were large within-tree differences in MFA (Fig. 2). The within-tree patterns of MFA of the cultivars were categorized into two types: (1) large MFA near the pith at the base of the stem that decreased with height and from pith to bark, and (2) small MFA near the pith that changed little with height and from pith to bark. Boka-sugi, yabukuguri, and aya-sugi showed the type 1 pattern, and ryuunohige and kumotooshi showed the type 2 pattern. The within-tree patterns of MFA were similar to those of α_L. Among the cultivars, MFA was larger in the cultivars with larger α_L.

Modulus of elasticity

There was a wide range of E_{fr} of logs with significant differences among cultivars and among heights within cultivars (Fig. 3, Table 3). The first log had the lowest E_{fr} in each of the five cultivars (P < 0.01), with the E_{fr} of logs increasing with height. Among the cultivars, the E_{fr} of logs were lower in boka-sugi and yabukuguri and higher in ryuunohige and kumotooshi at a given height.

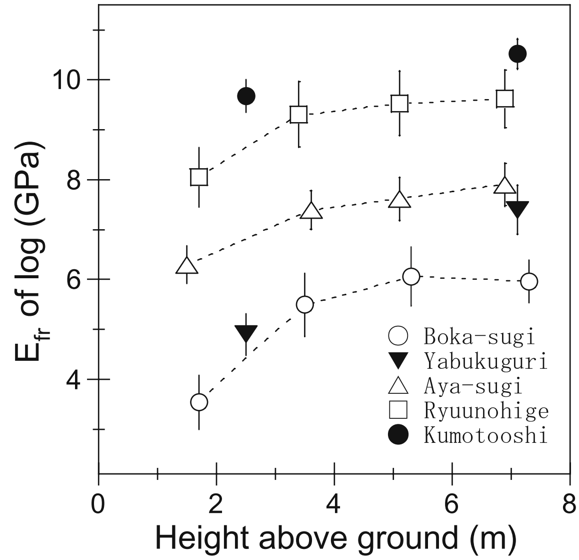

Fig. 3. Modulus of elasticity (E_{fr}) at different heights for the five sugi cultivars. *Error bars* indicate standard deviations

Table 3. Modulus of elasticity (E_{fr}) of the sugi cultivars at two heights

Cultivar	E_{fr} of logs (GPa)	
	2.5–2.8 m	6.9–7.1 m
Boka-sugi	4.53 d	5.97 e
Yabukuguri	4.88 d	7.43 d
Aya-sugi	6.84 c	7.90 c
Ryuuohige	8.68 b	9.62 b
Kumotooshi	9.68 a	10.55 a

There was significant difference among cultivars by ANOVA at each height (P < 0.001). Values in same column with different letters were significant different by Tukey-Kramer HSD test (P < 0.05)

Relationships between longitudinal shrinkage and basic density, microfibril angle

The relationships between α_L and BD and between α_L and MFA were examined for each cultivar with the specimens without compression wood (Fig. 4). There were very weak relationships between α_L and BD for all the cultivars, but strong relationships between α_L and MFA for boka-sugi, yabukuguri, and aya-sugi. The relationships with MFA were curvilinear increasing with MFA of 30° or more. Ryuunohige and kumotooshi had values of MFA that were generally below 30° and therefore the relationships between α_L and MFA were weak.

The relationships were examined for the combined cultivars (Fig. 5). There was a weak relationship between α_L and BD and a moderately strong curvilinear relationship between α_L and MFA. In multiple regression analysis with BD and MFA as dependent variables and α_L as an independent variable, the effect of MFA was significant (P < 0.01), but the effect of BD was not significant (P = 0.23).

Relationship between longitudinal shrinkage and modulus of elasticity

The relationships between α_L and E_{fr} of logs were significant for α_L of disk, the inner and outer parts in each cultivar (P < 0.01) except in the outer part of yabukuguri (Fig. 6). The relationships were curvilinear with lower E_{fr} of logs. The relationships were stronger for α_L of the inner part than

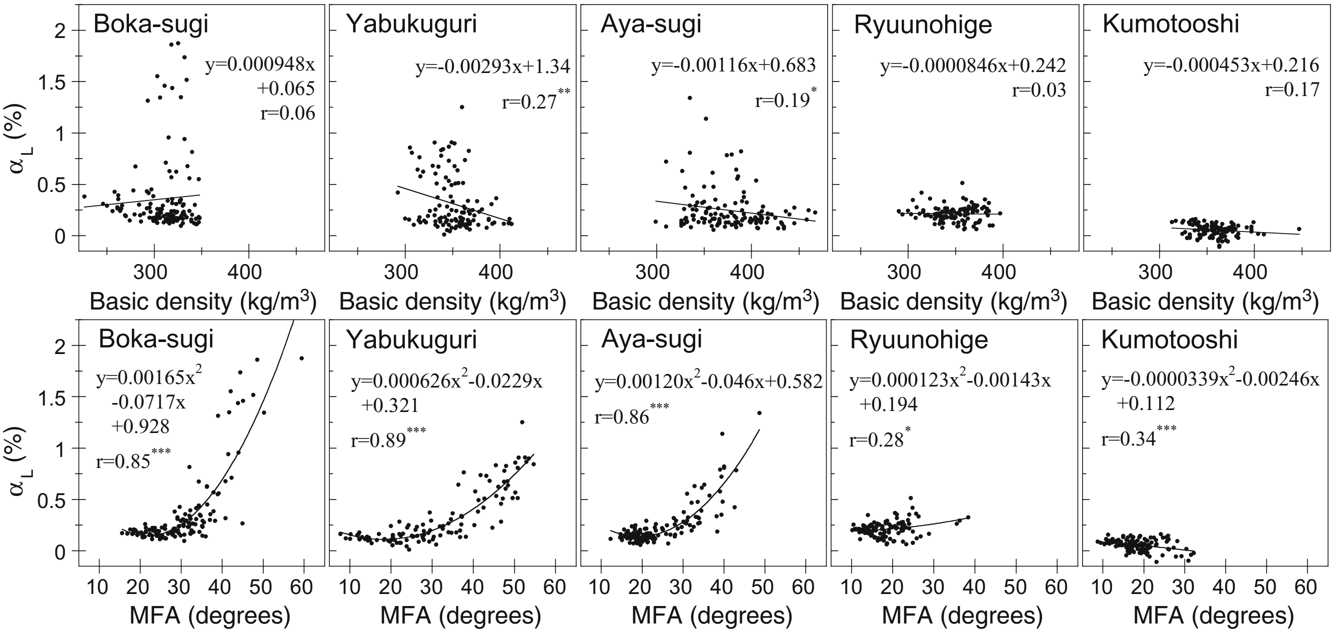

Fig. 4. Relationships between longitudinal shrinkage (α_L) and basic density, and MFA for the five sugi cultivars

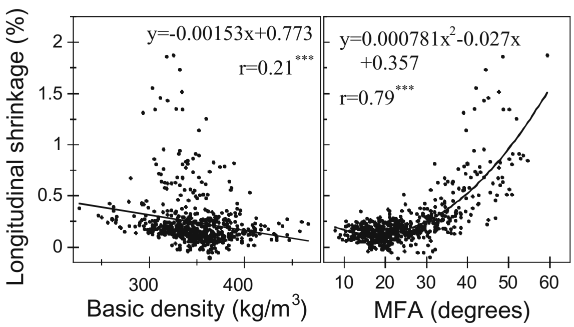

Fig. 5. Relationships between longitudinal shrinkage and basic density, and MFA for the combined samples of the five cultivars

α_L of the outer part in boka-sugi, yabukuguri, and aya-sugi. For the combined samples of all the cultivars, there were moderately strong curvilinear relationships between α_L and E_{fr} of logs for α_L of disk and the inner part ($P < 0.01$) (Fig. 7). The relationship was also significant for α_L of the outer part ($P < 0.01$). The α_L of disk was generally less than 0.3% for logs with E_{fr} greater than 7.0 GPa.

Discussion

The previous studies by Ono and coworkers[14–18] showed that longitudinal shrinkage at breast height was large near the core and the values were different among cultivars in young sugi trees. Fukuhara et al.[19] noted that it was difficult to find a consistent trend in noncultivar trees because the within-tree distributions varied between trees. Our study showed significant differences within stem, and remarkably different radial and height trends among cultivars. It might be concluded from the following observations that the differences in longitudinal shrinkage were affected by MFA. First, the within-tree longitudinal shrinkage trends were similar to those of MFA (Fig. 2). Second, the cultivars with larger MFA showed greater longitudinal shrinkage (Fig. 2). Third, there was a strong relationship between longitudinal shrinkage and MFA (Figs. 4, 5). It has been reported that longitudinal shrinkage is large near the core and that MFA contributes to it in other softwood species such as *Picea abies*,[20,21] *Pinus taeda*,[22,23] and *Pinus radiata*.[24] The importance of MFA as an indicator of longitudinal shrinkage might depend on whether MFA variation within a species is large.

The variations in longitudinal shrinkage might cause variations in the dimensional stability of lumber sawn from different trees or different positions within the stem. Distortion during drying might occur at a higher rate in lumber taken from the core of the stem where the values and the changes in longitudinal shrinkage are large, such as in boka-sugi, yabukuguri, and aya-sugi. Tooya[25] found a high tendency of distortion in the core of the stem at lower height in measa-sugi. In cultivars with small values and variations in longitudinal shrinkage such as ryuunohige or kumotooshi, the dimensional stability might be good in the whole stem.

Watanabe and Norimoto[26] reported a strong correlation between longitudinal shrinkage and specific Young's modulus for the combined samples of several softwood species. We found a strong relationship between longitudinal shrinkage and modulus of elasticity at log level in sugi (Figs. 6, 7). The relationship occurred because both longitudinal shrinkage and modulus of elasticity were affected by the same factor, MFA. The modulus of elasticity of lumber is nondestructively measured for strength grading at saw mills. Sorting logs or lumbers with low modulus of

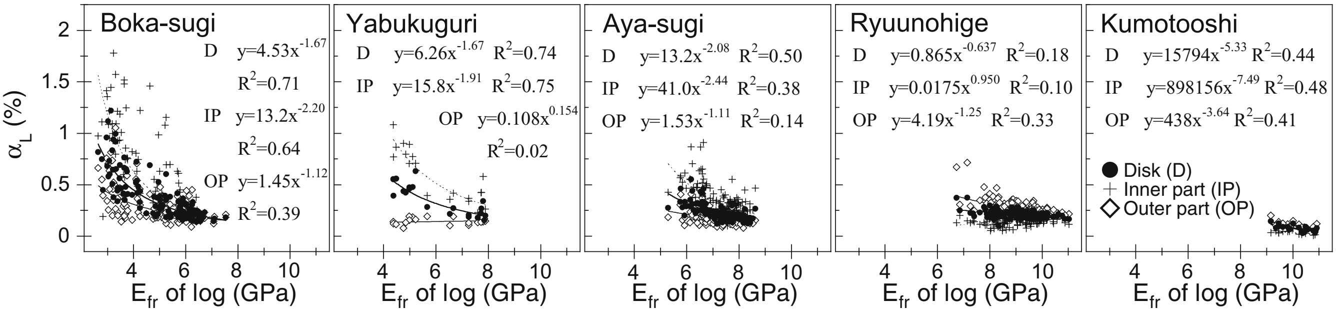

Fig. 6. Relationships between longitudinal shrinkage (α_L) and modulus of elasticity (E_{fr}) of logs for the five sugi cultivars

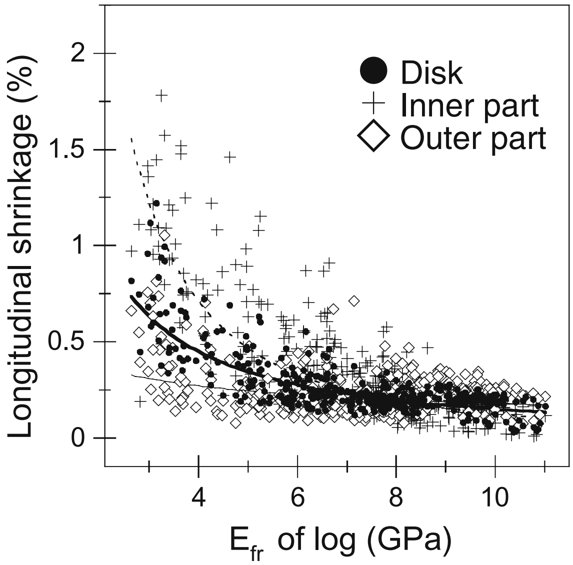

Fig. 7. Relationship between longitudinal shrinkage and modulus of elasticity (E_{fr}) of log for the combined samples of the five cultivars. The curvilinear regressions were: $y = 2.34x^{-1.19}$, $R^2 = 0.56$ for disk; $y = 9.68x^{-1.88}$, $R^2 = 0.55$ for inner part of stem; and $y = 0.506x^{-0.452}$, $R^2 = 0.10$ for outer part of stem

elasticity could exclude lumber having a high tendency for distortion during drying. This could increase the drying yield and reduce the energy used in drying.

A previous study[9] compared MFA and modulus of elasticity (E_{fr}) of logs among 18 sugi cultivars collected from a stand in Ibaraki Prefecture. It was found that boka-sugi and yabukuguri had larger MFA and smaller E_{fr}, kumotooshi had smaller MFA and larger E_{fr}, and MFA and E_{fr} of aya-sugi were in the middle of these cultivars. These results are similar to those obtained in this study. The study also showed that the within-tree patterns of MFA and E_{fr} were different among cultivars, and the patterns of the four cultivars were similar to those obtained in this study. These similarities between trees of the same cultivars planted in different stands suggest that the values and within-tree patterns of MFA and modulus of elasticity are under genetic control in sugi. The strong relationship between longitudinal shrinkage and MFA suggests that it might be possible to improve the dimensional stability of sugi lumber by genetic selection. Koshy and Lester[27] have shown some genetic control of longitudinal shrinkage in Douglas fir and the possibility of improvement by genetic means.

Contrary to our expectations, longitudinal shrinkage tended to increase slightly from pith to bark in ryuunohige and kumotooshi, although MFA did not increase (Fig. 2). There are other reports of an increase in longitudinal shrinkage in the outer stem of sugi.[19,28] In order to clarify this small difference, further studies are needed. There are other factors affecting shrinkage such as chemical components, cellulose crystallinity, anatomical structures including cell sizes and arrangements, and the release of residual stress, but the variations in these properties have not been investigated.

Abe and Yamamoto[6] showed the nonlinearity degree of longitudinal shrinkage with moisture change increased as MFA decreased in *Chamaecyparis obtusa*. They suggested that the longitudinal shrinkage in wood with small MFA might be restrained by the rigid cellulose microfibrils with a sudden increase in longitudinal shrinkage at low moisture content as the noncrystalline region of the cellulose microfibrils begin to shrink. Several lines of speculation have been made for the nonlinearity, such as the slipping of chain molecules,[29] changes in the elastic content,[30] and differences in water loss from cellulose chains and amorphous hemicelluloses.[24] The nonlinearity with moisture change might be varied within sugi trees because of the large variations in wood properties. Further studies are needed to clarify how water molecules bind in wood tissues at different levels of moisture content, using samples that have different shrinkage behavior.

Conclusions

Sugi cultivars showed significant differences in longitudinal shrinkage with different radial and height trends within the stem. There were strong relationships between longitudinal shrinkage and MFA and modulus of elasticity for boka-sugi, yabukuguri, and aya-sugi, with large values of longitudinal shrinkage associated with large MFA and low modulus of elasticity. The nonuniformity of MFA and modulus of elasticity contributed significantly to the nonuniformity of longitudinal shrinkage within stem and among cultivars. It might be possible to use the modulus of elasticity for sorting the lumber with a high tendency for distortion during drying.

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