Difference between juvenile wood and mature wood in compressive and shear strength of 55-year-old sugi (Cryptomeria japonica D. Don) trees originated from seedlings

55年生実生スギにおける圧縮強さ及びせん断強さの未成熟材と成熟材の違い

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Summary
Sugi (Cryptomeria japonica D. Don) is one of the main tree species which are extensively planted in Japan. Recently, the rotation period of sugi plantation has been prolonged. For effective utilization of sugi wood resources in the future, therefore, it is very important to understand the properties of wood derived from aged-sugi trees. In the present study, radial variation of wood properties (microfibril angle, MFA; air-dried density, ρ) and mechanical properties (compressive strength parallel to grain, σ; shear strength, τ) were investigated for 55-year-old sugi trees originated from seedlings. Based on the obtained results, differences in wood and mechanical properties between juvenile wood (JW) and mature wood (MW) were discussed. Significant differences between JW and MW were found in τ, but not in σ. Relatively highly correlation coefficients were recognized between ρ and σ in both JW and MW. By multiple regression analysis, MFA and ρ may also influence the σ in JW. On the other hand, significant positive correlation between τ and ρ was found in JW, but not in MW. In addition, τ was not strongly affecting by the MFA. These results suggest that wood property influencing the mechanical property was different between JW and MW.

Keywords: sugi (Cryptomeria japonica), compressive strength parallel to grain, shear strength, juvenile wood, mature wood

要旨
スギ（Cryptomeria japonica D. Don）は我が国に広く植栽されている主要樹種の一つである。近年、スギ人工林の伐期は長期化する傾向にある。そのため、今後、スギ材を有効利用するためには、高齢材の林分から得られるスギ材の木材性質を明らかにする必要がある。本研究においては、林齢55年生の実生スギを用いて、木材性質（ミクロフィブリル傾角MFA、気乾密度ρ）及び力学的性質（基圧縮強さσ、せん断強さτ）の年輪方向変動を調査した。また、得られた結果から、これらの性質における未成熟材と成熟材の違いについて考察した。未成熟材と成熟材を比較した場合、τにおいて有意差が認められたが、σにおいては認められなかった。σにおいては、未成熟材及び成熟材ともにρと高い正の相関関係が認められた。さらに、多重回帰分析の結果から、未成熟材のσは、MFA及びρに影響を受けていることが示唆された。一方、τにおいては、未成熟材においてρとの間に正の相関関係が認められたが、成熟材においては認められず、また、未成熟材及び成熟材ともにτは、MFAとの間に有意な相関関係を示さなかった。以上の結果から、未成熟材と成熟材では、それぞれの力学的性質に及ぼす木材性質が異なっていることが示唆された。

キーワード：スギ、圧縮強さ、せん断強さ、未成熟材、成熟材
1. Introduction

Sugi (Cryptomeria japonica D. Don) is one of the main plantation species in Japan. It is widely distributed throughout Japan, except for northern part of Hokkaido Island. Timber of sugi has been used mainly for construction of traditional wooden houses. Growth of sugi trees is relatively fast compared to other coniferous plantation species. From these reasons, sugi has been extensively planted throughout Japan after World War II.

Many researchers have focused on the wood properties of sugi grown in plantation. Many researches, however, deals with the young plantation trees up to 40-year-old or thinned trees under 25-year-old. Similar reports dealing with wood property of aged plantation sugi trees, such as over 50-year-old, are available.

In our previous study, radial variation of static bending properties in 55-year-old sugi was investigated. In addition, relationship between static bending property and basic wood property was also investigated. Modulus of elasticity (MOE) gradually increased up to 25th annual ring from pith, and then showed almost constant value thereafter. Modulus of rupture (MOR), however, showed almost constant value from pith to bark. We concluded that microfibril angle (MFA) mainly influences the bending property in juvenile wood (JW), whereas air-dried density (ρ) mainly influences on the bending property in mature wood (MW).

In the present study, differences between JW and MW in compressive strength (σ) and shear strength (τ) were investigated to obtain the basic knowledge of wood property in aged plantation sugi trees. In addition, relationship between strength properties and basic wood properties was also discussed.

2. Materials and Methods

Three trees of 55-year-old sugi were harvested from a plantation forest which is located in Motegi Town, Tochigi Prefecture, Japan. These trees were originated from seedlings, which are widely used in Tochigi Prefecture for establishing the plantation. Mean diameter at breast height position of three sample trees was 40.5 cm. After harvesting, logs in 1 m length were obtained from 0.2 to 1.2 m position from the base. Discs in 5 cm thickness were collected from the bud end and used for measuring the basic wood property. Basic wood properties, such as annual ring width (ARW), basic density (BD), latewood tracheid length (TL), and microfibril angle of S: layer of latewood tracheid (MFA), were measured at every three annual rings from pith to bark. Mean values of basic wood properties of three sample trees were listed in Table 1. In the previous study, from the radial variation of TL and MFA, boundary between juvenile wood (JW) and mature wood (MW) was defined as 24th rings from pith. This boundary between JW and MW was also used for the present study.

Compressive test parallel to grain and shear block test using small clear specimens were conducted by using universal testing machine (Orientec RTC-2410) under laboratory condition (ca. 25°C and 65% relative humidity) according to Japan Industrial Standard. Total 258 of small clear specimens for compressive test (60 L) by 20 (R) by 20 (T) mm and total 126 of shear blocks (shear area, 20 (R) by 20 (L) mm) were prepared from three sample trees. Annual ring number from pith at the center of cross section of the specimen was determined. Moisture content of the specimens under air-dried condition was 14.0 ± 0.9%. Before the tests, weight of each specimen was measured for determining the ρ. The load speed of compression test and shear block test were 1 mm/min. After the tests, compressive strength parallel to grain (σ) and shear strength in RL plane (τ) were determined. In addition, specific compressive strength (σ/ρ) and specific shear strength (τ/ρ) were also calculated by dividing σ or τ by ρ.

3. Results

Mean value of wood properties in three sample trees was shown in Table 1. Mean value of ARW, BD and MFA in JW showed higher value than in the MW. On the other hand, standard deviation in all properties in MW was smaller value compared to that in JW.

Table 2 shows ρ of specimens and the results of compressive and shear strength tests. In both compression and shear test specimens, ρ of JW was significant (1% level) higher value than that of MW. In addition, significant differences between JW and MW were found in σ/ρ and τ. On the other hand, there were no significant differences between JW and MW in σ and τ/ρ.

Correlation coefficients between wood properties (MFA

<table>
<thead>
<tr>
<th>Property</th>
<th>JW</th>
<th>MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARW (mm)</td>
<td>5.3</td>
<td>2.4</td>
</tr>
<tr>
<td>BD (g/cm³)</td>
<td>0.30</td>
<td>0.05</td>
</tr>
<tr>
<td>TL (mm)</td>
<td>2.41</td>
<td>0.47</td>
</tr>
<tr>
<td>MFA (degree)</td>
<td>20.5</td>
<td>5.7</td>
</tr>
</tbody>
</table>

Note: JW, juvenile wood (from pith to 24th annual ring); MW, mature wood (from 25th annual ring to bark side); SD, standard deviation; ARW, annual ring width; BD, basic density; TL, latewood tracheid length; MFA, microfibril angle of S: layer of latewood tracheid.

<table>
<thead>
<tr>
<th>Test</th>
<th>Property</th>
<th>JW</th>
<th>MW</th>
<th>Significance between JW and MW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ρ (g/cm³)</td>
<td>0.53</td>
<td>0.03</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>σ (MPa)</td>
<td>21.3</td>
<td>2.9</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>τ (MPa)</td>
<td>64.8</td>
<td>5.1</td>
<td>72.2</td>
</tr>
<tr>
<td></td>
<td>ρ (g/cm³)</td>
<td>0.32</td>
<td>0.04</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>τ (MPa)</td>
<td>4.6</td>
<td>1.0</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Note: JW, juvenile wood (from pith to 24th annual ring); MW, mature wood (from 25th annual ring to bark side); SD, standard deviation; ARW, annual ring width; ρ, air-dried density; σ, compressive strength; τ, shear strength; ρ/σ, specific compressive strength; τ/ρ, specific shear strength; *, significant at 5% level; **, significant at 1% level; ns, no significant.
and ρ) and mechanical properties (σ, σ/ρ, τ, and τ/ρ) are shown in Table 3. No significant correlation coefficient between MFA and mechanical property were found except for σ/ρ (τ = -0.521) in JW. On the other hand, relatively high significant correlations were found between ρ and mechanical properties except for τ in MW.

4. Discussion

In our previous study, basic density showed higher value near the pith, then rapidly decreased up to 9th annual ring from pith, and finally showed almost constant value. As a result, significantly higher value of basic density was found in JW compared to MW. In the present study, ρ of JW in both compression and shear test specimens was significantly higher than that of MW (Table 2).

Several reports on the radial variation of σ in aged-sugi trees are available (10). Kuboijima et al. reported that σ in 86-year-old sugi tree grown in Chiba, Japan, increased from pith to bark. In addition, Zhu et al. reported that MOR in static bending and σ showed a 12% - 16% increment from JW to MW. In the present study, as shown in Table 2, the same mean value (21.3 MPa) in σ was obtained in JW and MW, not corresponding to the results obtained by the other researcher (10). The σ was strongly influenced by the density, i.e. there is a high correlation between ρ and σ. Therefore, density may influence the σ in MW.

When radial variation of σ/ρ in 90-year-old sugi was examined, σ/ρ gradually increased and then showed almost constant value from pith to bark side (10). As the results, σ/ρ in JW was lower than that in MW (10). Our results obtained are similar to those obtained by Watanabe et al. (10).

It is well known that there is a highly positive correlation between ρ and σ (11). In aged-sugi trees, correlation coefficient between density and σ is relatively small (10). On the other hand, when the correlation coefficient in JW and MW was separately calculated, relatively high correlation coefficient was obtained in both JW and MW (10). As shown in Table 3, significantly, high correlation coefficient between ρ and σ were obtained in both JW and MW, indicating that σ in both JW and MW is strongly influenced by the density. On the other hand, Ishiguri et al. suggested that in JW of hinoki (Chamaecyparis obtusa), especially in the xylem up to 10th annual ring from pith, σ was effected not only by density but also MFA. To confirm the influence of MFA on σ, correlation coefficient between σ/ρ and MFA was examined. As a result, significantly negative correlation was found in JW (Table 3). In addition, multiple regression analysis for σ by MFA and ρ was performed for JW and MW (Table 4). Correlation coefficient (τ = 0.901) obtained by multiple regression analysis using both MFA and ρ was higher than that (τ = 0.849, Table 3) calculated by single regression analysis using only ρ. These obtained results suggested that σ in JW was influenced by both MFA and ρ. On the other hand, no significant correlation coefficient was found between MFA and σ in MW (Table 3). In addition, almost the same correlation coefficient was obtained by single (ρ) and multiple (MFA and ρ) regression analyses (Tables 3 and 4). Therefore, it can be said that σ in MW was mainly influenced by ρ. This tendency in MW may be due to the lower value of standard deviation of MFA than that of ρ (Tables 1 and 2).

Zhu et al. reported that, in 78-year-old sugi trees originated from seedlings, τ showed 6 to 13% increment from juvenile to mature wood. In the present study, τ of JW was significantly higher value than that of MW (Table 2), not corresponding to previous reports (10, 20). In general, it is well known that there is a highly significant correlation coefficient between wood density and τ (11). In aged-sugi trees, similar results were obtained by several researchers (10, 20). In the present study, significant correlation coefficient between ρ and τ was found in JW, but not in MW (Table 3). Thus, our results may be not corresponding to previous reports (10, 20). On the other hand, significant correlation coefficient was not obtained between MFA and τ in both JW and MW (Table 3). Zhu et al. also reported that significant correlation coefficient was found between specific gravity and τ, but not between MFA and τ. In addition, there were no significant differences between MFA and τ/ρ, indicating that τ of both JW and MW is not strongly influenced by the MFA. Further research, however, is still needed for clarifying the relationship between basic wood property and τ.

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