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Calculation of index value of heartwood moisture content in sugi log using longitudinal vibrational properties

Toshiyuki Fukui[1*], Yoshiyuki Yanase[2], Koji Murata[3] and Yoshihisa Fujii[4]

Abstract

An index value as an indicator of heartwood moisture content (MC) of sugi (*Cryptomeria Japonica*) green logs is proposed, based on longitudinal vibrational properties. In previous studies the average log MC was estimated from flexural vibration of logs using high negative correlation between specific Young's modulus (E/ρ) and loss tangent (tan δ); however, it is difficult to estimate sapwood and heartwood MC separately using this method. Accordingly, we developed a quantitative index (U), in which the longitudinal vibrational properties of the log are substituted for the flexural vibrational properties. It has been reported that tan δ based on longitudinal vibration is larger than that from flexural vibration, given the large differences in the density of sapwood and heartwood. The index value U is smaller than the estimated average MC because of larger tan δ from longitudinal vibration when heartwood MC is smaller than average MC. The results of the vibration test (using 35 4-m sugi logs) showed that the index value U is well-correlated with heartwood MC. When six of the logs (in which the sapwood had begun to dry) were removed from the data analysis, the correlation coefficient was sufficiently high, at 0.78.

Keywords Moisture content estimation, Heartwood moisture content, Wetwood, Non-destructive evaluation, Green wood, Log, Longitudinal vibration

Introduction

Sugi (*Cryptomeria japonica*) is a major timber plantation species in Japan, accounting for 40% of plantation forest area and 60% of wood production. Because more than 60% of plantation stands in Japan are over 50 years, the Japanese government has initiated a plan to increase the demand for sugi timber by 38% over the next decade [1]. Sugi is characterized by a large variation in heartwood moisture content (MC) among individuals; the heartwood MC of some individual trees is markedly high, due to genetic differences, and this heartwood is called 'wetwood' [2, 3]. Hirakawa et al. [4] reported a minimum sugi heartwood MC of 41% and a maximum of 284%; in contrast, the MC of tree species without apparent wetwood—such as hinoki, akamatsu, and karamatsu—ranges from 30 to 50% [5]. Because of differences among sugi trees, combined with the fact that heartwood is known to take longer to dry due to high pith closing and high osmotic pressure by extractives [6–8], the variation in MC of sugi sawn timber after drying is considerable [9]. This characteristic of sugi wood impedes larger scale use of sugi in construction work in Japan; the industry demands improved log drying processes to minimize the size variation of pre-cut lumber, as it is difficult to adjust the size of the lumber on site. Therefore, establishing technology to measure sugi heartwood MC before

*Correspondence:
Toshiyuki Fukui
fukui.toshiyuki.p08@kyoto-u.jp
[1] Daiken Corporation R&D Center, Minami-ku, Okayama 702-8045, Japan
[2] Research Institute for Sustainable Humanosphere, Kyoto University, Uji, Kyoto 611-0011, Japan
[3] Graduate School of Agriculture, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan
[4] Emeritus, Graduate School of Agriculture, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan

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cutting the logs and identifying the wetwood will help to reduce the variation in MC in the sawn lumber after processing by adjusting the drying schedule, thereby encouraging commercial utilization of sugi.

It is often pointed out that the heartwood of sugi wetwood appears black, whereas normal sugi heartwood is red. In some studies, a negative correlation was found between heartwood brightness and its MC. However, Nakada [2] concluded that color alone is not reflective of the MC of the heartwood. Methods based on the heartwood color in a cross section of log are not reliable, given that heartwood color readily changes when the crosse section is exposed to the air after cutting. The relationship between the heartwood MC and the concentration of potassium ion (the direct cause of heartwood color change) was investigated; however, the correlation was not sufficient to estimate either heartwood color or heartwood MC [10, 11].

Dielectric constant and dielectric loss—which are measured by subjecting wood to electromagnetic wave energy through electrodes—are measurable parameters that are known to relate to MC [12] and thus are suitable as direct and non-destructive measures of MC. Suzuki et al. [13] measured phase shift and impedance of electromagnetic waves in the range of 10^2–10^6 Hz and showed there are distinctive differences in frequency dependency between logs with high MC in heartwood and logs with low MC in heartwood. Ikeda et al. [14] estimated heartwood MC of large-diameter sugi logs by transmitting high-frequency electromagnetic waves through the radial direction and devising indices based on wave attenuation and phase shift.

To achieve simplified and more accurate MC estimation, a new density-independent method was developed by combining E/ρ and tan δ from flexural vibration of green logs [15, 16]. This method is based on the high negative correlation between E/ρ and tan δ in wood [17–19]. Because the value of E/ρ changes according to MC in the range of values above the fiber saturation point (FSP) and tan δ is stable above FSP, the regression line of this correlation changes with respect to MC only at values above FSP [20]. Therefore, MC can be calculated by locating the measured value on one or another of the regression lines. However, it seems impossible to determine the breakdown of MC between sapwood and heartwood, because MC is calculated from apparent density. On the other hand, we have found that tan δ determined from longitudinal vibration (tan δ_l) is greater than that from flexural vibration when there is large difference in density between sapwood and heartwood because of larger shear deformation generated except for pure axial deformation with larger value in the ratio of sapwood to heartwood density [21]. Considering these previous findings and the fact that heartwood MC is always lower than sapwood MC due to the nature of wood, it was hypothesized that the numerical result obtained by substituting longitudinal vibrational properties in place of flexural vibrational properties in the method would result in improved estimation of heartwood MC when the heartwood MC of the log is lower than the average MC. In other words, the larger the value of substituted tan δ, the smaller the numerical result (U value).

The index U is obtained by substituting longitudinal vibrational properties in place of flexural vibrational properties into our MC estimating method. The correlation between the actual measured heartwood MC of 35 sugi 4-m logs and the calculated value of U was assessed.

Materials and methods

Preparation of log specimens

In this study, 35 sugi (*Cryptomeria japonica*) logs that had been previously purchased at a timber market in Kyoto were used in the experiment. These were exactly the same logs that had been used in our previous studies [16, 21]. The diameter range of all logs at the top end was 200–300 mm, and the length of each log was approximately 4 m. The ratio of the heartwood diameter, including the transition zone, to the log diameter was in the range of 0.61–0.81 (average of 0.68), and the ratio of the log length to the average log diameter was 30.8–37.2 (average of 33.4). The average oven-dry density of sapwood and heartwood was 0.377 and 0.385 g/cm^3, respectively. The sapwood and heartwood MC values were obtained from four disks cut from the logs after the vibration test (same procedure as in the previous study).

Measurement of vibrational properties of log specimens

The same values of vibrational properties of logs measured in our last study were used in this study [16, 21]. To measure longitudinal vibration, the log was supported at the center, and vibration was produced by striking the top end cross section with a plastic mallet. To obtain the flexural vibration values, the log was supported at two nodal positions of primary flexural vibration, and vibration was excited by striking the side of the log near the bottom end with a plastic mallet.

Calculation of index value *U* of heartwood MC

We define the index U as the numerical result obtained by substituting longitudinal vibrational properties into our MC estimation equation, which was originally established for estimating average MC using flexural vibrational properties [15, 16]. The original MC estimation equation (based on flexural vibrational properties) was developed as follows. It is well-known that there is high negative correlation between E/ρ and tan δ at certain

MC, including FSP. Thus, the regression line of the correlation in 30% MC can be expressed as

$$\log(\tan\delta) = a\log\left(\frac{E}{\rho_{30}}\right) + b, \tag{1}$$

where E/ρ_{30} denotes E/ρ at 30% MC, a (< 0) and b denote slope and intercept, respectively. In this study, we regard a and b as − 0.880 and 9.57, respectively, as previous study [16] reported from flexural vibration of sugi green small specimens.

When the value of MC rises above FSP, E/ρ decreases as apparent density ρ increases and tan δ is stable. As a result, the intercept of the regression line of this correlation decreases in accordance with the ratio of increase in apparent density, although the slope does not change [15] (bold line in Fig. 1). From the ratio of increase in apparent density, the average MC u can be calculated using the regression line at 30% MC (Eq. 1) and flexural vibrational properties (E_f/ρ and tan δ_f) measured from wood specimens:

$$u = 130 \times 10^{p\log(\tan\delta_f) - \log\left(\frac{E_f}{\rho_u}\right) + q} - 100, \tag{2}$$

where $p = \frac{1}{a}$ and $q = -\frac{b}{a}$, ρ_u denotes density at u % MC. This method has been verified in previous studies [16] in which the average MC of a log was estimated with a standard deviation of 15.7% and a systematic error of 25.9%. However, taking it into consideration that MC is calculated from the increase in apparent density of whole specimen in this method, it seems impossible to separate sapwood MC and heartwood MC.

The purpose of using longitudinal vibrational properties rather than flexural vibration properties is as follows. In our previous research [21], the focus was longitudinal vibration, the displacement of which is parallel to log grain orientation, instead of flexural vibration. As Tonosaki et al. reported [22], when a beam specimen is long enough and uniform, nearly the same value of tan δ is obtained from either flexural or longitudinal vibration. However, we found that tan δ from longitudinal vibration (tan δ_l) of log and that from flexural vibration (tan δ_f) are not, in fact, related, and tan δ_l becomes larger than tan δ_f as heartwood MC falls below sapwood MC, although the E/ρ value from these two kinds of vibration almost coincide with each other [21]. It has been demonstrated that tan δ of some logs increases in longitudinal vibration, because shear deformation other than pure axial deformation was generated, resulting from large apparent differences in density between sapwood and heartwood [21].

As discussed above, if heartwood MC is smaller than sapwood MC, tan δ_l will be larger than tan δ_f, and the numerical result of Eq. (2) obtained by substituting tan δ_l will be smaller than the estimated MC (u) originally obtained by substituting tan δ_f. Clearly, longitudinal vibrational properties cannot be used to estimate average MC using Eq. (2). On the other hand, because heartwood MC is smaller than average MC when heartwood MC is smaller than sapwood MC, the numerical result (U) is more likely to be highly correlated with heartwood MC. Note that the pattern, where sapwood MC is lower than heartwood MC does not need to be considered, because heartwood MC is always below sapwood MC due to the

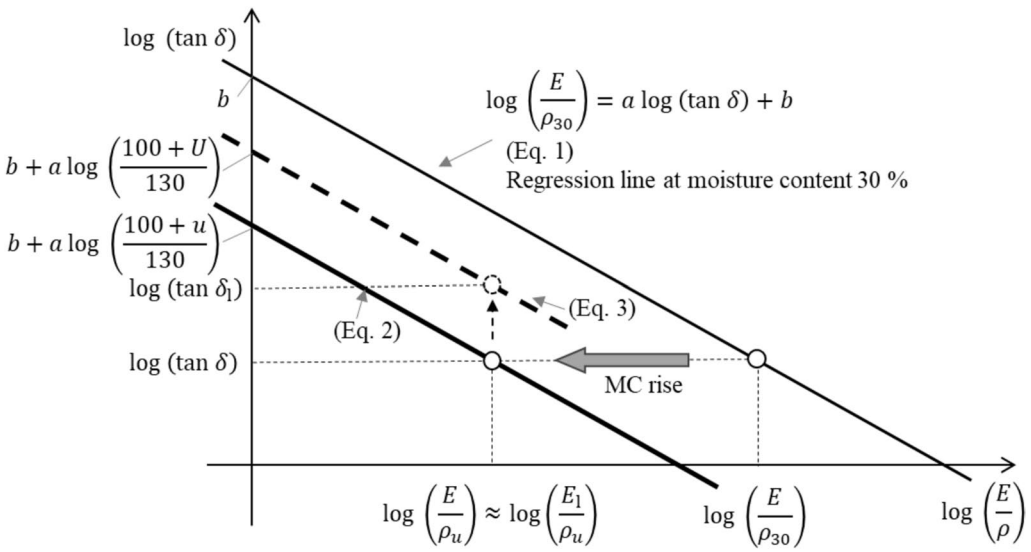


Fig. 1 Schematic diagram of the method for estimating MC using E/ρ and tan δ

nature of healthy tree. Therefore, the index value U is defined and expressed as

$$U = 130 \times 10^{p \log(\tan \delta_l) - \log\left(\frac{E_l}{\rho u}\right) + q} - 100, \quad (3)$$

where $\tan \delta_l$ and E_l denotes $\tan \delta$ and E measured from longitudinal vibration, respectively. The values of p and q are the same as those in Eq. (2), because the same regression line of the correlation in 30% MC used as standard in this study. Furthermore, the difference in E/ρ measured from flexural vibration and longitudinal vibration caused by the inhomogeneity of logs is considered negligible enough, which is supported by the result of actual comparison of E_l/ρ and E_f/ρ [21]. Therefore, U can be expressed using u and the ratio of $\tan \delta_l$ to $\tan \delta_f$ by transforming Eqs. (2) and (3) as

$$U = (100 + u) \times 10^{p \log(\tan \delta_l / \tan \delta_f)} - 100. \quad (4)$$

From Eq. (4), it can be seen that the value of U decreases with larger values of the ratio of $\tan \delta_l$ to $\tan \delta_f$, considering that p is negative.

Results and discussion

Change in simulated *U* with change in heartwood and sapwood MC

In our previous study [21], the positive relationship between the ratio of $\tan \delta_l$ to $\tan \delta_f$ and the ratio of sapwood density to heartwood density has already been described. The relationship between the ratio of $\tan \delta_l$ to $\tan \delta_f$ and the ratio of average density to heartwood density is shown in Fig. 2. Based on the regression line of the correlation shown in Fig. 2, the change in the value of U in relation to the change in sapwood and heartwood MC was simulated using Eq. (4) assuming that the oven-dry density of sapwood and that of heartwood were the same. Moreover, because average MC u was estimated with 25.9% synthetic error from Eq. (2) in our previous study [16] using the same logs as in the present study, the value of u in Eq. (4) was set at 25.9% lower than measured average MC. As shown in Fig. 3, the value of U simulated by applying these assumptions into Eq. (4) is highly correlated with heartwood MC regardless of the value of sapwood MC.

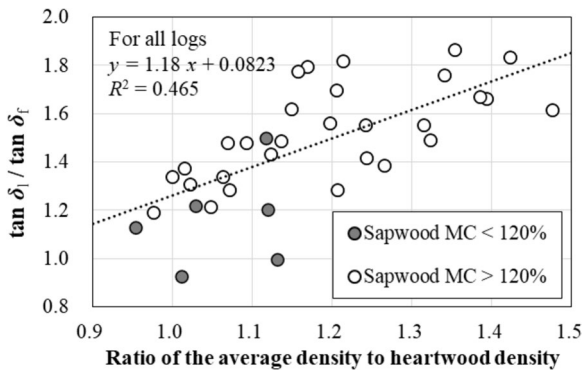


Fig. 2 Relationship between the ratio of the average to heartwood density and ratio of tan δ of longitudinal to that of flexural vibration

Correlation between *U* and measured heartwood MC

The relationship between actual measured heartwood MC and the value of the index U, as calculated by substituting the longitudinal vibrational properties of 35 sugi 4-m log specimens into Eq. (3), is shown in Fig. (4). As evidenced by the results shown in Fig. 3, a high correlation was found in most of logs. On the other hand, given that no correlation was found in some of the logs, the overall correlation coefficient was only 0.43, which is not high enough to estimate heartwood MC (bold line in Fig. 4). Here, according to the relationship between sapwood MC and sapwood oven-dry density investigated by

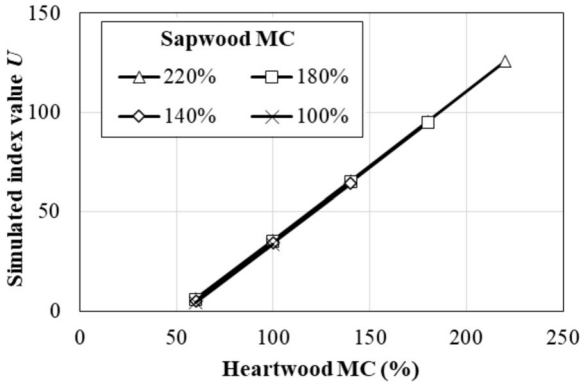


Fig. 3 Simulated index value U with varying sapwood and heartwood MC

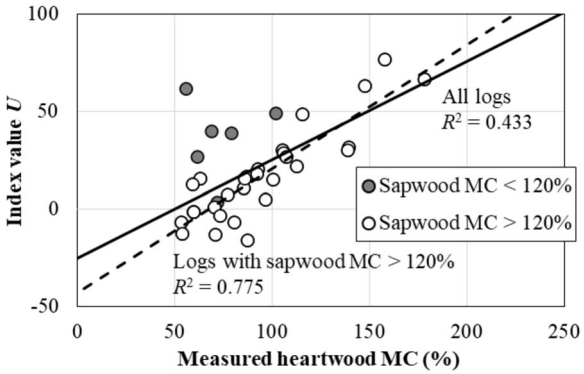


Fig. 4 Relationship between index value U and measured heartwood MC of 35 sugi logs. The bold regression line was calculated from all logs, and broken regression line was calculated from logs with sapwood > 120%

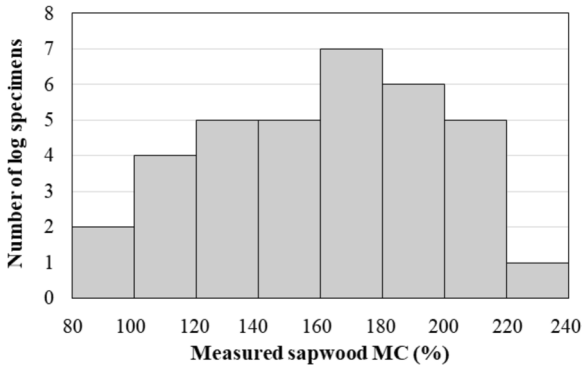


Fig. 5 Frequency distribution of measured sapwood MC of 35 sugi logs

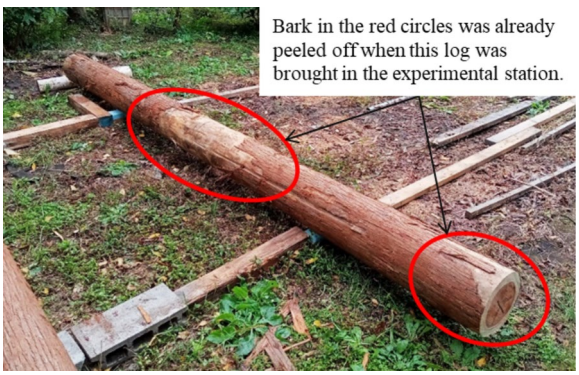


Fig. 6 Appearance of log with bark peeled off. The bark in the red circles is peeled off before the vibration measurement

Nakada [2] using sugi, sapwood MC will be 130 to 260% when the sapwood oven-dry density varies 0.30 to 0.45 g/cm^3 as in our log specimens. Therefore, it is defined in this study that logs with sapwood MC below 120% was drying before measurement. In Figs. 2 and 4, logs whose sapwood MC were below 120% (six logs, as shown in Fig. 5) were shown separately and it can be seen that these logs tend not to fit the correlation. In the case of the most out-of-correlation log, the bark was peeled off over nearly one-third of the area of the log (Fig. 6); in some parts of this log the sapwood MC was approximately 50%, which is lower than the heartwood MC. Therefore, it is suggested that the accuracy of index value U as an indicator of heartwood MC decrease when sapwood MC is below a certain level. When the six logs in question were removed from the analysis, the correlation coefficient increased sharply, to 0.78 (broken line in Fig. 4). However, this result contradicts the result obtained from our simulating (Fig. 3), which showed good agreement between U and heartwood MC, even when sapwood MC is 100%. A possible reason for large U values in the drying logs can be attributed to small tan δ_l, which is suggested by the fact that some of the drying logs have much lower ratio of tan δ_l to tan δ_f than do the other logs, as shown in Fig. 2. Because the increase in tan δ_l was explained by larger MC variation in radial direction [21], tan δ_l of drying logs is expected to be much smaller compared to that of logs with high MC both in sapwood and heartwood when taking it into consideration multiple factors that cause MC variation—other than the difference between sapwood and heartwood as represented by transition zone [2].

Conclusion

Our analysis shows that the index value U obtained by basing the calculation on the longitudinal vibrational properties of the logs is considered to be a good proxy measure of heartwood MC. These calculations will aid in setting the drying parameters for green logs. Due to the lower heartwood MC compared to sapwood MC, a larger tan δ is obtained from using longitudinal vibration rather than flexural vibration. Through the simulation base on some assumption as well as experimental tests of 35 sugi 4-m logs, the value of the index, U, was confirmed to be highly correlated with heartwood MC regardless of sapwood MC. When six logs with lower sapwood MC (< 120%) were excluded from the analysis, the coefficient of correlation between U and heartwood MC was sufficiently high, at 0.78.

Abbreviations

FSP Fiber saturation point
MC Moisture content

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Not applicable.

Author contributions

TF: conceptualization, investigation, methodology, visualization, and original draft of the manuscript. YY and KM: data curation, formal analysis, investigation, methodology, and review and editing of the manuscript. YF: conceptualization, data curation, funding acquisition, investigation, methodology, project administration, supervision, validation, visualization, and review and editing of the manuscript. All authors have read and approved the final manuscript.

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Data availability

The datsets used and/or analyzed during this study are available upon request from the corresponding author.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interest

The authors declare that they have no competing interest.

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