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Investigation of wood properties that influence the final moisture content of air-dried sugi (*Cryptomeria japonica*) using principal component regression analysis

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Abstract Sugi (*Cryptomeria japonica* D. Don) lumber is known to have a large variability in final moisture content (MC_f) and is difficult to dry. This study investigated the variability in MC_f of sugi in relation to wood properties. The wood property variables included initial moisture content (MC_i), basic density (BD), annual ring orientation (ARO), annual ring width (ARW), heartwood ratio (HR) and CIE L^* color (L^*). Sugi samples were cut from flat-sawn lumbers and air-dried; a principal component regression (PCR) model for predicting MC_f was developed with the wood property variables. The wood properties that contributed to the prediction of MC_f were evaluated by PCR analysis. Significant positive regression coefficients of the PCR model were observed in the MC_i, BD, ARO and HR, whereas negative ones in the L^*. There were no significant regression coefficients in the ARW. These results suggest that the MC_i, BD, ARO and HR had a positive influence, the L^* had a negative influence, and the ARW had little influence on the MC_f of air-dried sugi wood. This finding is in line with the general view on the drying characteristics in relation to these wood properties.

Keywords Air drying · Final moisture content · Wood property · Sugi (*Cryptomeria japonica*) · Principal component regression analysis

Introduction

In the process of drying lumber, the variability in final moisture content (MC_f) between lumbers is one of the

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major concerns. Factors that influence the MC_f of lumber have been studied extensively and it has been shown that MC_f depends on many wood properties, such as initial MC (MC_i) [1–3], basic density (BD) [2–6], annual ring orientation (ARO) [3, 6–8], heartwood ratio (HR) [1, 3, 8–10], as well as dimensions of lumber and species. The ARO refers to the growth ring orientation relative to the main drying surfaces as seen from the lumber's end. However, the past studies generally have employed simple linear correlation analysis between the pair of MC_f and the above wood properties, and rarely have accounted for their interrelations. Therefore, the correlations obtained in the past studies were significant but weak. An exception is the study by Berberović [3], who used multiple regression analysis to investigate the impact of many wood properties on the drying rate of *Tsuga heterophylla* lumber. It was found that MC_i, BD, HR and ARO influenced drying rate for the drying at 80 °C and only MC_i for the drying at 115 °C. However, the wood property variables in the multiple regressions are intercorrelated with each other, and this makes it impossible to assess the relative importance of individual variables from the equation. Hence, more sophisticated multivariate data analysis is required to evaluate the wood properties that influence the MC_f and the extent to which it is influential.

Sugi (*Cryptomeria japonica* D. Don) is one of the dominant species in Japan, but is very difficult to dry. Sugi lumber is well known to have a large variability in MC_f, probably due to the large variability in MC_i. The MC_i of sugi heartwood is excessively variable, with black-colored heartwood having much higher MC_i than normal red-colored heartwood [11, 12]. The increase in MC_i relates to the blackening of heartwood [13], and the MC_i was found to be strongly negatively correlated with brightness (CIE L^* color) [12], which is considered to represent the difference

in heartwood color. Furthermore, Sugimori et al. [1] demonstrated that the heartwood color of green sugi lumber was a good indicator of MC_f after kiln-drying. Thus, the L^* seems to be a potential important factor to determine MC_f of sugi lumber in addition to MC_i, BD, ARO and HR.

Purpose of this study was to investigate the wood properties that influence the MC_f of sugi wood and the extent to which it is influential. Drying tests were conducted with small samples of sugi that had varying MC_i, BD, ARO, HR and L^*. Although few studies have reported that annual ring width (ARW) has an influence on MC_f, ARW was also included as a potential factor, because ARW is an annual ring characteristic as well as ARO. A principal component regression (PCR) model for predicting MC_f was developed, and the wood properties that contributed to the prediction of MC_f were evaluated by PCR analysis.

Materials and methods

Sample preparation

Ten green flat-sawn lumbers of sugi (*Cryptomeria japonica* D. Don), 70 cm long, 12 cm wide, and 4 cm thick, were obtained from different trees in Ehime Prefecture, Japan. A clear section was taken from each lumber and was cut into a thickness of 3 cm with a band saw. The section was further cut into eight similar blocks in size (Fig. 1a). One block was lost during the cut, and a total of 79 blocks were prepared. The block was split into two matched samples (Fig. 1b). One sample with a dimension of 30 × 10 × 10 mm was subjected to measurement of wood properties, and the other one with a dimension of 30 × 20 × 10 mm was subjected to drying test (Fig. 1c).
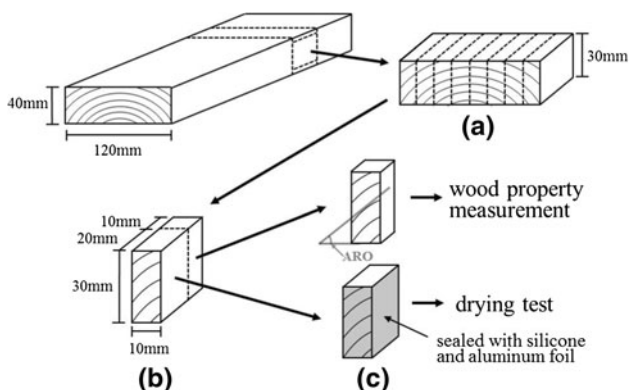

Fig. 1 Sample preparation procedure: **a** section, **b** block and **c** samples for wood property measurement and drying test

Measurement of wood properties

The ARO, ARW, HR and L^* of the samples were measured from their cross-sectional images, while the BD was measured gravimetrically. The image of the samples was taken using a digital scanner (GT-X900, Seiko Epson Co., Tokyo, Japan) and analyzed by means of ImageJ software [14], so that ARO, ARW, HR and L^* in the cross section were obtained for each sample. The volume of the samples was measured with a digital caliper. The samples were oven-dried, and the oven-dry weight and the BD of the samples were determined.

Drying test

Prior to the drying test, the surfaces of the sample, except the two surfaces normal to the thickness direction of original lumber, were sealed with silicone and aluminum foil (Fig. 1b). The weight of the sealing was calculated by subtracting the weight before sealing from the one after sealing. Thereafter, the samples were placed and air-dried for 28 days in a conditioning room at a temperature of 20 ± 1 °C and a relative humidity of 44 ± 2 % RH. The weight of each sample was measured once in a day. After the drying, the samples were oven-dried until the constant weight was attained and their MC_i and moisture content during drying were determined by oven-dry method. The moisture content of the samples took 8 days on average to reach 15 %, which is often regarded as a desired MC_f of dried lumber for general construction use. Therefore, the MC_f of the samples was defined as the moisture content after a drying period of 8 days.

Multivariate data analysis

Principal component regression (PCR) analysis [15] was used to develop a regression model for predicting MC_f, and to measure how each wood property affects the model. The PCR is a two-step procedure which computes to find a few linear combinations [called principal components (PCs)] of the several predictors (X variables), then fits a multiple linear regression using only these PCs. The PCs are created such that the first PC accounts for the maximum variation in the X variables, the second PC accounts for as much of the remaining variance as possible, and so on. The PCs are not intercorrelated with each other, and irrelevant and unstable information is discarded and only the most relevant part of the variation is used to correlate with a response variable (Y variable).

The PCR was performed using Unscrambler X version 10.2 (Camo Software Inc., Woodbridge, NJ, USA). The Y variable included MC_f, while the X variables included MC_i, BD, ARO, ARW, HR and L^*. All the variables were

mean centered and scaled to unit variance so that the variables with different scales have the same chance to influence the prediction of MC_f. A PCR model for predicting MC_f was developed with the data set. The optimal number of PCs was determined by full cross-validation (also called leave-one-out cross-validation), which removes one sample from the data set and constructs the model without these data. In the full cross-validation, the response of the residual variance with added PCs was observed. The number of PCs which corresponded to the first minimal residual variance was adopted as optimal.

The predictive ability of the model was assessed by two ways. First, the MC_f for each sample was predicted using the PCR model and was compared with the measured one. Second, the PCR model in the full cross-validation was used to predict the MC_f of the removed sample, and the predicted MC_f was compared with the measured one. The former and the latter are called here "calibration" and "cross-validation", respectively.

Results and discussion

Variability in wood properties and MC_f

The wood properties and the MC_f of the samples were listed in Table 1. A large variation was obtained in the individual wood properties and the MC_f. The MC_f variation and its correlation with these properties were analyzed using Pearson's matrix correlation (shown in Table 2), by which the variability in MC_f of *Gmelina arborea* in relation to distance from the pith and anatomical elements was evaluated [3]. Note that in this study the absolute value of the correlation coefficient (r) higher than 0.7 is regarded as strong, the value between 0.5 to 0.7 as moderate, and the value below 0.5 as weak. The MC_f showed a statistical positive correlation with MC_i but the correlation ($r = 0.33$) was weak (Fig. 2), indicating that it was difficult to predict the MC_f based on the MC_i. A weak positive correlation between MC_f and HR showed that the MC_f increased with increasing the HR. This result is in agreement with the

Table 1 Range and standard deviation (SD) of MC_i, MC_f, BD, ARO, ARW, HR and L^* ($n = 79$)

	Max	Min	Mean	SD
MC_i (%)	284.4	39.8	80.3	37.4
MC_f (%)	36.2	8.8	15.2	6.1
BD (kg/m^3)	516	264	314	40
ARO (°)	65	0	32.1	17.7
ARW (mm)	8.2	1.6	4.5	1.5
HR	1.0	0	0.8	0.3
L^*	52.3	11.9	34.4	8.5

slower drying in heartwood than sapwood due to lower heartwood permeability than sapwood [16]. As is depicted in Fig. 3, the L^* showed a moderate negative correlation with the MC_f ($r = -0.60$), meaning that the MC_f decreased with increasing the L^*. Sapwood, which dries faster than heartwood [16], is considered to have higher L^* than heartwood, because HR was negatively correlated with L^*, as shown in Table 2. In addition, it has been reported that sugi heartwood with higher L^* has lower MC_i. [12]. Hence, the samples with higher L^* might probably result in the lower MC_f.

MC_f has been shown to depend on BD [2–6] and ARO [3, 6–8]. In the matrix correlation, however, the BD and the ARO showed no significant correlation with the MC_f. This is because the simple linear correlation analysis did not account for the interrelation among wood properties, some of which were found in the significant correlations, as shown in Table 2.

Interpretation of PCR model

The optimal number of PC was 4, so the PCR model consisted of first 4 PCs. Y-explained variance and X-explained variance were used to interpret how much of Y variable and X variable, respectively, are described by the PCR model. The Y-explained variance shows the contribution of each factor to explain the deviation of Y variable (MC_f), while the X-explained variance to explain the deviation of X variables (MC_i, BD, ARO, ARW, HR and L^*). As listed in Table 3, the Y-explained variance of PC1 and PC4 were 20.2 and 30.6 %, respectively, and those of the other PCs were close to 0 %. Thus, the PC1 and PC4 significantly contributed to the prediction of MC_f in the PCR model. It is unexpected that the highest Y-explained variance among 4 PCs was observed in the PC4, which had only 13.1 % of the X-explained variance.

X loading is directly related to how well X variables are taken into account by factors in the model. Figure 4 shows the X loadings of PC1 and PC4 for each variable. The PC1 explaining 38.7 % of X variances was mainly related to ARO, ARW, HR and L^*, rather than to MC_i and BD. The PC4 with the highest Y-explained variance was mainly related to ARO and L^*. This indicates that the ARO and L^* largely contributed to the prediction of MC_f.

Important variables contributed to the prediction of MC_f

The weighted regression coefficients in the PCR model were useful to determine important wood properties correlated to the prediction of MC_f. The Marten's uncertainty test [17] was used to find the wood properties with significant regression coefficients. The regression coefficients

Table 2 Pearson's matrix correlation for each variable ($n = 79$)

	MC_i	MC_f	BD	ARO	ARW	HR	L^*
MC_i	1	–	–	–	–	–	–
MC_f	0.33*	1	–	–	–	–	–
BD	−0.14	0.24	1	–	–	–	–
ARO	0.04	0.09	−0.03	1	–	–	–
ARW	0.38**	0.29	0.28	−0.51**	1	–	–
HR	−0.21	0.38**	0.08	−0.46**	0.19	1	–
L^*	−0.37**	−0.60**	−0.07	0.31*	−0.43**	−0.57**	1

* $P < 0.01$; ** $P < 0.001$
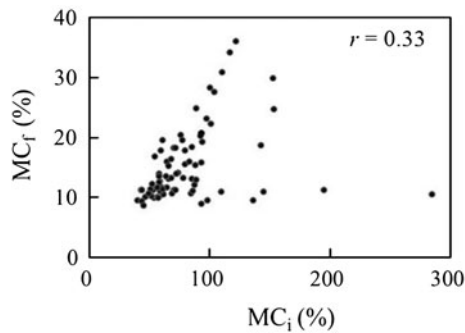
Fig. 2 Relationship between MC_i and MC_f

Fig. 3 Relationship between L^* and MC_f

Table 3 Y-explained variance and X-explained variance for each PC

Explained variance (%)	PC1	PC2	PC3	PC4
Y	20.2	2.9	0.4	30.6
X	38.7	22.6	17.7	13.1
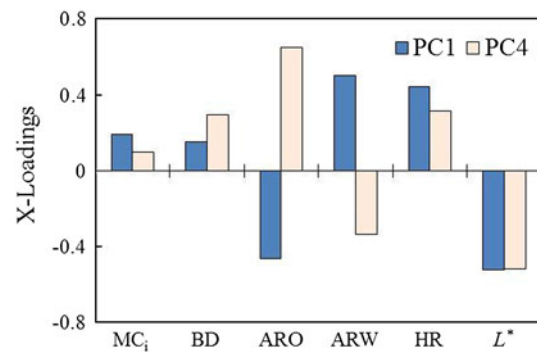
Fig. 4 X loadings of PC1 and PC4 for each variable

Fig. 5 Weighted regression coefficients in the PCR model
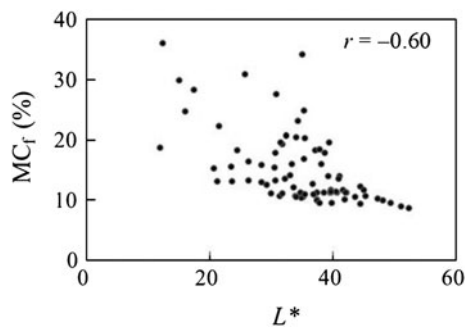
of all wood properties except ARW were significantly different from zero according to the Martens' uncertainty test (Fig. 5). No significant regression coefficients in the ARW shows that the ARW had little impact on the MC_f. Significant positive regression coefficients were observed in the MC_i, BD, ARO and HR, while negative ones were observed in the L^*. These results demonstrate that many wood properties had an influence on MC_f; that is, the MC_i, BD, ARO and HR had a positive influence on the MC_f, while the L^* had a negative influence on the MC_f.

It is apparent that the regression coefficients of L^* and ARO were obviously higher than that of MC_i. Thus, the L^* and ARO contributed more to the prediction of MC_f than

did the MC_i. MC_i is often used as an indicator of MC_f, but is very difficult to measure accurately without oven-drying. Meanwhile, L^* and ARO can be measured easily from a lumber's end. Therefore, it is expected that the L^* and ARO have a potential to be used as an indicator of MC_f, instead of MC_i.

The positive regression coefficients in the BD and ARO are in consistent with the findings that MC_f increases with increasing BD [2–6] and ARO [3, 6–8]. In general, wood with lower BD dries faster than that with higher BD, because the structure of wood with lower BD contains thinner cell walls and more openings per unit volume, which contributes to an increase in the diffusion of bound water and free water, respectively. Radial diffusion, perpendicular to the growth rings, is somewhat faster than tangential diffusion, parallel to the rings [18]. This explains why the samples with lower ARO resulted in the higher drying rate and consequently the lower MC_f. Pang [19] gave a reasonable explanation why the radial diffusion of free water is faster than the tangential diffusion in *Pinus radiata*. During drying, the moisture within the wood material can either flow along the radial ray cells or through bordered pits which are on the radial-longitudinal face [20]. However with drying, the bordered pits aspirate but the ray cells are cleared. This increases the gas permeability and the moisture flow in radial direction [21, 22].

In the PCR model, the BD and ARO were judged as important variables for MC_f, although the matrix correlation, as shown in Table 2 showed no significant correlation between MC_f and these wood properties. Therefore, it is reasonable to suggest that the PCR model could to some extent account for the interrelation between MC_f and the wood properties that was ignored by the traditional simple linear regression.

The above findings are in line with the general view on the drying characteristics in relation to these wood properties. It should be noted, however, that the PCR model was useful within the limited conditions of this study in which

the samples were cut from the flat-sawn lumbers and did not cover the entire range of wood properties, for example, no sample with ARO over 65° was included in the PCR model. Therefore, samples from quarter-sawn as well as flat-sawn lumbers should be examined to confirm that the findings obtained from the PCR analysis can be generalized to the entire range of wood properties.

Prediction of MC_f

Figure 6 shows the plots of measured MC_f versus predicted MC_f. For both the calibration and the cross-validation, the predicted MC_f was correlated with the measured one strongly and moderately, respectively. The predictive ability in the cross-validation was slightly poorer than the one in the calibration. The PCR model gave higher correlation coefficient than the matrix correlation among all pairs, as shown in Table 2. Thus, The PCR model could predict MC_f of the samples more accurately than the single linear correlation analysis. However, the remaining 26–33 % of the variance in MC_f was not explained by the PCR model. This result implies that the PCR analysis with these wood properties is insufficient to fully describe the interrelation between MC_f and wood properties. In our next paper, we will present a nonlinear analysis for more comprehensive description of the interrelation, as an alternative to the PCR analysis based on a linear regression.

Conclusions

Drying tests were conducted with small sugi samples with varying MC_i, BD, ARO, ARW, HR and L^*. A PCR model for predicting MC_f was developed and the wood properties that had an impact on the model were evaluated. The PCR analysis demonstrated that many wood properties had an influence on MC_f. The MC_i, BD, ARO and HR had a positive impact on the MC_f, the L^* had a negative impact

Fig. 6 Plots of measured MC_f versus predicted MC_f for calibration (**a**) and cross-validation (**b**). *Solid line* shows a one–one relationship between measured and predicted values
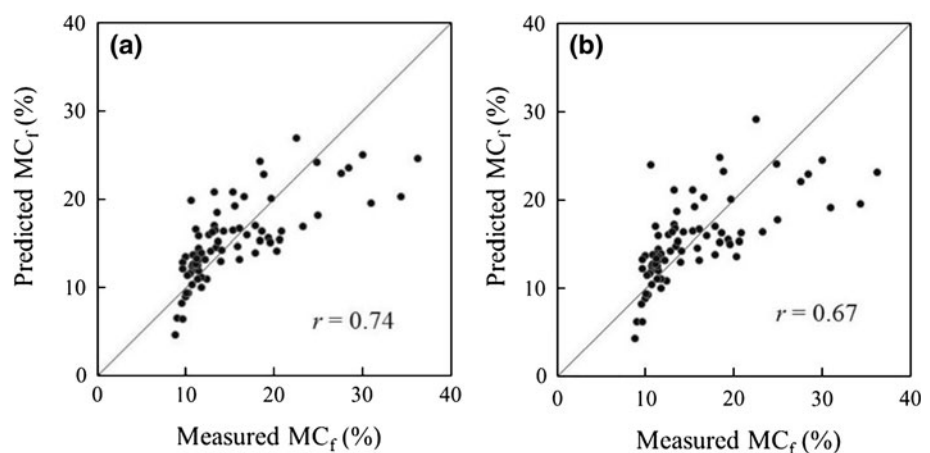
on the MC_f, and the ARW had little impact on MC_f. On the other hand, the traditional simple linear regression could not find significant correlations between MC_f and BD and between MC_f and ARO. These results indicate that the PCR is more useful for the comprehensive evaluation of the variability in MC_f in relation to wood properties than the traditional simple linear regression. This study adds value to existing research by presenting statistical evidence on sources of variation that may influence the MC_f of sugi lumber.

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