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A new method for nondestructive evaluation of solid wood moisture content based on dual-energy X-ray absorptiometry

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Abstract

This paper presents a new method to determine the moisture content of solid wood based on the principle of dual-energy X-ray absorptiometry. The study0 investigates the theoretical relationship between X-ray wavelength and mass attenuation coefficients of wood, water, and reference substance. In accordance with this relationship, a theoretically obtained equation is proposed to calculate the moisture content in wood. The proposed equation is compared to experimental results using small blocks of sugi wood, which showed that the change in mass attenuation coefficient of wood with X-ray tube voltage increased with increasing moisture content as expected from the theoretical equation. A regression equation for moisture content estimation was determined based on the experimental results, and the standard error of estimate in the 0–120 % dry-basis moisture content range using the regression equation was determined to be 21.9 % with the most appropriate pair of tube voltages, 15 and 40 kVp. The accuracy of the method will be improved by reducing the duration of X-ray radiography and by increasing the disparity between paired tube voltages. This method has the potential to determine moisture content of solid wood using X-ray without oven-drying or assuming oven-dry density.

keywords: moisture content, non-destructive evaluation, mass attenuation coefficient, Dual-energy X-ray absorptiometry, sugi

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Introduction

Existing methods of evaluating the moisture content of solid wood for industrial uses are generally based on electrical resistance, capacitance, microwaves, or infrared technology. However, all of these methods are strongly influenced by surface moisture content, fiber direction, temperature, and oven-dry density of wood.

Since the X-ray densitometry principle has the potential to overcome these difficulties mentioned above, many methods have been proposed to evaluate moisture content and moisture distribution in solid wood using X-ray technology (Hattori and Kanagawa 1985; Lindgren 1991a; Lindgren 1991b; Watanabe et al. 2008; Tanaka et al. 2009). All of these methods, however, require two X-ray radiographs of a wood sample, in both wet and oven-dried condition, because these methods are based on a certain relationship between moisture concentration and the brightness difference between the two X-ray images. For industrial applications, since it is impractical to oven-dry timbers simply to determine the moisture content, there is a real need for a method of measuring moisture content in wood without requiring data on oven-dry density.

This study focused on the principle of Dual-energy X-ray absorptiometry (DXA), which was originally suggested in the field of medicine, particularly for analyzing human bone minerals (Sartoris and Resnick 1989, Mazess et al. 1990). The principle of DXA is based on the relationship between the variation in mass attenuation coefficient with X-ray photon energy, and the elemental composition, which reveals not only the total density of the material but the constituent substances of the material by comparing two X-ray radiographs obtained at different tube voltages. However, to the best of our knowledge, this innovative technique has never been applied to the field of wood science, except for a few articles (Kullenberg et al. 2010, Hultnäs and Fernandez-Cano 2012), in which feasibility studies were conducted to determine the moisture content in wood chips. It was shown that wet-basis moisture content in wood chips of spruce (*Picea abies*), pine (*Pinus sylvestris*), and a variety of mixtures thereof, was successfully measured with a standard error of estimate of 1.39–2.57 % using two X-ray tubes operated at 40 kVp and 90 kVp (Hultnäs and Fernandez-Cano 2012).

The objective of this study was to apply the DXA principle to the measurement of moisture content in solid wood. The PMMA-equivalent thickness was defined as the thickness of poly(methyl methacrylate) (PMMA) at the pixel which had the same brightness as that of the sample on an X-ray radiograph; the proposed method for estimating moisture content in solid wood was based on measuring the change of PMMA-equivalent thickness with tube voltages, which is equivalent to

measuring the change of mass attenuation coefficient ratio of wood-to-PMMA. Based on experimental results, a regression equation was determined for estimating moisture content in wood. The standard error of estimate was calculated and the advantage of this method and potential to improve the accuracy of measurement were discussed.

Symbols

d : sample thickness in the X-ray direction, cm

d_w : thickness of the wood sample in the X-ray direction, cm

d_p : PMMA-equivalent thickness, cm

d_{p1} : PMMA-equivalent thickness for a primary X-ray beam, cm

d_{p2} : PMMA-equivalent thickness for a secondary X-ray beam, cm

$\bar{d}_p$: average PMMA-equivalent thickness, cm

$\bar{d}_{p1}$: average PMMA-equivalent thickness for a primary X-ray beam, cm

$\bar{d}_{p2}$: average PMMA-equivalent thickness for a secondary X-ray beam, cm

e_w : measurement error in wet-basis moisture content, %

e_m : measurement error in dry-basis moisture content, %

I : transmitted photon intensity of an X-ray beam, /s

I_0 : incident photon intensity of an X-ray beam, /s

M : dry-basis moisture content of a wood sample, %

M_e : estimated dry-basis moisture content of a wood sample, %

w_i : proportion of i th element by mass

W : wet-basis moisture content of a wood sample, %

W_e : estimated wet-basis moisture content of a wood sample, %

ρ : sample density, g/cm³

ρ_w : density of a wood sample, g/cm³

ρ_p : density of the reference wedge made of PMMA, g/cm³

λ : linear attenuation coefficient, /cm

μ : mass attenuation coefficient, cm²/g

μ_i : mass attenuation coefficient of i th element, cm²/g

μ_H : mass attenuation coefficient of hydrogen, cm²/g

μ_C : mass attenuation coefficient of carbon, cm²/g

μ_{O} : mass attenuation coefficient of oxygen, cm^2/g

μ_{m} : mass attenuation coefficient of moisture, cm^2/g

μ_{m1} : mass attenuation coefficient of moisture for a primary X-ray beam, cm^2/g

μ_{m2} : mass attenuation coefficient of moisture for a secondary X-ray beam, cm^2/g

μ_{p} : mass attenuation coefficient of PMMA, cm^2/g

μ_{p1} : mass attenuation coefficient of PMMA for a primary X-ray beam, cm^2/g

μ_{p2} : mass attenuation coefficient of PMMA for a secondary X-ray beam, cm^2/g

μ_{s} : mass attenuation coefficient of wood substance, cm^2/g

μ_{s1} : mass attenuation coefficient of wood substance for a primary X-ray beam, cm^2/g

μ_{s2} : mass attenuation coefficient of wood substance for a secondary X-ray beam, cm^2/g

μ_{w} : mass attenuation coefficient of a wood sample, cm^2/g

μ_{w1} : mass attenuation coefficient of a wood sample for a primary X-ray beam, cm^2/g

μ_{w2} : mass attenuation coefficient of a wood sample for a secondary X-ray beam, cm^2/g

Theory

Principles of single X-ray densitometry

When an X-ray beam with single wavelength is directed into a homogeneous material, the incident photon intensity and the transmitted photon intensity are related as shown in Eq. (1).

$$\frac{I}{I_0} = \exp(-\lambda d) \quad (1)$$

The value of λ depends upon the material density ρ and the X-ray wavelength. The mass attenuation coefficient of the material μ is given as

$$\mu = \frac{\lambda}{\rho} \quad (2)$$

Thus, Eq. (1) may be written as

$$\rho = -\frac{1}{\mu d} \cdot \ln \frac{I}{I_0} \quad (3)$$

The density ρ can be estimated by measuring the ratio of the incident- and transmitted photon intensity, using radiographic X-ray equipment.

Relationship between mass attenuation coefficient and X-ray wavelength

Mass attenuation coefficient of a compound is dependent on the gravimetric proportion of the component elements (Jackson and Hawkes 1981, Ida 2008), as shown in Eq. (4).

$$\mu = \sum_{i=1}^N w_i \mu_i \quad (4)$$

where the compound is composed of N elements.

Wood is considered to be composed of two different components, which are wood substance and moisture. The mass attenuation coefficient of wood can be expressed using μ_m , μ_s , and W , as shown in Eq. (5).

$$\mu_w = \frac{W}{100} \mu_m + \frac{100-W}{100} \mu_s \quad (5)$$

The general elemental composition of wood substance is approximately H: 6.0%, C: 49.5%, and O: 44.0%, irrespective of species (Migita 1968). The composition of water is H: 11.1% and O: 88.9%. The molecular formula of PMMA, which was used in this study as a reference substance for X-ray radiography, is expressed as $[(CH_2)C(CH_3)(COOCH_3)]_n$. The gravimetric proportion of the elements is thus H: 8.0%, C: 60.0%, and O: 32.0%. According to Eq. (4), mass attenuation coefficients of wood substance, water, and PMMA are expressed as shown in Eqs. (6) to (8).

$$\mu_s = \frac{6.0}{100} \mu_H + \frac{49.5}{100} \mu_C + \frac{44.0}{100} \mu_O \quad (6)$$

$$\mu_m = \frac{11.1}{100} \mu_H + \frac{88.9}{100} \mu_O \quad (7)$$

$$\mu_p = \frac{8.0}{100} \mu_H + \frac{60.0}{100} \mu_C + \frac{32.0}{100} \mu_O \quad (8)$$

The mass attenuation coefficients of hydrogen, carbon, and oxygen are known as a function of wavelength (National Astronomical Observatory of Japan 2010). According to this data and Eqs. (5) to (8), the relationship between X-ray wavelength and mass attenuation coefficient of each compound was calculated as shown in Fig. 1.

Basic concept of moisture content evaluation based on DXA

The basic concept of the moisture content evaluation in this study is based on the relationship between mass attenuation coefficient and X-ray wavelength shown in Fig. 1. When an X-ray radiograph of an oven-dried wood sample is taken, the mass attenuation coefficient of the wood

sample μ_w/μ_p is nearly equal to μ_s/μ_p . As the moisture content of the wood sample increases, the value of μ_w/μ_p gradually moves from μ_s/μ_p toward μ_m/μ_p . Therefore, moisture content can be indirectly evaluated from the change in μ_w/μ_p with X-ray wavelength.

Since it is difficult to measure μ_w/μ_p directly, it was obtained indirectly, using a reference wedge, as shown below. X-ray radiographs of a wood sample were taken with a reference wedge made of PMMA, which has a triangular shape with variable thickness. The thickness of the wedge at the pixel with the same brightness as that of the sample was obtained on the radiograph. This thickness, d_p , is termed “PMMA-equivalent thickness” in this study. Among the pixels with the same brightness, transmitted photon intensity I should be equal. Therefore, Eq. (9) is obtained using Eqs. (1) and (2).

$$\frac{I}{I_0} = \exp(-\mu_w \rho_w d_w) = \exp(-\mu_p \rho_p d_p) \quad (9)$$

Solved for μ_w/μ_p ,

$$\frac{\mu_w}{\mu_p} = \frac{\rho_p d_p}{\rho_w d_w} \quad (10)$$

Since ρ_p , ρ_w , and d_w are independent of the X-ray wavelength, measuring the d_p change with variation in X-ray wavelength allows us to indirectly calculate the change in μ_w/μ_p .

Calculation to obtain wet-basis moisture content

When two X-ray radiographs of a wood sample are taken with two different X-ray wavelengths, termed primary and a secondary X-ray beam, Eq. (10) gives Eqs. (11) and (12).

$$\frac{\mu_{w1}}{\mu_{p1}} = \frac{\rho_p d_{p1}}{\rho_w d_w} \quad (11)$$

$$\frac{\mu_{w2}}{\mu_{p2}} = \frac{\rho_p d_{p2}}{\rho_w d_w} \quad (12)$$

Dividing Eq. (11) by Eq. (12) gives Eq. (13).

$$\frac{\mu_{w1}}{\mu_{p1}} = \frac{d_{p1}}{d_{p2}} \quad (13)$$

Applying Eq. (5) gives Eqs. (14) and (15).

$$\mu_{w1} = \frac{W}{100} \mu_{m1} + \frac{100-W}{100} \mu_{s1} \quad (14)$$

$$\mu_{w2} = \frac{W}{100} \mu_{m2} + \frac{100-W}{100} \mu_{s2} \quad (15)$$

Substituted by Eqs. (14) and (15), Eq. (13) is rewritten as in Eq. (16).

$$\frac{d_{p1}}{d_{p2}} = \frac{\frac{\mu_{m1}}{\mu_{p1}} W + \frac{\mu_{s1}}{\mu_{p1}} (100 - W)}{\frac{\mu_{m2}}{\mu_{p2}} W + \frac{\mu_{s2}}{\mu_{p2}} (100 - W)} \quad (16)$$

Solved for W ,

$$W = \left(\frac{\frac{\mu_{s1}}{\mu_{p1}} \cdot \left(\frac{\mu_{m2}}{\mu_{p2}} - \frac{\mu_{s2}}{\mu_{p2}} \right) - \left(\frac{\mu_{m1}}{\mu_{p1}} - \frac{\mu_{s1}}{\mu_{p1}} \right) \cdot \frac{\mu_{s2}}{\mu_{p2}}}{\left(\frac{\mu_{m2}}{\mu_{p2}} - \frac{\mu_{s2}}{\mu_{p2}} \right)^2 \cdot \frac{d_{p1}}{d_{p2}} - \left(\frac{\mu_{m1}}{\mu_{p1}} - \frac{\mu_{s1}}{\mu_{p1}} \right) \cdot \left(\frac{\mu_{m2}}{\mu_{p2}} - \frac{\mu_{s2}}{\mu_{p2}} \right)} - \frac{\frac{\mu_{s2}}{\mu_{p2}}}{\left(\frac{\mu_{m2}}{\mu_{p2}} - \frac{\mu_{s2}}{\mu_{p2}} \right)} \right) \times 100 \quad (17)$$

In Eq. (17), μ_{m1}/μ_{p1} , μ_{s1}/μ_{p1} , μ_{m2}/μ_{p2} , and μ_{s2}/μ_{p2} are constant irrespective of moisture content.

Therefore, by obtaining the ratio of PMMA-equivalent thickness d_{p1}/d_{p2} , the wet-basis moisture content W can be calculated using Eq. (17).

In the X-ray apparatus in the present study, a continuous X-ray beam comprising various wavelengths is radiated from the tungsten target. The spectrum of wavelengths is determined by the tube voltage. According to the relationship between tube voltage and the resulting X-ray spectrum (Tawara 1999), the wavelength peak of a continuous X-ray beam generated by 15 kV, 20 kV, and 40 kV was 0.11 nm, 0.08 nm, and 0.05 nm, respectively. The mass attenuation coefficient with the wavelength peak of an X-ray beam, which has a greatest effect on the overall wavelengths, was used for the calculation. The mass attenuation coefficient ratios μ_{m1}/μ_{p1} , μ_{s1}/μ_{p1} , μ_{m2}/μ_{p2} , and μ_{s2}/μ_{p2} were thus calculated using paired tube voltages of (a) 15 kV and 40 kV; (b) 20 kV and 40 kV; and (c) 15 kV and 20 kV, in accordance with Fig. 1. Substituting these ratios into Eq. (17), the relationship between wet-basis moisture content W and PMMA-equivalent-thickness ratio d_{p1}/d_{p2} was obtained as shown in Fig. 2.

Materials and methods

Materials

Eighteen blocks, of dimensions 15 mm (L) $\times$ 15 mm (R) $\times$ 15 mm (T), were cut from one large sapwood block of oven-dried sugi (*Cryptomeria japonica* D. Don), grown in Akita Prefecture. Each

block was weighed and placed into a small, plastic zipper-bag together with a certain amount of ion-exchanged water, and the 18 test specimens showed moisture contents ranging from 0% to 120%. A triangular wedge of PMMA, 140 mm in length, 20 mm in width and 50 mm maximum height (density = 1.19 g/cm³) was prepared as the reference substance.

Experimental procedure

All test specimens and the reference wedge were placed on a sheet of X-ray film (Fuji Industrial X-ray Film IXFR, Fujifilm Corporation, Tokyo, Japan) set in an X-ray radiography apparatus with high-voltage AC power (SR-1010, SOFTEX Co., Ltd., Ebina-shi, Japan), as shown in Fig. 3. The six radiographswere taken under the conditions shown in Table 1. Here, the test specimens were set on a film as the cross sections of specimens No. 1, 4, 7, 10, 13, and 16, the tangential sections of specimens 2, 5, 8, 11, 14, and 17, and the radial sections of the other specimens were turned upward, and were perpendicular to the direction of the X-ray beam. Shortly after taking all radiographs, the weights of the specimens were remeasured. The average moisture content before and after radiographing for each specimen was regarded as the moisture content during radiographing, and was used for the evaluation discussed below. The films were developed using Hi Rendol developer (Fujifilm Corporation, Tokyo, Japan) at 20 °C for four minutes, dipped in a solution of 1% acetic acid for one minute, and fixed (Hi Renfix, Fujifilm Corporation, Tokyo, Japan) for two minutes. The film slides were then washed thoroughly in water for several minutes and hung for one day, to dry. The films were scanned using a photo scanner (Epson Expression 10000XL, Seiko Epson Corporation, Tokyo, Japan) to obtain 600-dpi 8-bit grayscale bitmap images.

Calculation of average PMMA-equivalent thickness

The relationship between the thickness of the reference wedge and brightness value of the reference wedge was calculated for each radiograph. For example, Fig. 4 shows the relationship between the thickness and brightness value of the reference wedge on Radiograph 1. The observed relationship was used to derive a regression equation explaining the thickness of the reference wedge in relation to brightness on each radiograph. Here, because the X-ray intensity and the resulting brightness on the photos caused by the X-ray-induced chemical reaction in the film are not linear, the thickness shown in Fig. 4 cannot explain the brightness in exponential form like Eq (1). Polynomial regression equations of degrees 1 to 6 for predicting PMMA thickness from brightness values with a range of 0.45–2.20 cm in thickness were derived, and the equation with the highest coefficient of

determination was selected for each radiograph. Every selected equation was a sextic equation with a coefficient of determination greater than 0.99.

To obtain the PMMA-equivalent thickness of a wood sample, its heterogeneity must be considered. A brightness value of each pixel constituting each sample was calculated using image processing software (Image J 1.44p, Wayne Rasband, National Institutes of Health, USA) and saved in a spreadsheet. Substituting every brightness value into the regression equation, the PMMA-equivalent thickness d_p was obtained for each pixel. The average value of d_p (termed the average PMMA-equivalent thickness $\bar{d}_p$ in this study) was obtained for each sample.

Results and discussion

Relationship between PMMA-equivalent thickness and wet-basis moisture content

Table 2 shows the average PMMA-equivalent thickness of each sample on each radiograph. Fig. 5 shows the relationship between wet-basis moisture content and the ratio of the average PMMA-equivalent thickness to each pair of tube voltages: (a) 15 kVp and 40 kVp; (b) 20 kVp and 40 kVp; and (c) 15 kVp and 20 kVp. In Fig. 5, the PMMA-equivalent-thickness ratio increased as the moisture content was increased. The slopes of the experimentally obtained plots shown in Fig. 5 were largely consistent with the corresponding theoretically obtained slopes shown in Fig. 2. This consistency indicates that d_{p1}/d_{p2} is as dependent on wet-basis moisture content of wood as would be expected from Eq. (17), which are derived from the theoretical change in mass attenuation coefficient with X-ray wavelength between wood substance and moisture, as shown in Fig. 1. On the other hand, the experimentally obtained y-intercepts of the regression lines shown in Fig. 5 all differed from the corresponding theoretical y-intercepts shown in Fig. 2. Moreover, the experimental d_{p1}/d_{p2} was always less than 1, which is contrary to the theoretical d_{p1}/d_{p2} , which was always greater than 1. This means that the decline of mass attenuation coefficient with the increase of tube voltage was more significant in PMMA than wood. These differences between the theory and the experimental results may have been due to inaccurate assumption of the elemental composition of PMMA in Eq. (8). Therefore, it is necessary to derive the regression equation to predict moisture content according to the observed data, as shown in Fig. 5.

Determination and validation of the regression equation predicting moisture content from PMMA-equivalent-thickness ratio

The relationship between d_{p1}/d_{p2} and W shown in Fig. 5 suggests that Eq. (17) may be simplified as shown in Eq. (18).

$$W_e = a \frac{\bar{d}_{p1}}{\bar{d}_{p2}} + b \quad (W_e \geq 0) \quad (18)$$

where coefficients a and b are dependent on the primary and secondary tube voltages, and were determined by the method of least squares, as shown in Table 3. The measurement error e_w is defined in Eq. (19).

$$e_w = W - W_e \quad (19)$$

Fig. 6 shows a comparison of actual wet-basis moisture content W and estimated wet-basis moisture content W_e predicted by Eq. (18) and Table 3. Fig. 6 shows that the linear regression using Eq. (18) provided a non-biased prediction of moisture content. The standard errors of estimate in the wet-basis moisture content range 0–55% were 9.5%, 12.5%, and 13.3% using the average PMMA-equivalent-thickness ratios of 15 kVp to 40 kVp, 20 kVp to 40 kVp, and 15 kVp to 20 kVp, respectively; the values of the corresponding squared correlation coefficient R^2 were 0.73, 0.54, and 0.48, respectively. These results imply more accurate evaluation of moisture content is achieved using a pair of tube voltages with greater disparity. This is because the slope of d_{p1}/d_{p2} increases as the difference between tube voltages increases, as shown in Figs. 2 and 6. In Figs. 6, moreover, there seems to be no significant difference between the angle of the X-ray direction relative to the fiber direction and the measurement errors, which implies the angle of the X-ray direction does not have a significant effect on the measurement errors. This is a great advantage for the application of this method in industrial moisture meters as well as other X-ray methods.

Estimated dry-basis moisture content M_e was obtained by converting W_e , and measurement error e_m is defined as shown in Eq. (20).

$$e_m = M - M_e \quad (20)$$

Fig. 7 compares actual dry-basis moisture content M and estimated dry-basis moisture content M_e . The standard errors of estimate in the dry-basis moisture content range 0–120% were 21.9%, 26.9%, and 33.1% using the average PMMA-equivalent-thickness ratio of 15 kVp to 40 kVp, 20 kVp to 40 kVp, and 15 kVp to 20 kVp, respectively. The squared correlation coefficient R^2 was 0.74, 0.57, and 0.34, respectively. Fig. 8 shows the relationship between the actual oven-dry density of the test specimens and the measurement errors in Fig. 7a. In Fig. 8, no significant influence of variation in

oven-dry density on the results was shown. This is a great advantage that doesn't exist for the other existing X-ray methods.

Advantage of this method and potential to improve the accuracy of measurement

The proposed method for non-destructive evaluation of moisture content in wood has a strong advantage in that it does not require any information about oven-dry densities of test samples. To the best of our knowledge, this is the first application of the DXA principle to predicting moisture content in solid wood, whereas the previous studies (Kullenberg et al. 2010, Hultnäs and Fernandez-Cano 2012) were implemented in predicting the moisture content in wood chips. It also has an advantage in that it only uses a general-purpose X-ray inspection apparatus, whereas they used specialized DXA hardware.

However, the lowest standard error of estimate in wet-basis moisture content in this study was 9.5%, even with the most appropriate pair of tube voltages (15 kVp and 40 kVp). This is in contrast to the results of Hultnäs and Fernandez-Cano (2012), which achieved 1.51 % standard error of estimate in wet-basis moisture content with spruce chips and 2.57 % of with pine chips. Compared to the method proposed by Hultnäs and Fernandez-Cano (2012), the larger measurement errors in this study are attributed to the following three reasons.

The first reason is the measurement duration. In this study, the total duration of X-ray radiography was more than 60 min, whereas the duration of X-ray radiation in the work by Hultnäs and Fernandez-Cano (2012) was 60 s. In this study, the average change in dry-basis moisture content during radiography was 7.2%, which is likely to have strongly affected the accuracy of the measurement. Therefore, further efforts to reduce such loss of moisture content during X-ray radiographing are essential to a practical application of the DXA method in the present study. This problem may be addressed by drastically reducing the total duration of X-ray exposure. This could be achieved by using a photostimulable phosphor plate, which would provide a highly sensitive digital image rather than an analog X-ray film. This method also eliminates the manual stages of film processing (developing and fixing), and allows computerized automation of the processes, from X-ray imaging to calculating moisture content.

The second reason is the difference in tube voltages between the two studies. In this study, the maximum tube voltage was 40 kVp, due to the specification of the X-ray apparatus, whereas the maximum tube voltage in Hultnäs and Fernandez-Cano (2012) was 90 kVp. The wavelength peak of the continuous X-ray beam generated by 90 kV is determined to be approximately 0.03 nm (Kato 2010). According to the relationship shown in Fig. 1, the theoretical slope of the relationship

between W and d_{p1}/d_{p2} using 15 kVp and 90 kVp can be calculated to be more than two times the slope using 15 kVp and 40 kVp shown in Fig. 2. Therefore, using a pair of tube voltages with greater disparity will provide a more accurate prediction of moisture content.

The third reason is the inaccuracy of the regression equations in explaining the thickness of the reference wedge by brightness value. In general densitometry, a linear equation should be used when explaining the density of a sample by brightness value, whereas Fig. 4 shows a non-linear relationship and, in this study, the six-degree polynomial equation was used for calculation. The use of the non-linear range may introduce more errors than the use of the linear range. This may have negatively affected the prediction of moisture content. This problem may be solved by using a highly sensitive digital X-ray plate mentioned above, because it has a wider range of grayscale gradation than an analog film.

For these reasons, the method proposed in this study requires further investigation in order to improve the accuracy of prediction. Moreover, this method does not presently enable the two-dimensional evaluation of moisture content distribution perpendicular to the X-ray direction, whereas this is possible in the single X-ray method by comparing two radiographs of a wood sample in wet- and oven-dry condition (Watanabe et al. 2008, Tanaka et al. 2009). A new method, using the DXA principle to evaluate local moisture content within a wood sample, and moisture content distribution, is currently under investigation by the authors. It is hoped that this will offer the great advantage of evaluating moisture distribution without obtaining a radiograph of a wood sample in the oven-dry condition.

Conclusions

This study proposed a theoretical equation for calculating moisture content in solid wood by the average PMMA-equivalent-thickness ratio calculated from two X-ray radiographs obtained with two different tube voltages. The results of this equation were compared to experimental results using small blocks of sugi wood, and a regression equation for moisture content estimation was determined. The lowest standard error of estimate in the 0–120% dry-basis moisture content range was 21.9%, using paired tube voltages of 15 kVp and 40 kVp. The DXA approach may lead to a method for non-destructive measurement of solid wood moisture content without any assumption of oven-dry density.

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Table 1. Settings of X-ray apparatus

X-ray apparatus settings				
		Tube voltage peak (kVp)	Tube current (mA)	Exposure duration (s)
Radiograph	1	15	30	1200
	2	15	30	1800
	3	20	15	240
	4	20	15	360
	5	40	15	20
	6	40	15	30

Table 2. Experimental results of moisture content and average PMMA-equivalent thickness for each radiograph.

Sample No.	Ovendry density (g/cm ³)	Moisture content (%)		Average PMMA-equivalent thickness (cm)								
		Dry-basis	Wet-basis	15 kVp			20 kVp			40 kVp		
				Radiograph	Radiograph	Ave.	Radiograph	Radiograph	Ave.	Radiograph	Radiograph	Ave.
				1	2		3	4		5	6	
No. 1	0.368	1.4	1.3	0.602	0.600	0.601	0.622	0.627	0.624	0.646	0.652	0.649
No. 2	0.306	2.0	1.9	0.511	0.507	0.509	0.523	0.526	0.525	0.549	0.543	0.546
No. 3	0.368	1.8	1.8	0.623	0.617	0.620	0.645	0.643	0.644	0.678	0.677	0.677
No. 4	0.365	10.4	9.4	0.645	0.647	0.646	0.662	0.663	0.662	0.687	0.685	0.686
No. 5	0.332	11.5	10.4	0.593	0.591	0.592	0.612	0.605	0.609	0.646	0.629	0.637
No. 6	0.301	9.4	8.6	0.537	0.536	0.536	0.555	0.552	0.554	0.590	0.588	0.589
No. 7	0.457	16.8	14.4	0.835	0.832	0.834	0.849	0.855	0.852	0.890	0.876	0.883
No. 8	0.318	23.1	18.8	0.623	0.627	0.625	0.637	0.632	0.634	0.667	0.651	0.659
No. 9	0.305	17.5	14.9	0.603	0.605	0.604	0.620	0.617	0.619	0.657	0.643	0.650
No. 10	0.377	44.7	30.9	0.866	0.871	0.869	0.883	0.884	0.884	0.913	0.894	0.903
No. 11	0.314	31.2	23.8	0.696	0.703	0.700	0.713	0.707	0.710	0.761	0.725	0.743
No. 12	0.334	24.3	19.5	0.700	0.706	0.703	0.723	0.715	0.719	0.774	0.747	0.760
No. 13	0.335	71.2	41.6	0.938	0.947	0.943	0.965	0.965	0.965	1.002	0.981	0.992
No. 14	0.357	68.6	40.7	1.029	1.028	1.028	1.040	1.041	1.041	1.082	1.064	1.073
No. 15	0.385	39.1	28.1	0.881	0.881	0.881	0.891	0.892	0.892	0.929	0.917	0.923
No. 16	0.477	101.8	50.5	1.511	1.524	1.518	1.555	1.559	1.557	1.585	1.553	1.569
No. 17	0.343	113.7	53.2	1.250	1.250	1.250	1.263	1.268	1.265	1.308	1.285	1.296
No. 18	0.309	118.3	54.2	1.180	1.181	1.180	1.194	1.203	1.199	1.239	1.216	1.228

Table 3. Determination of the coefficients in Eq. (18).

Pair of tube voltage	Coefficients in Eq. (18)		Coefficient of determination
	a	b	R^2
15 kVp / 40 kVp	8.70×10^2	-7.97×10^2	0.72
20 kVp / 40 kVp	1.02×10^3	-9.62×10^2	0.54
15 kVp / 20 kVp	1.50×10^3	-1.44×10^3	0.48

Fig. 1 Relationship between X-ray wavelength and mass attenuation coefficients of wood substance (μ_s), moisture (μ_m) and PMMA (μ_p); and relationship between X-ray wavelength and mass attenuation coefficient ratio of wood substance, moisture and wood (μ_w) to PMMA

Fig. 2 Theoretically obtained relationship between wet-basis moisture content and PMMA-equivalent-thickness ratio

Fig. 3 Schematic of the X-ray apparatus

Fig. 4 Relationship between the thickness of the reference wedge and brightness value of the reference wedge on Radiograph 1

Fig. 5 Comparison of experimentally and theoretically obtained relationship between wet-basis moisture content and average PMMA-equivalent-thickness ratio of (a) 15 kVp to 40 kVp, (b) 20 kVp to 40 kVp, and (c) 15 kVp to 20 kVp

Fig. 6 Relationship between the actual wet-basis moisture content and estimated wet-basis moisture content using the average PMMA-equivalent-thickness ratio of (a) 15 kVp to 40 kVp, (b) 20 kVp to 40 kVp, and (c) 15 kVp to 20 kVp. The samples were exposed to X-ray radiation parallel to the **L** longitudinal direction, **R** radial direction, **T** tangential direction

Fig. 7 Relationship between the actual dry-basis moisture content and estimated dry-basis moisture content using the average PMMA-equivalent-thickness ratio of (a) 15 kVp to 40 kVp, (b) 20 kVp to 40 kVp, and (c) 15 kVp to 20 kVp. The samples were exposed to X-ray radiation parallel to the **L** longitudinal direction, **R** radial direction, **T** tangential direction

Fig. 8 Relationship between the actual oven-dry density of the test specimens and the measurement errors in Fig. 7a.