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

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Short title: **Moisture content determination by DXA**

Improved method based on dual-energy X-ray absorptiometry (DXA) for nondestructive evaluation of solid wood moisture content

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10 **Abstract:** An accurate, rapid, and convenient method is presented for moisture content (MC) determination of solid wood based on dual-energy X-ray absorptiometry (DXA). Poly(methyl methacrylate)-equivalent thicknesses (PMMA-EThs) of sugi (*Cryptomeria japonica* D. Don) wood blocks and pure water were measured by means of a wide range of X-ray tube voltages (20–100 kV). The ratio of the PMMA-ETh of pure water to that of wood decreased as X-ray

15 tube voltage was increased, suggesting that an appropriate pair of tube voltages for DXA is 20 kV and 100 kV. According to this result, X-ray images of thirty wood samples were taken at 20 kV and 100 kV tube voltages, and their average PMMA-Eths from both images was determined. There was a strong negative correlation between the wet-basis MC of the wood sample and the ratio of its PMMA-Eth at 100 kV to that at 20 kV. A regression equation was

20 developed for estimating the dry-basis MC of wood samples from their PMMA-ETh ratios. The standard error of estimate was 2.2%, which is better than those determined for electric moisture meters. This approach may lead to the development of a practical, nondestructive moisture meter for wood.

Keywords: dual-energy X-ray absorptiometry (DXA); moisture content (MC); nondestructive evaluation; sugi (*Cryptomeria japonica*); X-ray densitometry

Introduction

5 The usual moisture meters can be classified as conductivity-type, dielectric-type, and microwave-type instruments (Siau 1995). These instruments are widely distributed both for laboratory and practical applications, though the results are strongly influenced by surface moisture content (MC), fiber direction, temperature, or oven-dry density of wood (James 1968, Siau 1984, Siau 1995). In terms of MC determination, one has to differentiate between
10 the sophisticated determination of MC and MC distribution by means of the expensive NMR and neutron imaging techniques (Telkki et al. 2013; Javed et al. 2014; Lanvermann et al. 2014) in research laboratories and MC determination in the praxis. The methods based on NIR spectroscopy are better suited for the praxis (Kobori et al. 2013, 2014), but the stable calibration is a delicate matter.

15 Dual-energy X-ray absorptiometry (DXA) was originally developed in the field of medicine to analyze human bone minerals (Sartoris and Resnick 1989; Mazess et al. 1990) and body fat percentage (Haarbo et al. 1991; Svendsen 1993). DXA is a nondestructive method that is based on the relationship between the variation in mass attenuation coefficient at different X-ray tube voltages and the elemental composition of a sample. This technique
20 reveals the total density of the material and its constituents based on the comparison of two X-ray radiographs obtained at two different tube voltages.

The applicability of DXA to the estimation of the MC of wood chips was already tested (Kullenberg et al. 2010; Hultnäs and Fernandez-Cano 2012), who worked with X-ray tube voltages of 40 and 90 kVp to determine the MC_{wet-basis} of wood chips of spruce (*Picea abies* L.) and pine (*Pinus sylvestris* L.) and a variety of mixtures thereof; the standard error of estimate (SEE) was 1.4–2.6%. Tanaka and Kawai (2013) proposed an equation for estimating solid wood MC from differences in poly(methyl methacrylate)-equivalent thicknesses (PMMA-ET_h) at different X-ray tube voltages. However, when these authors estimated the MC of small sugi blocks (*Cryptomeria japonica* D. Don) at X-ray beams with 15 and 40 kVp tube voltages, the SEE of 21.9% was large. This may have been due to the long measurement duration, small difference in X-ray tube voltages, or the inaccuracy of the regression equations related to the thickness of the reference substance (based on its brightness value on analog X-ray films).

The objective of this study was to develop a more accurate, more rapid and more convenient DXA method for MC estimating of solid woods based on the work of Tanaka and Kawai (2013). The ratio of the PMMA-ET_h of pure water to that of wood was investigated over a wide range of X-ray tube voltages (20–100 kV). The expectation was that a more appropriate pair of X-ray tube voltages can be chosen based on these wide range experiments. A more convenient equation should be developed for estimating the MC of solid wood.

Materials and methods

Thirty-three sugi small blocks were cut with dimensions of $15.1 \times 15.1 \times 16.0 \text{ mm}^3$ (R $\times$ T $\times$ L) from an air-dried tree grown in Shizuoka Prefecture, Japan (Table 1). Samples were kept at 20°C and 65% RH for more than two weeks for conditioning.

5 Three small blocks (Blocks 1–3), a disposable paper cup containing 16 g pure water, and seven poly(methyl methacrylate) (PMMA) plates of various thicknesses (2.97, 3.99, 5.01, 6.07, 8.09, 9.98, and 13.06 mm) were set on a digital X-ray scanner (NX-06SN, Softex Co., Ltd., Ebina, Japan) in an X-ray radiation apparatus (M-100 Toku, Softex Co., Ltd., Ebina, Japan) (Figure 1). X-ray images were taken at a variety of X-ray tube voltages with a
10 moderate tube current, an adequate X-ray filter, and appropriate exposure duration (Table 2). The X-ray images were automatically saved into a personal computer in “.dcm” format at a resolution of 2610×2160 pixels (10 pixel mm^{-1}) in 12-bit (0–4095) grayscale. The average brightness value of each PMMA plate in each image was calculated by ImageJ 1.45s software (Wayne Rasband, National Institute of Health, Bethesda, Maryland, USA). An equation
15 explaining PMMA thickness by brightness value was regressively determined for each image. All pixels of each image were converted to PMMA-ETH and the average PMMA-ETH of wood samples and pure water were calculated by ImageJ.

Pure water (0.0807–1.2357 g) was added to the remaining wood blocks (Blocks 4–33) in plastic bags to create wood samples with a wide variety of MC (Table 1). Each sample was

placed on the X-ray scanner together with the seven PMMA plates described in the previous paragraph. Two X-ray images were taken: one at 20-kV tube voltage with 3.00-mA tube current and 30-s exposure through a 0.50-mm-thick aluminum filter; and one at 100-kV tube voltage with 3.00-mA tube current and 1-s exposure through a 1.00-mm-thick copper filter.

- 5 The average brightness value of each PMMA plate was calculated for each image and an equation explaining the relationship between PMMA thickness and brightness value was regressively determined for each image in the same manner as described above. Brightness values of the images were converted to PMMA-ET_h and the average PMMA-ET_h was calculated. Finally, the PMMA-ET_h ratio was calculated by dividing the average PMMA-ET_h at 100 kV by that at 20 kV.

The actual dry-basis MCs were determined by oven-drying at 105°C for 12 h and weighing on an electric balance.

Results and discussion

- 15 Table 3 shows the average PMMA-ET_hs of Blocks 1–3 and pure water at X-ray tube voltages 20–100 kV. The PMMA-ET_h of water decreased relative to that of wood with increasing tube voltage (Figure 2). This indicates that estimates of solid wood MC will be more accurate based on two highly disparate tube voltages than those based on relatively two similar tube voltages. Therefore, within the tested range, the most appropriate pair of tube voltages for

DXA is 20 kV and 100 kV.

Figure 3 shows the relationship between the actual wet-basis MCs of Blocks 4–33, as determined by the oven-drying method, and their PMMA-ETH ratios calculated from X-ray images. There is a strong negative correlation between wet-basis MC and PMMA-ETH ratios
5 ($R^2 = 0.94$). Accordingly, MC can be estimated from PMMA-ETH ratios, which is calculated only from the brightness information on X-ray images. Eq. (1) allows for MC determination:

$$W_e\% = -120.76P + 189.52 \quad (1)$$

where, $W_e\%$ is the estimated $MC_{\text{wet-basis}}$ of a wood sample and P is the PMMA-ETH ratio of the wood sample. The $MC_{\text{wet-basis}}$ can be converted to the $MC_{\text{dry-basis}}$ by Eq. (2):

$$w\% = 100W/(100-W) \quad (2)$$

where, $w\%$ is the $MC_{\text{dry-basis}}$ and W is the $MC_{\text{wet-basis}}$ (%). Thus, Eq. (1) can be written as:

$$w_e\% = \frac{-120.76P + 189.52}{100 - (-120.76P + 189.52)} \times 100 \quad (3)$$

where, $w_e\%$ is the estimated $MC_{\text{dry-basis}}$ of a wood sample (%).

Figure 4 shows the relationship between the experimental $MC_{\text{dry-basis}}$ of wood blocks, as
15 determined by the oven-drying method, and the $MC_{\text{dry-basis}}$ calculated by Eq. (3). The SEE calculated according to Eq. (4) was $\approx 2.2\%$, which is much more accurate than the previous DXA method ($SEE = 21.9$) (Tanaka and Kawai 2013).

$$s = \sqrt{\frac{\sum (w - w_e)^2}{N - 2}} \quad (4)$$

where s is the SEE (%) and N is the number of samples.

James (1968) investigated the accuracy of the instruments based on resistance, capacitive-admittance, and a power-loss measurements and calculated the coefficient of variation (CV), which is defined as the ratio of the standard deviation (StD) to the mean. The CVs of measurements on a black spruce (*Picea mariana* Mill.) blocks with MC 80% at 26.7°C were between 0.03–0.12 for the three types of moisture meters, i.e. the StDs were 2.4–9.6%. As these StD values express virtually the same thing as SEE, it can be concluded that the proposed DXA method in the present study is more accurate than those in the quoted study, which are currently widely used in practice.

The DXA method in the present study needs only 31 s total exposure time to obtain two X-ray images, whereas the method of Tanaka and Kawai (2013) required more than 50 min of exposure. Moreover, analog X-ray film is not needed and thus the process steps related to X-ray film developing, fixing, and scanning are not necessary. These circumstances are encouraging for practical applications.

Conclusions

The presented improved DXA-based method is promising for MC estimation of solid wood, which is possible with a standard error of estimate (SEE) of 2.2%, if two X-ray images are analysed based on tube voltages of 20 kV and 100 kV. This method is simple and needs 31 s exposure time. In order to develop a practical nondestructive moisture meter for wood based

on DXA, further studies are needed to clarify the effects of wood species and timber dimensions.

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Table 1. Characteristics of sugi wood blocks made of sapwood (sW) or heartwood (hW).

Block No.		Density* (g cm ⁻³)	MC** (%)	Block No.		Density* (g cm ⁻³)	MC** (%)
1	sW	0.313	-	18	sW	0.290	35.7
2	sW	0.315	-	19	sW	0.308	59.8
3	sW	0.325	-	20	sW	0.298	106.9
4	sW	0.329	14.3	21	sW	0.306	99.8
5	sW	0.312	14.1	22	sW	0.323	115.3
6	sW	0.310	37.7	23	sW	0.310	138.6
7	sW	0.291	22.8	24	hW	0.368	14.7
8	sW	0.319	53.2	25	hW	0.369	14.7
9	sW	0.310	75.9	26	hW	0.346	31.4
10	sW	0.306	100.6	27	hW	0.349	33.0
11	sW	0.318	79.6	28	hW	0.356	63.8
12	sW	0.311	117.7	29	hW	0.338	62.5
13	sW	0.309	129.1	30	hW	0.373	87.9
14	sW	0.310	14.0	31	hW	0.369	94.8
15	sW	0.323	14.6	32	hW	0.360	121.7
16	sW	0.304	56.7	33	hW	0.378	111.8
17	sW	0.314	28.6				

*Air-dried density at 20°C and 65% RH; **MC after adding pure water (dry-basis)

Table 2. Specific X-ray conditions for each tested tube voltage.

Tube voltage (kV)	Tube current (mA)	Radiating duration (s)	Filter mate- rials	Filter thickness (mm)
20	3.00	30	Al	0.50
30	3.00	4	Al	0.50
40	2.40	1	Al	0.50
50	2.10	1	A	1.00
60	1.40	1	Al	1.00
70	1.00	1	A	1.00
80	3.00	1	Cu	0.30
90	3.00	1	Cu	0.50
100	3.00	1	Cu	1.00

Table 3. PMMA-EThs of wood blocks and pure water at tube voltages between 20 and 100

kV.

Sample, Ratio	PMMA-equivalent thickness (PMMA-ETh) in (mm) at the voltages of								
	20 kV	30 kV	40 kV	50 kV	60 kV	70 kV	80 kV	90 kV	100 kV
Block 1	4.46	4.62	4.78	5.01	5.16	5.25	6.35	6.56	6.65
Wood Block 2	4.57	4.73	4.88	5.14	5.30	5.39	6.56	6.79	6.92
Block 3	4.57	4.73	4.88	5.20	5.29	5.43	6.68	6.95	7.09
Pure water	7.86	7.66	7.58	7.47	7.45	7.43	7.52	7.55	7.52
Water / Wood	1.74	1.63	1.56	1.46	1.42	1.39	1.15	1.12	1.09

Figure 1. Schematic of the X-ray radiation apparatus

Figure 2. Relationship between X-ray tube voltages and the *ratio of the poly(methyl methacrylate)-equivalent thickness ((PMMA-ETh) of pure water to that of wood blocks

Figure 3. Relationship between wet-basis moisture content of sugi samples and poly(methyl methacrylate)-equivalent thickness ratio (PMMA-ETH ratio)

Figure 4. Relationship between the actual MC_{dry-basis} of sugi samples, as determined by oven drying and that estimated from PMMA-ETH ratio