Estimating the Moisture Content of Lumber above the Fiber Saturation Point Using Stress Wave Velocity during the Natural Drying Process

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Abstract

Determining the moisture content of wood during its drying process is important for the quality control of lumber. This study investigated the potential for using stress wave velocity to estimate moisture content in boxed-heart lumber from Japanese cedar (*Cryptomeria japonica* D. Don) and examined a methodology using Monte Carlo simulation for applying estimated moisture content to quality control. Lumber was subjected to natural drying for about half a year, from the green wood condition to near the fiber saturation point, during which time stress wave velocity and moisture content were measured about seven times. Stress wave velocity was confirmed to increase with decreasing moisture content, even for lumber whose cross-sectional dimensions were comparatively large. The relation between stress wave velocity and moisture content was expressible by a regression line over a range of moisture content above the fiber saturation point. The database for the relation between stress wave velocity and moisture content was further divided into three groups based on apparent density, and the same analysis was conducted. Estimation precision was found to improve over the entire moisture content range when analyzed within each individual group compared with analysis values obtained when ungrouped. Finally, application of Monte Carlo simulation to the moisture content estimations was able to account statistically for the variation in the relation between stress wave velocity and moisture content. This method was found to be effective in reducing estimation error for quality control purposes.

In Japan, the conifer forests planted under the expanded afforestation policy after World War II are now older than 60 years, and timber production from logs with top diameters of over 30 cm is becoming mainstream. Lumber obtained from such logs contains large amounts of mature wood, and an ideal end use that allows people to take advantage of this property is the production of structural lumber, such as beams. Because the drying process for sawn timber requires large amounts of time and energy, natural drying and coordinated drying (which combines natural drying with partial, artificial drying) have become the methods of choice. Japanese cedar (*Cryptomeria japonica* D. Don) is the most produced wood in Japan, but it is considered a difficult tree species to dry because the moisture content of its heartwood is high and moisture content variation between individuals is large (Nakada et al. 1998). For this reason, monitoring the moisture content of wood during the drying process and determining whether it reaches a defined moisture content value are important steps to take on the way to promoting the use of domestic timber. At lumber mills in Japan today, a portable high-frequency type of moisture content meter is a typical means to ascertain the moisture content of sawn timber. However, the range for which measurement is possible with such devices is a mere few tens of millimeters interior to the surface of the wood. Accordingly, values from lumber with large cross sections would be neither necessarily average nor representative, and the reliability of estimated values would fall for wood having large

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differences in moisture content between its surface and its interior.

The number of methods to measure natural frequency and stress wave velocity in order to obtain Young's modulus of lumber and to obtain dynamic Young's modulus have increased in recent years. These measures and their relations with moisture content continue to be investigated in contemporary research. For example, Wang and Chuang (2000) conducted experiments on small Japanese cedar specimens, finding an inflection point near the fiber saturation point in the relation between stress wave velocity and moisture content. They suggested the relation should be expressed by a quadratic regression equation or two linear regression equations in the case of dividing the relation into that of being below and above the saturation point. In addition, Guan et al. (2002) conducted fundamental research with the objective of estimating wood moisture content during the drying process. Briefly, they investigated what kind of relationship the ratio of two dynamic Young's moduli obtained from longitudinal vibration and from stress wave velocity, respectively, has with moisture content, using small specimens and boards. Their research was only on small specimens and boards, and to our knowledge, few studies have used large cross-section lumber, including, e.g., Montero et al. (2015), who used structural lumber. Japanese cedar is a tree species that contains a comparatively large amount of moisture and whose drying properties differ greatly between its heartwood and its sapwood. It is therefore unclear whether previous findings can be applied to the moisture content estimation of lumber with large cross-sectional dimensions. The purposes of this study were (1) to ascertain the relation between stress wave velocity and moisture content for Japanese cedar lumber at and above the fiber saturation point and to construct a database for them and (2) to evaluate moisture content during the drying process using this database and apply this methodology to the quality control of lumber. Monte Carlo simulation was then introduced to the moisture content estimation, and methods to evaluate the overall moisture content of lots consisting of certain amounts of sawn timber were considered. The Monte Carlo simulation was used to find characteristic values that were statistically possible for the wood; this was done by generating a random number to impart bias to an arbitrarily selected value, based on the probability distribution of a given database. Yamasaki and Sasaki (2010) applied this methodology to develop a way to estimate Young's modulus of lumber from stress wave velocity without measuring density. In this study, the application of estimated moisture content values obtained via Monte Carlo simulation to quality control during the wood drying process was attempted.

Materials and Methods

Test specimens

The test specimens were 89 logs of Japanese cedar (*C. japonica* D. Don), produced from seeding plantations in Aichi Prefecture, aged 40 to 107 years. From these logs, 89 pieces of boxed-heart lumber were sawn. The dimensions of the boxed lumber were 132 by 253 by 4,000 mm. Table 1 shows the moisture content immediately after sawing the log specimens as well as the dry density of the boxed lumber. After sawing, the 89 pieces of boxed lumber were stacked on stickers in a storage lot with an attached roof and subjected to natural drying for about half a year from summer to autumn. Atmospheric temperature during the test periods was in the range of 12°C to 26°C.

Table 1.—Mean value, standard deviation (SD), maximum value (Max), and minimum value (Min) of the moisture content immediately after sawing (MC) and dry density (ρ_0).

	MC (%)	ρ_0 (kg/m^3)
Mean	74.3	332
SD	19.4	28
Max	131.3	399
Min	36.2	276

Measurement of stress wave velocity and moisture content

This study performed successive measurements of changes over time in stress wave velocity (V_t) and weight (W_t) for the stacked boxed lumber during the drying process. In short, measurements were performed about seven times over the approximately half-year period, from immediately after sawing to near the fiber saturation point, creating a data set with a total of 617 points (V_t, W_t).

A FAKOPP device (Fakopp Enterprise) was used for stress wave measurements. Sensors were knocked into the pith at the open end of each lumber specimen, and stress waves were generated by striking a transmitting sensor with an iron hammer (Fig. 1). V_t was calculated by measuring the propagation time of the stress wave (Δt) and wood length (L). After completing about seven successive measurements during the drying process, test pieces (about 30 mm thick) were cut out from both ends of the lumber specimens (measuring from the end to a point 1 m inward) for use in moisture content measurement and left inside a drying apparatus (temperature set at 103°C) for 48 hours, and the ovendry weight of the wood was obtained. Next, moisture content (MC$_t$) corresponding to V_t measured over time was determined based on this ovendry weight.

The above procedure enabled the determination of changes over time in V_t and MC$_t$ of the boxed lumber specimens during the drying process.

Figure 1.—Placement of sensors for stress wave test.

Estimation of moisture content by linear regression

The measurements in the previous section were used to form a data set (V_t, MC_t) to express the relation between the stress wave velocity and moisture content of wood. By using the regression line for the two measures, moisture content can be estimated by substituting measured values for V_t into the regression equation. Moisture content estimated using this regression line is denoted as MC_{er}.

Estimation of moisture content using Monte Carlo simulation

MC_{er}, estimated as in the previous section, returns the average value when the stress wave velocity is V_t. Consequentially, estimated values are a mixture of values higher than the observed value and values lower than the observed values. In fact, the estimated values should contain variation based on a certain probability distribution. Accordingly, Monte Carlo simulation was introduced in an attempt to apply these variation-containing estimated values to the control of moisture content during the drying process. The simulation procedure is shown below.

The model assumes that data of the relation between stress wave velocity and moisture content have been obtained (Fig. 2); these data form the baseline database. The regression line for this relation between stress wave velocity and moisture content is then obtained. Substituting a measured stress wave velocity value as V_t yields $MC_{t\mathrm{ave}}$, the average moisture content value corresponding to the velocity data V_t. This is shown in Figure 2.

Next, a regression residual RR (Ott and Longnecker 2001) is randomly selected and added to the $MC_{t\mathrm{ave}}$ obtained above in order to calculate moisture content at a given location (MC_{ei}). The procedure is as follows. First, the regression residual for moisture content corresponding to an arbitrary velocity V_t is assumed to form a normal distribution (mean, $MC_{t\mathrm{ave}}$; variance, SD^2). Specifically, a standard normal variable, SV (Eq. 1), is calculated using a method based on multiple random numbers using the central limit theorem, and RR is obtained by multiplying SV by the residual standard deviation, SD (Eq. 2). Here SD, obtained by Equation 3, is constant and independent of V_t (Hirashima et al. 2004). The RR thus obtained is added to $MC_{t\mathrm{ave}}$, and the result is the simulated moisture content value MC_{ei} corresponding to velocity V_t (Fig. 2):

$$\mathrm{SV} = \sum_{j=1}^{n} r_j - \frac{n}{2} \quad (1)$$

$$\mathrm{RR} = \mathrm{SV} \times \mathrm{SD} \quad (2)$$

$$\mathrm{SD} = \mathrm{SD}_{\mathrm{mc}} \times \sqrt{1 - \mathrm{COD}^2} \quad (3)$$

SD_{mc} is the standard deviation of the total moisture content data set, and COD is the coefficient of determination for the relation between stress wave velocity and moisture content. In addition, in Equation 1 with regard to the standard normal variable SV, r_j denotes the random number for the jth item, and the first term is the sum of n uniform random numbers ($r_1, r_2, \ldots, r_n$) over the interval [0, 1]; $n = 12$ is considered sufficient (James 1980, Miyagawa 1998).

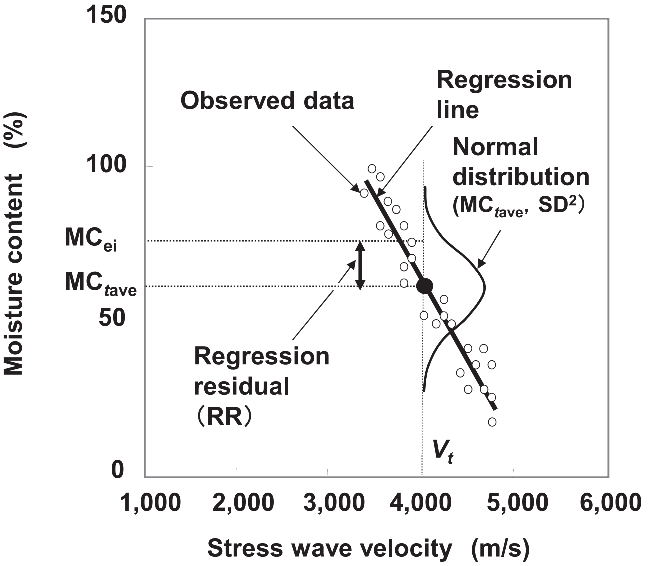

Figure 2.—Schematic of estimation method by Monte Carlo simulation. MC_{tave} = average moisture content corresponding to the observed stress wave velocity (V_t); $MC_{ei} = MC_{\mathrm{tave}} + RR$, an estimated value corresponding to the observed V_t; SD^2 = variance, where SD is the residual standard deviation.

By repeating the above process a sufficient number of times, a data group was accumulated of MC_{ei} values corresponding to the measured V_t values. Random numbers were generated using the RAND( ) function in Microsoft Excel spreadsheet software. The count for repeated calculations was set at 5,000. In other words, 5,000 values for MC_{ei} were obtained for a given V_t. Considerations of how to evaluate these data groups to obtain estimated moisture content (MC_{em}) are described below.

Results and Discussion

Relation between stress wave velocity and moisture content

Figure 3a shows the measurement results for V_t and MC_t. Specimens' stress wave velocity and moisture content values measured successively during the drying process were distributed over 3,370 to 5,019 m/s and 28.0 to 131.3 percent, respectively. Stress wave velocity increased with decreasing moisture content, and the relation between them could be expressed as a significant linear regression equation (significant at $P < 0.01$; Table 2). It is suggested that stress wave velocity is also affected by wood temperature (Sandoz 1993, Van Dyk and Rice 2005, Chan et al. 2011). In this study, the effect of temperature was not considered because its effect was thought to be limited. Figure 3b shows the relation between stress wave velocity and moisture content as successively measured during the drying process when, in contrast, specimens were divided into groups by apparent density. The specimens were divided into groups by apparent density for the following reason. Because dynamic modulus of elasticity is expressed by $V^2\rho$, the relation between stress wave velocity and moisture content is influenced by Young's modulus of the wood. This causes increased variation in the relation between stress wave velocity and moisture content. Accordingly, to mitigate this influence, this study attempted

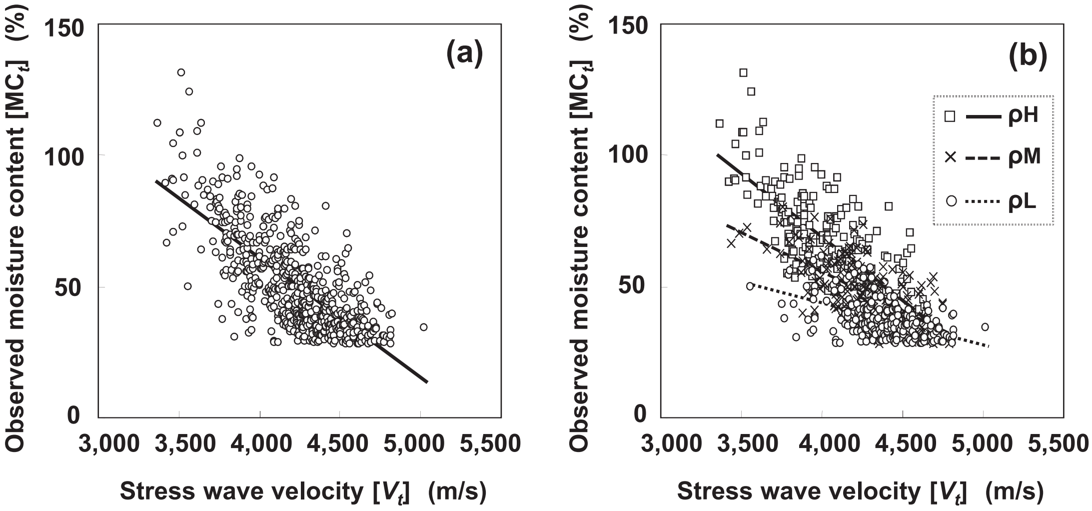

Figure 3.—Correlation between stress wave velocity (V_t) and observed moisture content (MC_t): (a) whole and (b) grouping by apparent density (ρH, ρM, and ρL). ρH = high-density group (521 to 727 kg/m^3); ρM = medium-density group (466 to 520 kg/m^3); ρL = low-density group (361 to 465 kg/m^3).

to artificially divide specimens into groups based on apparent density. Apparent density was divided into three groups—ρH ($n = 206$), 521 to 727 kg/m^3; ρM ($n = 200$), 466 to 520 kg/m^3; and ρL ($n = 211$), 361 to 465 kg/m^3—as the number of each group data set is approximately equal. The corresponding moisture content ranges for the respective groups were 28.0 to 61.7 percent, 28.2 to 80.5 percent, and 30.5 to 131.3 percent. As with the results in Figure 3a, each group exhibited increased stress wave velocity with decreasing moisture content ($P < 0.01$). In addition, according to Figure 3b, the smaller the apparent density of the group was, the larger the changes in stress wave velocity became with respect to changes in moisture content. In this manner, the fact that stress wave velocity increases with decreasing moisture content even for large cross-section, full-size wood specimens was confirmed, a finding similar to past research results for small test specimens and boards (Wang and Chuang 2000, Guan et al. 2002).

Next, the estimated moisture content ($\mathrm{MC_{er}}$) was determined from observed V_t based on the regression line in Figure 3a. Figure 4a shows the relation between $\mathrm{MC_{er}}$ and MC_t. Estimation precision depends on the COD of the correlation equation for stress wave velocity versus moisture content (here, 0.537), so estimated moisture content values for data points separated from the regression line were likewise separated from $y = x$ (the dashed line in Fig. 4a). To validate the estimation precision in further detail, values for the difference between estimated and observed values for moisture content ($\Delta\mathrm{MC} = \mathrm{MC_{er}} - \mathrm{MC}_t$) were divided into four groups according to observed moisture content (28% to <40%, 40% to <60%, 60% to <80%, and 80% or more; ''Whole'' in Table 3; Fig. 5a). Trends were observed of estimated values being higher than observed values for the moisture content ranges of 28 to <40 percent and 40 to <60 percent, while they were lower for moisture content above 60 percent.

For comparison, Figure 4b shows the relation between $\mathrm{MC_{er}}$ and MC_t when divided into groups by apparent density. The data set clustered around $y = x$ (dashed line in Fig. 4b), and accordingly, improvement in estimation precision by using the regression lines classified by apparent density was inferred (COD = 0.714). According to ''Average'' in Table 3 and Figure 5b, the mean of the ΔMC was close to 0 for all groups, and variation in ΔMC was smallest for the moisture content range of 28 to 40 percent. The following reason is considered to explain the improvement in estimation precision when specimens were classified by apparent density. As stated before, variation in the relation between stress wave velocity and moisture content arises owing to influence from Young's modulus. Related to this, Liu et al. (2014) sought to reduce variation in the relation between stress wave velocity and moisture content by using boards of Cathay poplar (*Populus cathayana*). They first obtained the stress wave velocity when the wood was completely dry (V_0), and then divided successively measured V_t by V_0 to obtain corresponding

Table 2.—Mean value, standard deviation (SD), maximum value (Max), and minimum value (Min) of apparent density and correlation between stress wave velocity (V_t) and observed moisture content (MC_t) for each group (whole and three groups divided by apparent density [ρH, ρM, and ρL]).[a]

Group	Apparent density (kg/m^3) Mean	SD	Max	Min	Linear regression model	COD	SD$_{\mathrm{mc}}$ (%)
Whole	500	68	727	361	$\mathrm{MC}_t = -0.04542V_t + 242.6$ (A)	0.537	18.3
ρH	576	44	727	521	$\mathrm{MC}_t = -0.04762V_t + 259.4$ (B)	0.516	18.0
ρM	492	16	520	466	$\mathrm{MC}_t = -0.02996V_t + 174.9$ (C)	0.403	11.9
ρL	430	25	465	361	$\mathrm{MC}_t = -0.01587V_t + 106.9$ (D)	0.266	7.7

[a] COD = coefficient of determination; SD$_{\mathrm{mc}}$ = standard deviation of MC_t.

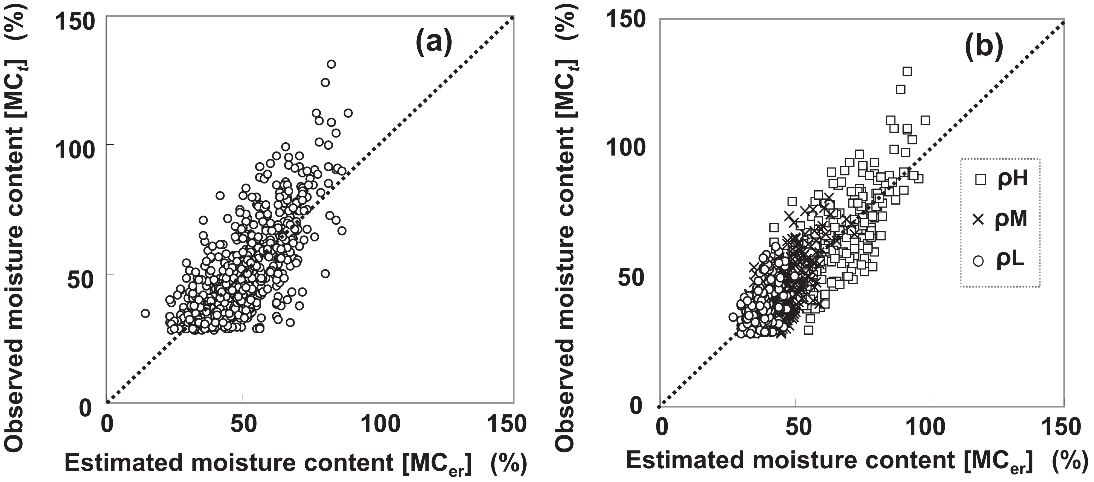

Figure 4.—Correlation between estimated moisture content (MC$_{er}$) and observed moisture content (MC$_t$): (a) whole and (b) grouping by apparent density (ρH, ρM, and ρL). ρH = high-density group (521 to 727 kg/m^3); ρM = medium-density group (466 to 520 kg/m^3); ρL = low-density group (361 to 465 kg/m^3).

relative values (V_t/V_0). They went on to depict the relation of the relative value V_t/V_0 with moisture content measured over time MC$_t$ by using a bilinear regression joined at the fiber saturation point. It would be ideal if the variation in the relation between stress wave velocity and moisture content were able to be eliminated using relative values in this way. However, measuring V_0 when wood is completely dried is difficult for lumber having a large cross section, as the sample specimens did. Therefore, our study attempted to classify lumber artificially, by apparent density, in order to mitigate the effects of Young's modulus on the relation between stress wave velocity and moisture content. Classification by apparent density overlaps with both classification by moisture content and classification by Young's modulus. This analytic detail informed the conclusion that the influence of Young's modulus on the relation between stress wave velocity and moisture content was successfully mitigated to a certain extent. Classification based on apparent density was thus suggested to be an effective means to reduce variation in the relation between stress wave velocity and moisture content.

Moisture content estimation using Monte Carlo simulation

As stated in the previous section, setting the simulation calculations to repeat 5,000 times results in 5,000 data points for simulated MC$_{ei}$ (i = 1 to 5,000) for a V_t value.

Table 3.—Number, mean value, and standard deviation (SD) of difference between MC$_{er}$ and MC$_t$ (ΔMC = MC$_{er}$ − MC$_t$) for each group (whole and three groups divided by apparent density [ρH, ρM, and ρL]).[a]

		ΔMC with an MC$_t$ range (%) of:				
Analysis unit	Group	28–<40	40–<60	60–<80	≥80	Linear regression equation[b]
Whole	No.	216	233	118	50	A
	Mean	7.6	1.3	−7.9	−20.1	
	SD	9.0	9.4	9.8	11.0	
Apparent density group	ρH					B
	No.	11	63	88	49	
	Mean	15.4	8.4	−1.4	−11.8	
	SD	6.1	8.7	9.5	11.2	
	ρM					C
	No.	61	110	28	1	
	Mean	8.2	−1.6	−10.0	−17.8	
	SD	5.1	7.2	7.5	—	
	ρL					D
	No.	144	60	2	0	
	Mean	3.1	−7.0	−17.0	—	
	SD	4.3	5.1	1.7	—	
	Average[c]					
	No.	216	233	118	50	
	Mean	5.2	−0.3	−3.9	−4.6	
	SD	5.7	9.2	10.0	9.3	

[a] MC$_{er}$ = moisture content estimated using the regression line; MC$_t$ = moisture content corresponding to stress wave velocity.

[b] A, B, C, and D = linear regression equations used for this analysis; see Table 2.

[c] Average = average of results obtained by each analysis of ρH, ρM, and ρL.

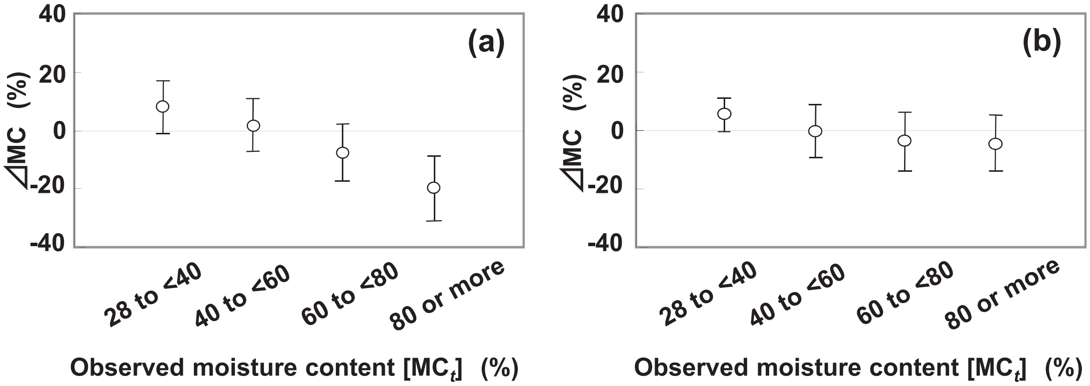

Figure 5.—Difference between estimated moisture content (MC_{er}) and observed moisture content (MC_t): $\Delta MC = MC_{er} - MC_t$: (a) whole and (b) grouping by apparent density (ρH, ρM, and ρL). ○ = average; error bar = standard deviation.

Figure 6a shows a cumulative frequency curve for MC_{ei} obtained by a Monte Carlo simulation using the database shown in Figure 3a for a V_t value of 4,004 m/s as an example. Specifically, 5,000 MC_{ei} values ranging from 21.1 to 106.1 percent were obtained for $V_t = 4{,}004$ m/s; the MC_t for this velocity was 69.2 percent. The black square in Figure 6 indicates the 500th simulated moisture content value ($MC_{e500} = 44.0\%$; 10th percentile value) counting data points from the lowest estimated value ($MC_{e1} = 21.1\%$) upward. Similarly, the black circle indicates the 50th percentile value at the 2,500th simulated value ($MC_{e2,500} = 60.5\%$), and the white square indicates the 90th percentile value at the 4,500th simulated value ($MC_{e4,500} = 77.1\%$).

The question then arose about which of these 5,000 simulated values would be best to adopt as a representative value. A probability density curve for these simulated values is drawn in Figure 6b. Because a normal distribution was assumed, there were many simulated moisture content values MC_{ei} near the median and mean simulation MC_{ei}. One way of thinking, accordingly, would be that the mean of the 5.000 MC_{ei} values, 60.6% percent, should be selected as the MC_{em} corresponding to $V_t = 4{,}004$ m/s. After setting the mean of 5,000 simulated values as MC_{em}, the relation of MC_{em} to observed moisture content MC_t can be plotted as in Figure 7a. The data set is uniformly distributed above and below the $y = x$ line (dashed line) in the figure, appearing quite similar to Figure 3a in this respect. Next, Figure 7b shows the relation between MC_t and MC_{em} for when the 10th and 90th percentile values (MC_{e500} and $MC_{e4,500}$, respectively) were adopted as MC_{em}. Setting the 10th percentile value as MC_{em} results in underestimation of moisture content, with most of the estimated values falling below their corresponding observed value (MC_t). This signifies that the wood drying had not proceeded to a point where estimation would have been suitable. Setting the 90th percentile value as MC_{em}, on the other hand, results in overestimation of moisture content, with most of the estimated values rising above their corresponding observed value. This signifies that the wood drying had proceeded past the point where estimation was suitable. In relation to this, Figure 8 is an illustration of the relation between the proportion of MC_{em} values that fell below their observed MC_t value (i.e., the ratio of

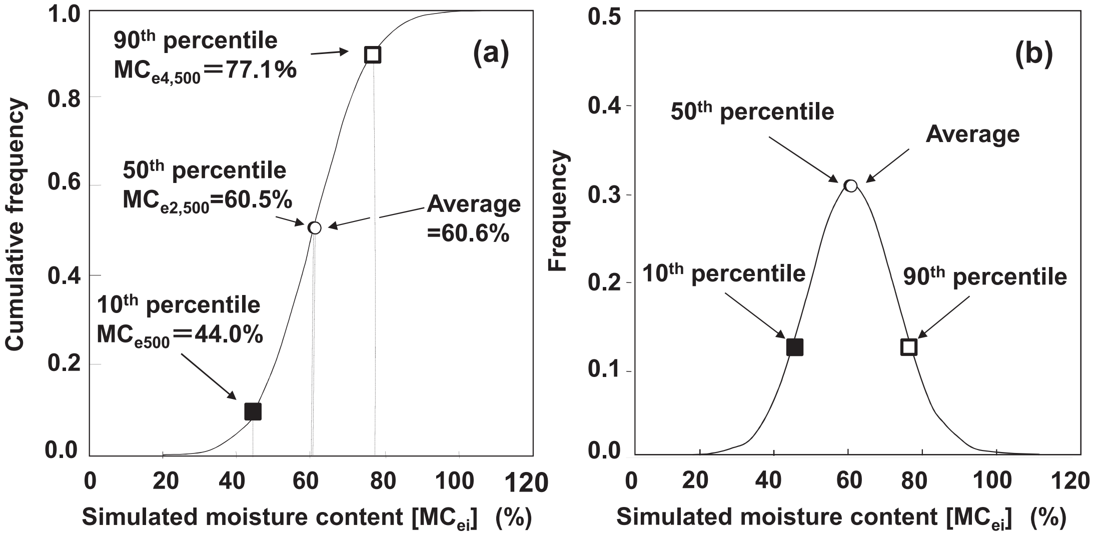

Figure 6.—An example of cumulative frequency distribution and normal probability density distribution of simulated moisture content: 10th , 50th, and 90th percentile are the 500th, 2,500th, and 4,500th simulated values (MC_{e500}, $MC_{e2,500}$, and $MC_{e4,500}$, respectively) counting upward from the lowest value on the cumulative frequency distribution. Average is the mean of the 5,000 simulated values.

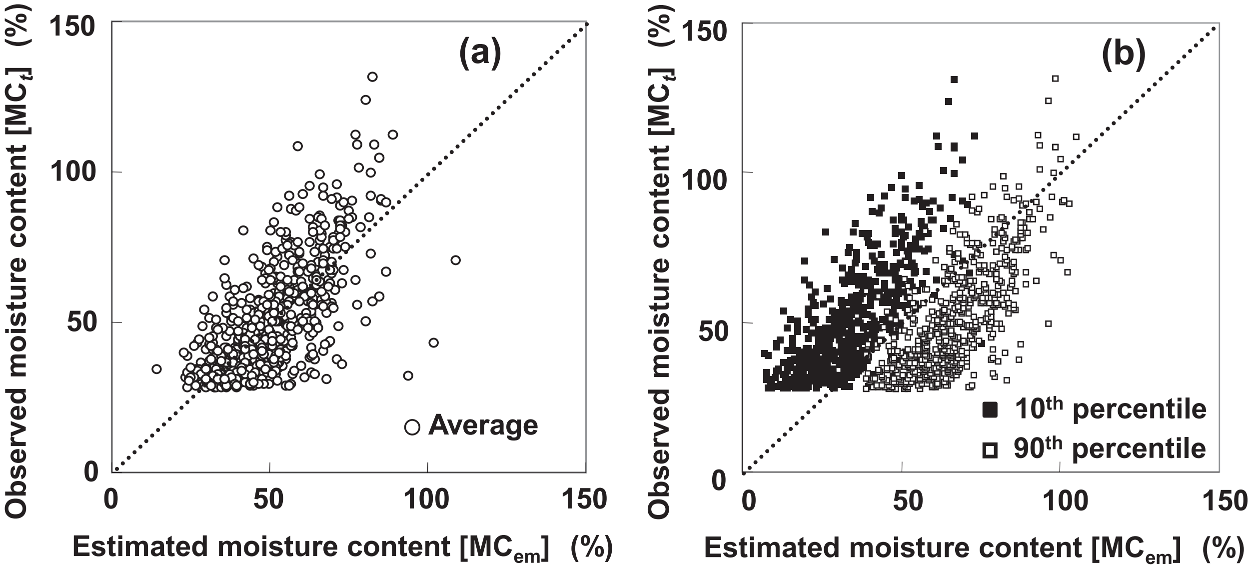

Figure 7.—Correlation between estimated moisture content (MC_{em}) and observed moisture content (MC_t): (a) MC_{em} = average of 5,000 simulated values, and (b) MC_{em} = 10th and 90th percentile values (MC_{e500} and $MC_{e4,500}$, respectively).

underestimation) and the percentile for MC_{em} (th; $x = i/5{,}000 \times 100$). In short, it shows how the proportion of estimated values falling below the observed value changes, depending on differences in the MC_{ei} selected as the MC_{em} value. According to Figure 8, if the estimated moisture content at the 10th percentile (i = 500) is selected as MC_{em}, 93 percent of the wood is underestimated, meaning that most of the wood has not yet dried to a point at which estimation is suitable. This finding suggests there are hazards associated with shipping unseasoned lumber. In contrast, if the estimated moisture content at the 90th percentile (i = 4,500) is selected as MC_{em}, 12 percent of the wood is underestimated. The proportion of wood for which drying has proceeded past the point of suitable estimation clearly increases with increasing i, and one would expect these conditions to result in the nonshipment of unseasoned lumber. On the other hand, there are situations where one would want to prevent excessive drying for lumber quality control purposes. In this case, choosing the 10th percentile value allows for an evaluation that suits the objective of preventing excessive drying. Wood is a material that inherently possesses great variation in its quality. Consequently, moisture content values estimated using linear regression include a mixture of values that are larger and smaller than the actual moisture content, and their variation is constant. Introducing the concepts in this study to lumber management protocols would certainly allow for improvements in reliability surrounding wood quality.

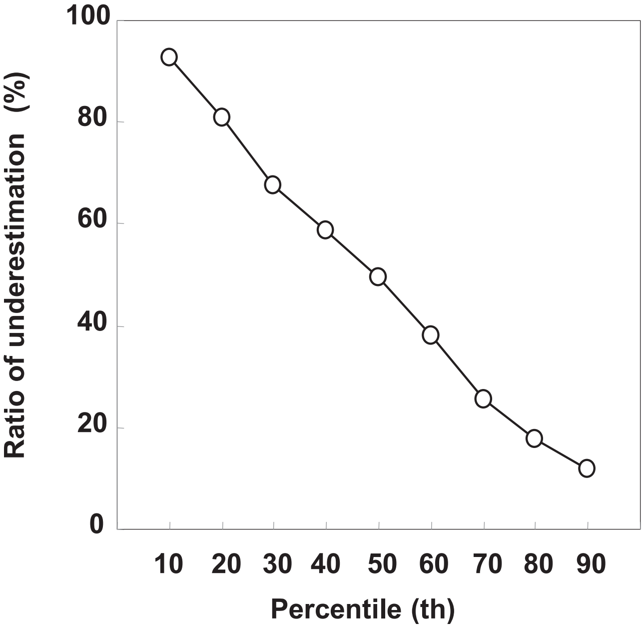

Figure 8.—Ratio of underestimation: n/617 × 100%. n = number of samples for which $MC_{em} < MC_t$; 617 = number of data sets with stress wave velocity (V_t) versus observed moisture content (MC_t); MC_{em} = each percentile value from 10th to 90th.

Conclusions

Using 89 pieces of boxed-heart lumber from Japanese cedar, stress wave velocity and moisture content were measured multiple times at the range of 12°C to 26°C during their drying process, starting from the time they were green timber. A database (617 data points) was then constructed for the relation between stress wave velocity and moisture content over a range of moisture content values above the fiber saturation point. Along with this database being used to conduct lumber moisture content estimations during the natural drying process, the database was experimentally applied to the quality control of lumber by means of a statistical technique using Monte Carlo simulation.

1. Stress wave velocity increased with decreasing lumber moisture content. The relation between the two was largely expressible using a linear regression. When estimating moisture content from stress wave velocity based on this regression line, estimation error was

smallest for the medium-moisture-content (40% to <60%) range. The results showed trends of higher estimated than observed values for the low-moisture-content range and of estimated values for moisture content decreasing with increasing moisture content for high-moisture-content ranges.

2. The data in the database for the relation between stress wave velocity and moisture content were divided into three groups based on specimen apparent density. Stress wave velocity increased with decreasing moisture content for each of the groups. Regarding changes in moisture content, the results showed a trend of stress wave velocity changing more greatly the lower the apparent density of the group was. Moisture content estimations by apparent density group were conducted as well based on regression lines of the relation between stress wave velocity and moisture content. The results showed improved estimation precision, with smaller measurement errors between estimated and observed values over all moisture content ranges compared with the values estimated without grouping first.
3. Applying Monte Carlo simulation to moisture content estimation allowed the analysis to account statistically for variation in the relation between stress wave velocity and moisture content. In other words, the range of moisture content values corresponding to the measured stress wave velocity values was successfully obtained. A methodology was proposed of expressing this range as a percentile value: using this percentile value allows one to reduce the probability of estimation error in quality control settings.

The findings above reveal that in this study, moisture content was estimable from stress wave velocity with good precision, using a database for the relation between stress wave velocity and moisture content for Japanese cedar lumber with large cross-sectional dimensions.

Literature Cited

Chan, M. J., J. C. Walker, and C. A. Raymond. 2011. Effects of moisture content and temperature on acoustic velocity and dynamic MOE of radiata pine sapwood boards. *Wood Sci. Technol*. 45:609–626.

Guan, H., Y. Nishino, and C. Tanaka. 2002. Estimation of moisture content in Sugi wood with sound velocity during the natural drying process. *Mokuzai Gakkaishi* 48(4):225–232. (In Japanese.)

Hirashima, Y., M. Sugihara, Y. Sasaki, K. Ando, and M. Yamasaki. 2004. Strength properties of aged wood I—Tensile strength properties of aged Keyaki and Akamatsu woods. *Mokuzai Gakkaishi* 50(5):304–309. (In Japanese.)

James, F. 1980. Monte Carlo theory and practice. *Rep. Prog. Phys*. 43:1151–1153.

Liu, H., J. Gao, Y. Chen, and Y. Liu. 2014. Effects of moisture content and fiber proportion on stress wave velocity in Cathay poplar (*Populus cathayana*) wood. *BioResources* 9(2):2214–2225.

Miyagawa, K. 1998. Elementary Statistics. 3rd ed. Yuhikaku, Tokyo. (In Japanese.)

Montero, M. J., J. de la Mata, M. Esteban, and E. Hermoso. 2015. Influence of moisture content on the wave velocity to estimate the mechanical properties of large cross-section pieces for structural use of Scots pine from Spain. *Maderas Cienc. Tecnol*. 17(2):407–420.

Nakada, R., Y. Fujisawa, Y. Hirakawa, and K. Yamashita. 1998. Longitudinal change moisture content in the stem of *Cryptomeria japonica* D. Don. *Mokuzai Gakkaishi* 44(6):395–402. (In Japanese.)

Ott, R. L. and M. Longnecker. 2001. An Introduction to Statistical Methods and Data Analysis. 5th ed. Duxbury/Thomson Learning, San Francisco.

Sandoz, J. L. 1993. Moisture content and temperature effect on ultrasound timber grading. *Wood Sci. Technol*. 27:373–380.

Van Dyk, H. and R. W. Rice. 2005. Ultrasonic wave velocity as a moisture indicator in frozen and unfrozen lumber. *Forest Prod. J*. 55(6):68–72.

Wang, S. Y. and C. T. Chuang. 2000. Experimental data correction of the dynamic elasticity on the basis in moduli, velocity and density of solid wood as a function of moisture content above the fiber saturation point. *Holzforschung* 54:309–314.

Yamasaki, M. and Y. Sasaki. 2010. Determining Young's modulus of timber on the basis of a strength database and stress wave propagation velocity I—An estimation method for Young's modulus employing Monte Carlo simulation. *J. Wood Sci*. 56:269–275.