Correction Factors for a Radio frequency-Type Moisture Meter for Heat-Treated Wood

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Moisture content (MC) has an important effect on the performance of wood in service. In an attempt to rapidly and non-destructively acquire the MC of heat-treated wood, a radio frequency-type moisture meter was used to take the MC of 170, 185, and 200 °C heat-treated Manchurian ash and Mongolian pine wood samples as well as reference (conventional kiln-dried) samples. A linear regression analysis was applied to assess the relationship between the MC values obtained using the meter and those obtained using the oven-dry method by fitting the data points according to the least squares method. From the results of the high coefficients of determination of the regression equation, it was concluded that the meter could be effectively used to obtain the MC of heat-treated wood. Finally, to ensure the simple and reliable application of the meter, the meter correction factors corresponding to each species and heat treatment temperature were calculated and listed.

Keywords: Wood; Heat treatment; Moisture content; Radiofrequency-type moisture meter; Calibration

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INTRODUCTION

The moisture content (MC) of wood, defined as the ratio of the weight of water in wood to that of oven-dried wood, has a highly significant effect on wood properties. It is important to the effective utilization of wood that the MC of semi-manufactured or finished wood products be well controlled according to the final conditions of use (Skaar 1988). If not, serious problems of dimensional instability, such as warping, twisting, and cracking, could arise due to the hygroscopicity of the wood. Fortunately, more and more enterprises in China have paid attention to this issue and have taken steps as follows: a conditioned storage, in which environmental conditions of 20 to 30 °C and 40 to 60% RH can be maintained all year around, is used to equalize and retain the MC of wood and wood products at the desired MC level before and after wood processing; a special production line, as shown in Fig. 1 taken from a solid wood flooring factory, has been introduced to manually check the drying quality and MC of kiln-dried planks (the boards with poor performance would be returned to the kiln or conditioned storage for re-drying or re-conditioning) in preparation for subsequent secondary manufacturing operations. Thus, it is essential that a reliable and efficient method of measuring wood MC be developed for use in these two operations. In comparison to the oven-dry method, which is the most precise determination method based on the physical definition of wood MC, MC determination with electric moisture meters is much more practical and convenient for field use, in which the MC of wood and wood products during kiln drying, conditioning, processing, or even in service can be instantly obtained, because they are rapid, non-destructive, economical, and simple to use.

Fig. 1. A special production line for checking the drying quality and MC of kiln-dried planks

Currently, two general types of moisture meters are available in the wood industry. Unlike the conductance-type moisture meter, which has two or four nail-like electrodes that make holes in and slightly destroy the surface of the wood during measurement, the radio frequency-type moisture meter has no need to penetrate the surface of the wood with its surface-contact electrode (James 1988). Therefore, such a device has been mainly used for obtaining the MC values of semi-manufactured or finished wood products around the world.

The principle of operation of the radio frequency-type moisture meter hinges upon a fundamental relationship between MC and the dielectric properties (such as dielectric constant and loss factor) of moist wood. There are some factors that affect the accuracy of the MC measurements by the radio frequency-type moisture meter. For ordinary use at room temperature, the species or density of the wood has been found to be the most significant factor affecting the meter reading (Milota 1994). Douglas-fir was the main species used to calibrate the meter (Gillis *et al.* 2001; Wu 1997; Milota and Gupta 1996), and the correction factors for other common species based on the values of specific gravity are generally provided in the instruction manual as well as preset in the meter by the manufacturer. Some calibration has been conducted for uncommon or unfamiliar species, and the correction factors have been established, in accordance with a standard procedure for moisture meter calibration recommended by ASTM in D4444 (the newest edition published in 2013), for 13 US southern hardwood species (Shupe *et al.* 2002), four Brazilian wood species (Gillis *et al.* 2001), bald cypress (Wu 1997), Dahurian larch (Milota and Gupta 1996), and jelutong (Milota 1991). Meanwhile, there have been other projects developed to establish the meter calibration equations for use on pine woods modified by wood preservation treatments with ACQ, CCA, and several newgeneration wood preservatives, in which the linear regression relationships between the meter reading and the oven-dry MC were also found by means of kiln-dried wood (Blakemore *et al.* 2005, 2008; Smith *et al.* 2007).

In the last two decades, numerous studies have been reported regarding the thermal modification of wood and wood-based panels (Esteves and Pereira 2009; Srinivas and Pandey 2012; Råberg *et al.* 2012; Huang *et al.* 2012; Bazyar 2012; Mendes *et al.* 2013), as well as some heat treatment methods. Thermowood in Finland, Plato in Netherlands, Rectification and Le Bois Perdure in France, and Oil heat treatment in Germany were successfully developed in industrial practice during the 1990s (Hill 2006). It is generally accepted that the dimensional stability and durability of wood can be significantly improved without the use or impregnation of chemical substances during the heat treatment process at 160 to 240 °C (Esteves and Pereira 2009). Because of the superior properties of the modified wood, heat-treated wood products have been mainly used in outdoor and special indoor applications, such as sauna furnishing and under-floor heating systems that are not suitable for the application of common kiln-dried solid wood. Since 2005, the Wood Drying Laboratory of Nanjing Forestry University has conducted research on the relationships between the process parameters and wood properties of heat-treated wood of Chinese species, and on the design and development of pilot-scale superheated vapor heat treatment kilns (Gu *et al.* 2007; Li *et al.* 2009; Ding *et al.* 2011; Cai *et. al* 2013). The fruits of these efforts have been effectively applied in the wood industry in the Zhejiang Province of China over the course of the past five years. Commercial modified wood products made of heat-treated wood, such as solid wood flooring, garden furniture, and external cladding and decking, are now seeing extensive activity in the Chinese market.

Currently, there is little information that focuses on the calibration of moisture meters for heat-treated wood. Garrahan (1988) investigated the effects of high-temperature kiln drying at the maximum dry bulb temperature of 116 °C on the conductance-type moisture meter readings of dried wood. However, in contrast to the conditions used in the heat treatment, the high-temperature kiln drying could not induce a significant change in the chemical structure and constitution of the wood cell walls. The aim of the present study was to determine whether the radio frequency-type moisture meter could be readily and reliably used to obtain the MC of heat-treated wood and to establish new correction factors for the meter based on the process parameters of heat treatment temperature and species used.

EXPERIMENTAL

Materials

Conventional kiln-dried and rough-sawn Manchurian ash (*Fraxinus mandshurica)* and Mongolian pine (*Pinus Sylvestris* L. var. Mongolica) boards, with nominal thicknesses of 25 mm, were obtained from Zhejiang Shiyou Timber Co. Ltd. in China. All boards were flat-sawn blanks, and their initial moisture contents (MCs) ranged from 9% to 13%. In the laboratory, 15 clear boards of each species were carefully selected for use in the study. To obtain a good comparison of the effects of heat treatment on the dielectric properties of wood, each board was cut and sawn into four end- and edge-matched rectangular samples, each measuring 70 mm in the tangential direction, and 250 mm along the grain. The 15 samples in each group, with four groups per species, were collected and randomly assigned for the following testing: three groups were applied to the next three heat-treatment experiments, and the remainder was used as the reference.

Methods of Heat Treatment and Conditioning

In accordance with the heat-treatment procedure described in a previous study (Cai *et al.* 2013), three heat-treatment experiments, with temperatures of 170, 185, and 200 °C, were conducted in a small modified laboratory variation of the high-temperature drying kiln, in which superheated vapor was used as both a protection gas and a heat transfer medium. The duration of each experiment was kept to a constant 3 h. Following the heat treatment, to provide a uniform surface on which to place the moisture meter for MC determination, all reference specimens were planed to a thickness of 20 mm. Then, three small cubic wood blocks, with edges of 20 mm, were obtained from one end of each sample to be used to determine the oven-dry density of the sample. The remains of each sample, with dimensions of 20 × 70 × 230 mm^3, were the specimens used for the MC determination.

The procedure of conditioning occurred as follows: all specimens were first oven-dried at 60 °C until the MC decreased below 3%. Then, they were placed successively in a laboratory conditioning chamber under four different environments until practical equilibrium was reached at each condition. To speed up the conditioning, the temperature used during this stage was higher than that of the ambient environment, as shown in Table 1. Prior to each MC determination, the specimens were re-conditioned in the conditioning chamber to the target MC at 25 °C and at various relative humidity levels. In this way, the duration of the equilibration of the specimens to each MC level was decreased to about two weeks, and it could also be ensured that the effects of temperature on the moisture meter reading at the time of testing were minimal.

Table 1. Environments Used for Equilibrating Specimen to Four MC Levels

No. of testing	First rapid conditioning of specimens			Second re-conditioning of specimens		
	Temperature °C	Relative humidity %	Estimated EMC for the reference %*	Temperature °C	Relative humidity %	Estimated EMC for the reference %
1	60	45	7.0	25	36	7.0
2	60	65	10.0	25	55	10.0
3	60	78	13.0	25	70	12.9
4	60	86	15.8	25	80	15.8

Note: The equilibrium moisture content (EMC) of the reference specimens at different temperatures and relative humidity levels was calculated based on a sorption model introduced by Simpson (1973).

Determination and Analysis of MC by Two Methods

A radio frequency-type PM1-E moisture meter (Merlin, Austria) was used in this study. The MC sensor plate is a 106 mm by 41 mm rectangle located on the backside of the meter. The meter can set the oven-dry density in the range of 0.30 to 1.10 g/cm^3 and the penetration depth of waves in the range of 2 to 40 mm according to the wood species and thickness, respectively. It is well known that the density of wood varies greatly within species. To adapt the density setting for each board would be cumbersome and not suitable for field use. Accordingly, the average oven-dry density of each group, as shown in Table 2, was used to calibrate the meter's density setting for each specimen in the group. At each of the four MC levels, the weight of each equalized specimen was first measured for the calculation of the oven-dry MC based on the standard procedure in ASTM D4442 (2007), and then one non-destructive MC measurement using the meter was made at the center of both planed faces of each specimen, which was supported on wooden sticks at both ends to provide an air gap underneath the specimen. The average value of the two meter readings from each specimen was recorded. Finally, each specimen was oven dried at 103 °C for 48 h, and its weight in the absolutely dried condition was measured and recorded.

Table 2. Average Oven-Dry Density of Each Group Determined and Used in the Measurement of MC Using a Moisture Meter

Group	Manchurian ash				Mongolian pine			
	The reference	170 °C	185 °C	200 °C	The reference	170 °C	185 °C	200 °C
Oven-dry density (g/cm^3)	0.61 (0.03)	0.60 (0.04)	0.59 (0.02)	0.57 (0.03)	0.35 (0.02)	0.35 (0.02)	0.34 (0.03)	0.32 (0.02)
Note: The value in parentheses is standard deviation based on 45 specimens.								

In accordance with previous studies (Shupe *et al.* 2002; Gillis *et al.* 2001; Wilson 1999; Wu 1997; Milota and Gupta 1996; Milota 1991), linear regression analysis was applied to assess the relationship between the MC values obtained by the oven dry method and those obtained using the meter. A regression equation was used to fit the scatter plot data points by the least squares method, with the oven-dry MC as the independent variable and the meter reading as the dependent variable. Its format was as follows:

$$\mathrm{MC_{meter}} = \mathrm{aMC_{oven-dry}} + \mathrm{b},$$

where a and b are the regression coefficients, *i.e.*, the slope and intercept, respectively, of the linear regression line.

The correction factors (CFs) for the species and heat treatment temperature were then calculated from the following equation:

$$\mathrm{CFs} = \mathrm{MC_{oven-dry}} - \mathrm{MC_{meter}} = \frac{\mathrm{MC_{meter}} - \mathrm{b}}{\mathrm{a}} - \mathrm{MC_{meter}} = \left(\frac{1}{\mathrm{a}} - 1\right)\mathrm{MC_{meter}} - \frac{\mathrm{b}}{\mathrm{a}}$$

RESULTS AND DISCUSSION

The plots of meter reading against oven-dry MC for the reference and heat-treated specimens are illustrated in Fig. 2 for Manchurian ash and Fig. 3 for Mongolian pine. The data points for each group of specimens on the graph are in four clusters, which correspond to four moisture content levels, as practical equilibrium was reached at four different moisture conditions. It is well known that the degradation of hemicelluloses in wood during heat treatment can reduce the amount of free hydroxyl groups that can easily gain moisture from the environment (Brito *et al.* 2008; Tjeerdsma and Militz 2005). As shown in the two graphs, Table 3, and Table 4, the MC of heat-treated wood was lower than that of conventional kiln-dried (reference) wood at the same moisture condition, and the difference increased with the temperature used in the heat treatment process. Meanwhile, it was noticeable that for the same heat treatment temperature, the decline in hygroscopicity was always higher for the heat-treated Manchurian ash specimens than it was for the Mongolian pine specimens; for example, the oven-dry MCs of the reference specimens and 185 °C heat-treated wood equilibrated with the 25 °C and 70% RH moisture environment were 12.75% and 9.12%, respectively, for Manchurian ash and 12.86% and 9.90%, respectively, for Mongolian pine. The results were similar to the conclusions drawn in previous works on the differences in mass loss between heat-treated softwood and hardwood (Aydemir *et al.* 2011; Pierre *et al.* 2011).

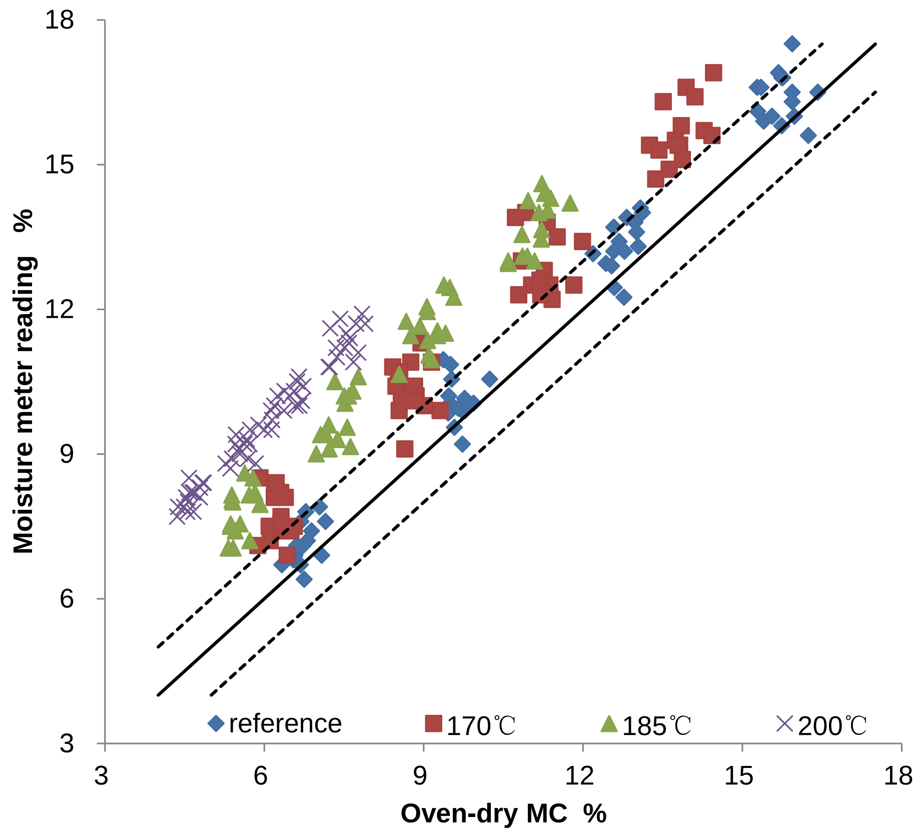

Fig. 2. Moisture meter reading *versus* oven-dry MC for the reference specimens and heat-treated wood of Manchurian ash

As shown in the results of the linear regression analysis (see Table 5), the coefficients of determination (R^2) for these different groups of specimens ranged from 0.9555 to 0.9805. The high coefficients of determination indicated that the linear regression equations for the heat-treated wood of Manchurian ash and Mongolian pine were quite suitable and that using the radio frequency-type moisture meter is a reliable method for non-destructively determining the MC of heat-treated wood with the same results as obtained with conventional kiln-dried wood. The straight line of y=x, which is the best and ideal fit for the calibration of moisture meters, would be fitted were the oven-dry MC measurement equal to the meter reading. However, as a general rule of thumb, the wood industry accepts an error range for the difference between electric moisture reading and actual MC (*i.e.*, oven-dry MC) of no more than ±1% (Milota and Gupta 1996), which corresponds to the area between the two dashed lines of y=x+1 and y=x-1 in Figs. 2 and 3.

Table 3. Average MC Value for Each Group of Manchurian Ash at Different Conditions by Two Methods

Relative Humidity of various conditions at 25 °C	Oven-dry Method				Radio frequency-type moisture meter			
	The reference	170 °C	185 °C	200 °C	The reference	170 °C	185 °C	200 °C
36%	6.75	6.24	5.55	4.62	7.14	7.73	7.79	8.09
55%	9.65	8.76	7.42	5.61	10.11	10.35	9.78	9.14
70%	12.75	11.24	9.12	6.44	13.33	12.93	11.64	10.09
80%	15.75	13.83	11.10	7.53	16.39	15.67	13.71	11.33

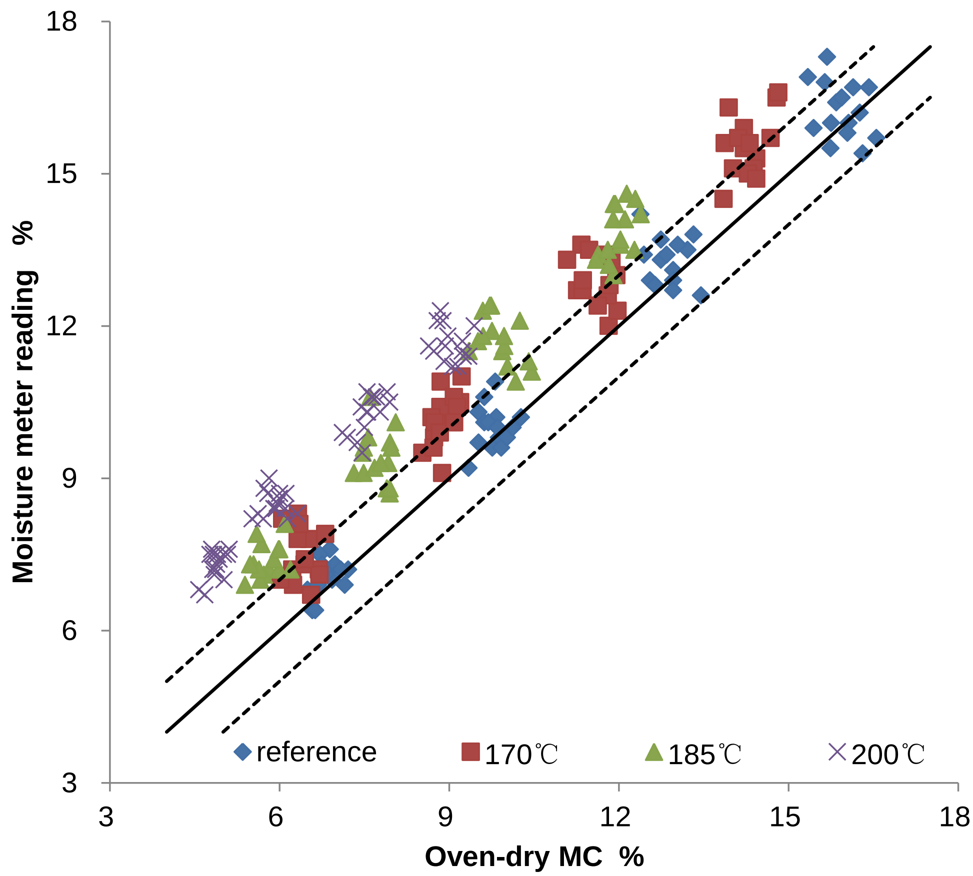

Fig. 3. Moisture meter reading *versus* oven-dry MC for the reference specimens and heat-treated wood of Mongolian pine

Table 4. Average MC Value for Each Group of Mongolian Pine at Different Conditions by Two Methods

Relative Humidity of various conditions at 25 °C	Oven-dry Method				Radiofrequency-type moisture meter			
	The reference	170 °C	185 °C	200 °C	The reference	170 °C	185 °C	200 °C
36%	6.83	6.40	5.78	4.87	7.06	7.53	7.38	7.29
55%	9.78	8.91	7.74	5.91	10.01	10.15	9.42	8.49
70%	12.86	11.62	9.90	7.56	13.25	12.92	11.70	10.26
80%	15.94	14.29	11.98	9.00	16.25	15.55	13.83	11.68

Table 5. Results of Linear Regression Analysis

Regression and coefficient of determination	Manchurian ash				Mongolian pine			
	The reference	170 °C	185 °C	200 °C	The reference	170 °C	185 °C	200 °C
a	1.0258	1.0368	1.0707	1.1044	1.0055	1.0125	1.0301	1.0376
b	0.2282	1.279	1.8466	2.9843	0.2257	1.1063	1.4662	2.3239
R^2	0.9805	0.9599	0.9651	0.9609	0.9757	0.969	0.9555	0.96

The scatter plot of data points shown in Figs. 2 and 3 and the linear regression equation for the reference (conventional kiln-dried) samples of Manchurian ash and Mongolian pine wood indicated that the meter reading need not be transferred and that the actual MC could be taken directly without any correction. At the same time, it is obvious that the data points corresponding to three temperatures of heat-treated wood of the two species are scattered outside the above-mentioned area. Some possible mechanisms for the difference between the kiln-dried and heat-treated wood could be partially explained as follows:

a. In previous related research on the relationships between wood and moisture it was concluded that the most stable bonds were between the wood cell walls and mono-molecular moisture (Skaar 1988), which would have no positive contribution to the dielectric parameters of moist wood (Torgovnikov 1993). Because the hydroxyl group sites, which can easily be occupied by primary water, decrease during the heat treatment process (Brito *et al.* 2008; Tjeerdsma and Militz 2005), the ratio of monomolecular moisture to total moisture in heat-treated wood should decline, and consequently, the whole dielectric constant of heat-treated wood will be larger than that of kiln-dried wood at the same MC.
b. Certain chemical reactions occur during the heat treatment process (Esteves and Pereira 2009), and some new substances, such as furfural (Peters *et al.* 2008), formic acid (Sundqvist *et al.* 2006), and methanol (Bourgois and

Guyonnet 1988), have been observed to form in wood. At 20 °C, the dielectric constants of these substances are about 42, 57, and 34, respectively (Gokel 2004), far higher than that of oven-dried wood, of which the dielectric constant was recorded to be only 2 (Skaar 1988). The free radicals that formed (Ahajji *et al.* 2009), the decreased pH values, and the increasing acidity of wood caused by the heat treatment process (Awoyemi *et al.* 2009) also promote the interaction between heat-treated wood and the external electric field.

These factors, dominated by the heat treatment temperature, had an integrative influence on the meter's reading for heat-treated wood, resulting in higher readings by the moisture meter relative to the measurements gained by the oven-dry MC method, a difference that increased with heat treatment temperature, as shown in Tables 3 and 4. Therefore, to accurately acquire the MC of heat-treated wood using the radiofrequency-type moisture meter, the corrections factor for the meter reading, tabulated in Table 6, should be pre-calculated by subtracting the predicted value of the regression equation from the oven-dry MC and then by applying this value to the meter reading. For example, if a 12% MC reading was obtained from the moisture meter placed on the 185 °C heat-treated ash wood, then the actual MC could be obtained as 12 - 2.52 = 9.48%.

Table 6. Correction Factors for Heat Treatment Temperature and Species Used

Moisture meter reading %	Manchurian ash				Mongolian pine			
	The reference	170 °C	185 °C	200 °C	The reference	170 °C	185 °C	200 °C
7	-0.40	-1.48	-2.19	-	-0.26	-1.18	-1.63	-2.49
8	-0.42	-1.52	-2.25	-3.46	-0.27	-1.19	-1.66	-2.53
9	-0.45	-1.55	-2.32	-3.55	-0.27	-1.20	-1.69	-2.57
10	-0.47	-1.59	-2.38	-3.65	-0.28	-1.22	-1.72	-2.60
11	-0.50	-1.62	-2.45	-3.74	-0.28	-1.23	-1.74	-2.64
12	-0.52	-1.66	-2.52	-3.84	-0.29	-1.24	-1.77	-2.67
13	-0.55	-1.70	-2.58	-	-0.30	-1.25	-1.80	-
14	-0.57	-1.73	-2.65	-	-0.30	-1.27	-1.83	-
15	-0.60	-1.77	-	-	-0.31	-1.28	-	-
16	-0.62	-1.80	-	-	-0.31	-1.29	-	-

From Table 6, as expected from the results of the slopes and intercepts of wood heat-treated at different temperatures listed in Table 5, it can be seen that the absolute value of correction factors ranged from 1.18% to 3.84%, with the absolute value increasing as heat treatment temperature increased. Meanwhile, it was also evident that the absolute value of correction factors for heat-treated Manchurian ash specimens were always higher than those for heat-treated Mongolian pine specimens at the same meter reading and heat treatment temperature, *e.g.*, 3.65% *versus* 2.60% for 200 °C heat-treated wood that produced a 10% meter reading. The result was the same regarding the above-mentioned differences in the decline of hygroscopicity between the heat-treated woods of these two species. As Aydemir *et al.* (2011) and Pierre *et al.* (2011) pointed out, at the same heat-treatment conditions, the effects of the treatment on the wood properties of softwood and hardwood were different. This may have been due to the differences in the proportions, especially regarding hemicelluloses, of the wood chemical compositions that are more susceptible to thermal degradation during the heat treatment process.

CONCLUSIONS

1. The radio frequency-type moisture meter readings were higher than the actual MCs for the heat-treated wood. The difference increased with heat treatment temperature, and the difference was always higher for hardwood than it was for softwood. The different effects of heat treatment on the wood properties because of the different chemical compositions of the woods could be seen as the main reason for the observed difference.
2. Based on the fact that correction factors can be previously determined, it may be feasible to use the radio frequency-type moisture meter for a determination of the actual MC of heat-treated wood.
3. In contrast to kiln-dried wood, heat treatment condition, in addition to wood species and density, should also be taken into consideration for the calibration of moisture meters for heat-treated wood.

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