Investigation of Electrical Characteristics Using Various Electrodes for Evaluating the Moisture Content in Wood

Sung-Wook Hwang,[a] Sung-Yun Hwang,[b] Taekyeong Lee,[a] Kyung-Sun Ahn,[c] Sung-Jun Pang,[a] Jinseok Park,[c] Jung-Kwon Oh,[a,b,c] Hyo Won Kwak,[a,b,c] and Hwanmyeong Yeo [a,b,c,]*

Electrical resistance and resistivity were measured with various types of electrodes to evaluate the moisture content of wood. The conventional two-pin method, electrically conductive fabrics, and multi-pin electrodes were used to measure the electrical resistance of Japanese larch (*Larix kaempferi*) wood, and a four-pin probe was used for resistivity measurements. The resistance in the longitudinal direction measured with the two-pin electrode was slightly affected by the dimensions of the wood sample, whereas the resistance measured with the conductive fabric and multi-pin electrodes was clearly affected by the end surface area in contact with the electrode and the length between electrodes. The resistivity calculated from the relationship between the electrical resistance and sample dimensions also showed differences based on the sample dimensions. The least squares regression model trained with the resistance data based on the two-pin method predicted the moisture content with a high coefficient of determination of 0.986. The four-pin probe produced the most stable resistivity regardless of the sample dimensions, making it a feasible approach for the moisture evaluation of large wood members.

Keywords: Electrical resistance; Electrode; Four-point probe; Moisture content; Resistivity

Contact information: a: Research Institute of Agriculture and Life Sciences, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea; b: Department of Forest Sciences, College of Agriculture and Life Sciences, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea; c: Department of Agriculture, Forestry and Bioresources, College of Agriculture and Life Sciences, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea;
** Corresponding author: hyeo@snu.ac.kr*

INTRODUCTION

Wood is a hygroscopic material that repeatedly shrinks and swells depending on atmospheric conditions. Dimensional changes caused by high moisture levels or moisture gradients in wood cause stress inside the wood, which is relieved by the formation of cracks (Dietsch *et al.* 2015). In addition, the high moisture content (MC) is a cause of decay and fungi (Kirker *et al.* 2016; Won *et al*. 2016). Therefore, accurate moisture evaluation and monitoring are required to secure and maintain the stability of wooden structures, which are being built larger with the developments in wood engineering.

Electrical methods, such as electrical resistance and high-frequency moisture meters, are most widely used to evaluate moisture in wood. High-frequency moisture meters measure MC (%) using the relationship between moisture and the dielectric constant or power loss of wood (Forsén and Tarvainen 2000; Kang *et al*. 2017). Although this approach allows for non-destructive measurements, it is difficult to determine the moisture gradient inside the wood and is relatively expensive. Various attempts, including near-infrared spectroscopy, have been made to measure the MC of wood (Eom *et al*. 2010; Chang *et al*. 2015; Yang *et al*. 2015; Reci *et al*. 2016), but they have technical and cost limitations for field applications. Therefore, electrical resistance-based methods are mainly used for MC monitoring in the management of wooden structures and the process of wood drying (Brischke *et al*. 2008; Franke *et al*. 2016; Hasfa *et al*. 2021).

Electrical resistance quantifies how strongly a material opposes the flow of electrons. The relationship between moisture and electrical resistance in wood has been used to measure MC for many years (Stamm 1927; Skaar 1988). The mechanism of electrical conduction in wood depends on the presence of ions, that is, the charge carrier. Lin (1965) reported that the number of charge carriers in wood is a major factor influencing electrical conductivity at MCs below 20%, and ionic mobility becomes a factor determining conductivity at a high MC level. The resistance has been investigated not only for moisture evaluation under various climatic conditions (Lebow and Lebow 2015; Nursultanov *et al*. 2017) but also for decay and fungi (Shortle and Smith 1987; Kirker *et al*. 2016). Long-term monitoring of moisture changes in wooden structures based on electrical resistance methods have been performed (Brischke *et al*. 2008; Björngrim *et al*. 2016; Franke *et al*. 2016), and improved electrodes have been proposed to perform the methods more effectively (Brischke *et al*. 2008; Fredriksson *et al*. 2013; Björngrim *et al*. 2016; Otten *et al*. 2017; Li *et al*. 2018).

Recently, a method for measuring wood MC using a four-point probe (4PP) has been reported (Hasfa *et al*. 2021). This method measures the electrical resistivity, which is the intrinsic electrical property of the material, regardless of the material dimensions. The 4PP method was proposed by Wenner (1916) to solve the inherent inaccuracy of the contact resistance of the electrodes of the two-pin (2P) method. The 4PP method is widely used in geophysics and geological investigations, such as electrical resistivity surveys (Meidav 1960; Fukue *et al*. 1999; Bevan 2000; Arshad *et al*. 2007) and has also been used to measure the resistivity of semiconductor wafers (Valdes 1954; ASTM 1990; Mackenzie *et al*. 2020). This method has also been applied to detect decay and hollows in living trees (Soge *et al*. 2019).

In this study, to initially develop a MC monitoring system for large wood members, electrical resistance was investigated with various types of electrodes to measure the internal MC of the wood. In addition, the potential of the electrical resistivity-based method using 4PP was explored, and considerations for applying electrodes to large members were discussed.

EXPERIMENTAL

Materials

Sample preparation and humidification

Japanese larch (*Larix kaempferi*) wood blocks were obtained from the Jungbu Lumber Distribution Center (Yeoju-si, Korea) and were prepared to measure electrical resistance. This species is widely used as a structural member for construction in Korea. The wood samples were cut into lengths of 2, 4, and 6 cm with end surface areas of 1 cm^2 (1 cm × 1 cm) and 4 cm^2 (2 cm × 2 cm) to measure the change in electrical resistance with dimensional change. In addition, the samples were cut in three orthogonal directions—

longitudinal, radial, and tangential—to investigate the anisotropy of electrical resistance induced by the structural direction of the wood. Three samples were prepared with the same dimensions in each structural direction.

To adjust the sample's moisture level, the samples were placed in a climate chamber and conditioned stepwise under the conditions listed in Table 1, corresponding to the equilibrium moisture content (EMC) range of 5.7 to 13.4%. Several low- and high-relative humidity (RH) conditions at temperatures of 10 °C and 40 °C, respectively, were excluded due to the operational limitations of the chamber. When the wood samples reached a constant weight under each environmental condition, the electrical resistance was measured from the samples in the chamber. The electrical characteristics of various electrodes were compared at 15 ℃, which is closer to the annual normal (12.5 ℃) of Seoul, Korea among the temperature tested (Korea Meteorological Administration 2011).

Table 1. Equilibrium Moisture Content (%) Under the Environmental Conditions Tested

Equilibrium Moisture Content (%)				
RH (%)	**Temperature (°C)**			
	10	**15**	**25**	**40**
30	-	6.3	6.1	5.7
40	-	7.8	7.6	7.1
50	9.5	9.4	9.1	-
60	11.2	11.1	10.8	-
70	13.4	13.3	12.9	-

Electrical Resistance Measures

Three different types of electrodes were used to measure the electrical resistance: 2P, electrically conductive fabric (ECF), and multi-pin (MP) (Fig. 1).

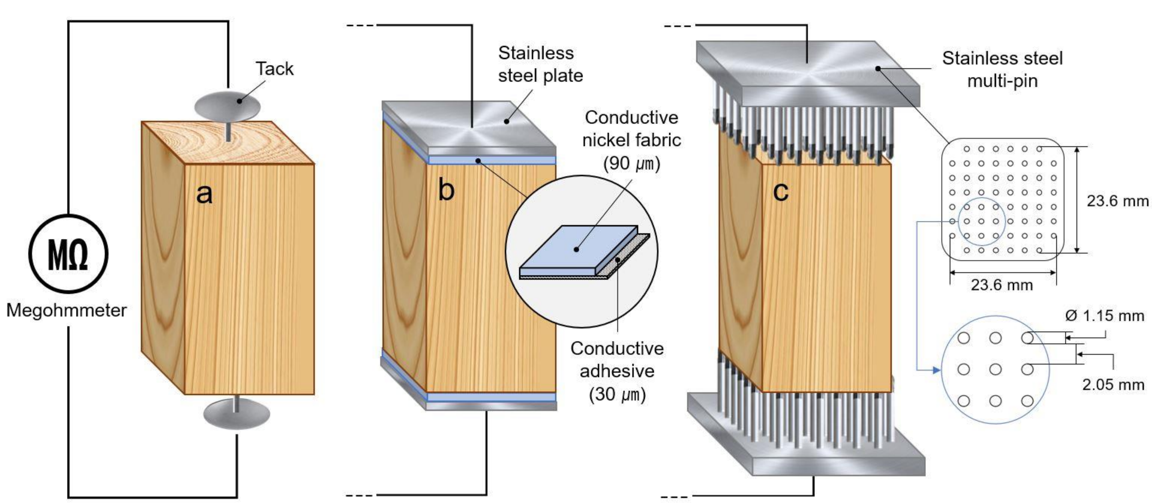

Fig. 1. Three types of electrodes were used to measure the electrical resistance of wood samples: (a) Point-to-point measurement using thumbtacks, face-to-face measurements using electrically conductive fabrics (b), and multi-pin electrodes (c)

The 2P method (Fig. 1a) was used for the point-to-point measurement of electrical resistance by inserting stainless-steel thumbtacks to a depth of 2 mm at both end surfaces of the sample, and ECF (Fig. 1b) and MP (Fig. 1c) electrodes were used for face-to-face measurements. The ECF (ST-610R; Daehyun ST Co., Ltd., Hwaseong-si, Korea) was made of nickel fabric with a thickness of 90 μm and was attached to the wood by a 30-μm-thick conductive adhesive layer. To measure the resistance, stainless steel plates were placed on both fabric layers to ensure close contact with the sample. The sheet resistance of the ECF was less than 0.02 Ω/cm^2. The MP consisted of 1.15 mm diameter stainless-steel pins arranged in a square at 2.05 mm intervals, covering a 23.6 mm × 23.6 mm area.

A super megohmmeter (SM-8220; HIOKI E. E. Corp., Nagano, Japan) with a maximum measurement range of 2×10^{16} Ω was employed to measure the electrical resistance of the wood samples. The megohmmeter measured the current (I) flowing through the wood using a constant direct current (DC) voltage (V) with a built-in high-precision ammeter and calculated the electrical resistance (R) according to Ohm's Law ($R = V / I$). The resistance was measured in a climate chamber to maintain a constant moisture level of the sample. The 2P method was used for electrical resistance measurements at all temperatures presented in Table 1, and the others were used only at 15 °C.

Model for Predicting Moisture Content

Least squares regression (LSR) was used to build a model for predicting MC. A prediction model that outputs MC (%) was established using the electrical resistance values measured by the 2P method under all climate conditions as input data. The model was validated by leave-one-out cross-validation (Hastie *et al*. 2009). The program for the LSR model was written in Python 3.8.3.

4PP Method

The 4PP method with the Wenner array (Reynolds 2011) was employed to measure the electrical resistivity in three orthogonal directions of the wood samples. The resistivity in the longitudinal and radial directions was measured in the radial section, and the tangential resistivity was measured in the tangential section. As shown in Fig. 2, this method calculates the resistivity by contacting the sample with four equally spaced in-line electrodes and measuring the voltage V between the two inner electrodes, while the current I is injected into the sample through the two outer electrodes.

The electrical resistance is expressed in the macroscopic form of Ohm's law,

$$R = \frac{V}{I} \tag{1}$$

where R is the resistance of a material in units of ohms, V is the voltage measured across the material in V, and I is the current through the material in units of amps. The resistance of the material is defined by the resistivity (ρ), length of the material (l), and cross-sectional area of the material (A), as shown in the equations below:

$$R = \rho \frac{l}{A} \tag{2}$$

$$\rho = \frac{RA}{l} \tag{3}$$

For bulk materials, such as wood, the current travels in a hemispherical shape from the electrode placed on the surface of the bulk material (Fig. 2); thus, the shell area (A) of the injected current becomes $2\pi r^2$, where r is the horizontal distance (cm) between the electrodes. Because wood is electrically anisotropic, current transfer in wood may appear in deformed shapes depending on the structural direction rather than the ideal hemispherical shape assumed by the conventional 4PP method, but this study followed the basic theory for electrical resistivity surveys. The electrical resistance R is expressed by the following equations,

$$\text{if } l = x \rightarrow dl = dx$$

$$dR = \rho \frac{dx}{A}$$

$$R = \int_{x_1}^{x_2} \rho \frac{dx}{A} = \rho \int_{x_1}^{x_2} \frac{dx}{2\pi x^2} = \frac{\rho}{2\pi}\left[-\frac{1}{x}\right]_{x_1}^{x_2} = \frac{\rho}{2\pi}\left[-\frac{1}{2s} + \frac{1}{s}\right] = \frac{\rho}{4\pi s} \quad (4)$$

where s is the spacing (cm) between electrodes. The current values of both outer probes are $+I$ and $-I$, so the resistance R is as follows by Ohm's law in Eq. 1.

$$R = \frac{V}{2I} \quad (5)$$

From Eqs. 4 and 5, the resistivity ρ is calculated using the following equation:

$$\rho = 2\pi s \frac{V}{I} \quad (6)$$

In this study, a current was injected into the sample through the two outer electrodes at a constant voltage of 50 V from a megohmmeter, and the resistance between the two outer electrodes was measured. The current I was calculated from voltage V and resistance R using Ohm's law ($I = V / R$). The voltage V between the two inner electrodes was measured using a digital multimeter (CDM-03D; CUSTOM Corp., Tokyo, Japan), and the spacing between the electrodes was 2 mm. In rare cases where the voltage V displayed on the multimeter was unstable, a voltage boosted to 100 V was injected from a megohmmeter.

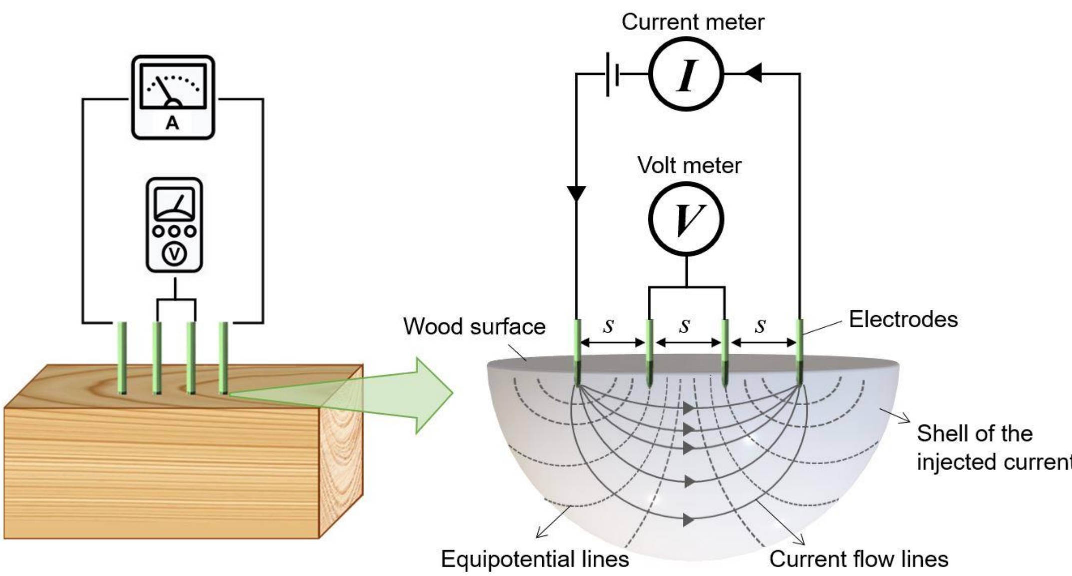

Fig. 2. Diagram of a four-point probe method with the Wenner array for measuring electrical resistivity of wood; *s*- spacing between electrodes

RESULTS AND DISCUSSION

Electrical Resistance

Point-to-point measurement

The electrical resistance of Japanese larch wood measured by the 2P method at 15 °C is shown in Fig. 3. The resistance in the longitudinal direction decreased exponentially as the MC increased so that the resistance corresponding to the EMC range of 6.3 to 13.3% was 1.67×10^6 – 2.53×10^3 MΩ (Fig. 3a). According to Eq. (2), the resistance was inversely proportional to the end surface area *A* in contact with the electrode and proportional to the length *l* between the electrodes. However, as shown in Fig. 3, the samples with (*A*) 1 cm^2 and (*l*) 6 cm, the smallest *A* (cm^2) and longest *l* (cm), respectively, had the highest resistance values, but the remaining samples had similar resistances.

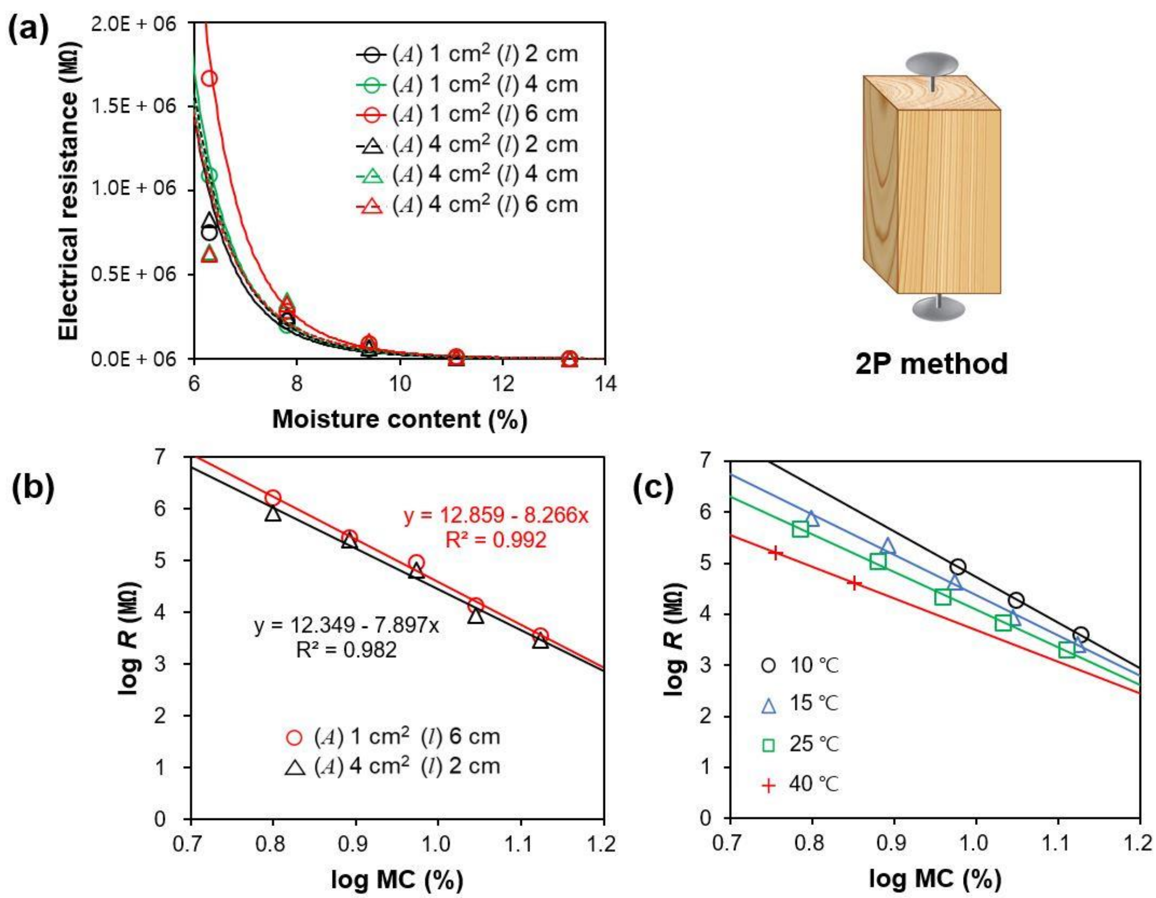

Fig. 3. (a) Electrical resistance in the longitudinal direction as measured by the two-pin method at a temperature of 15 °C, (b) relationship between electrical resistance and moisture content, and (c) effect of temperature [*A*, end surface area (cm^2) of the sample in contact with the electrode; *l*, length (cm) of the sample; *R*, electrical resistance; MC, moisture content; and R^2, coefficient of determination]

Several studies have proposed a regression model in the form of log *R* = *a* + *b* log *M* from the relationship between MC and electrical resistance (Stamm 1927; Norberg 2000; Fredriksson *et al*. 2013; Li *et al*. 2018), where *R* is the electrical resistance, *M* is the moisture content, and *a* and *b* are empirical constants depending on the species. Figure 3b shows the relationship between MC and *R* on a logarithmic scale in the longitudinal direction. The regression equation for (*A*) 1 cm^2 (*l*) 6 cm samples was log *R* = 12.859 – 8.266 log *M*, and that for (*A*) 4 cm^2 (*l*) 2 cm samples was log *R* = 12.349 – 7.897 log *M* (Table 2). The coefficients of determination (R^2) for the regression lines were 0.992 and 0.982, respectively. The regression lines for the samples with different dimensions were located between the two lines.

Table 2. Regression Equations and R^2 values Between Electrical Resistance and Moisture Content Measured by the 2P Method at a Temperature of 15 ℃

Sample	Regression Equation	R^2
(*A*) 1 cm^2 (*l*) 2 cm	log *R* (MΩ) = 12.410 – 8.030 log *M*	0.977
(*A*) 1 cm^2 (*l*) 4 cm	log *R* (MΩ) = 12.575 – 8.146 log *M*	0.991
(*A*) 1 cm^2 (*l*) 6 cm	log *R* (MΩ) = 12.859 – 8.266 log *M*	0.992
(*A*) 4 cm^2 (*l*) 2 cm	log *R* (MΩ) = 12.349 – 7.897 log *M*	0.982
(*A*) 4 cm^2 (*l*) 4 cm	log *R* (MΩ) = 11.875 – 7.323 log *M*	0.951
(*A*) 4 cm^2 (*l*) 6 cm	log *R* (MΩ) = 11.754 – 7.192 log *M*	0.950

The resistance decreased with increasing temperature. The effect of temperature was dependent on the MC (%), and the resistance tended to decrease approximately two-fold when the temperature increased 10 °C (Fig. 3c). The ionic mobility, a factor affecting electrical conductivity, is highly dependent on temperature, and ions are more active at higher temperatures (Bard and Faulkner 2001). Therefore, the decrease in electrical resistance with increasing temperature resulted from the increased ionic mobility of moisture in the wood.

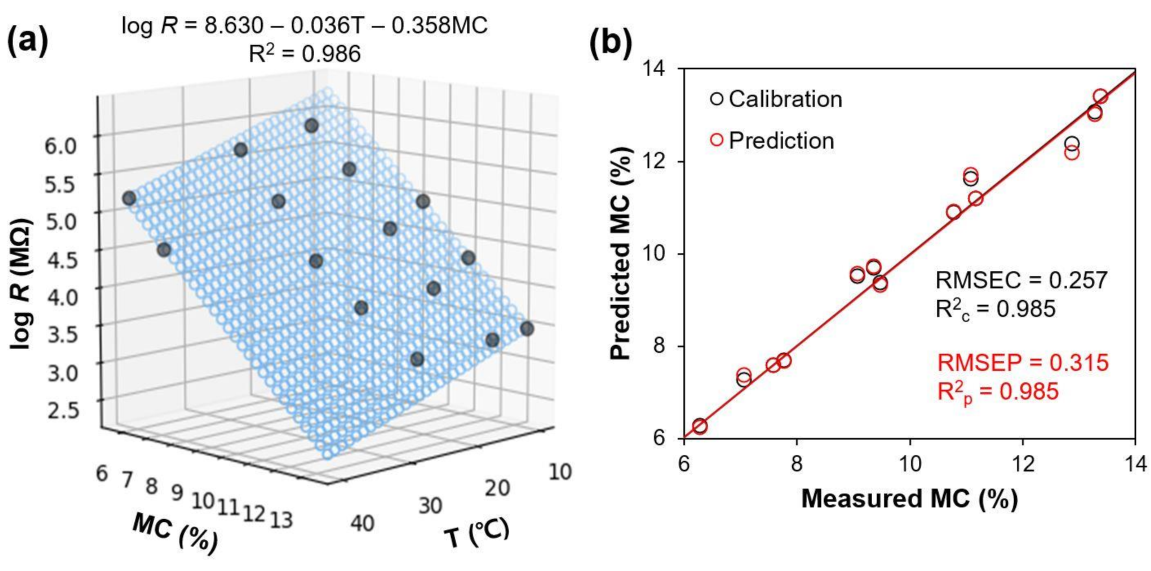

Fig. 4. (a) Relationship among electrical resistance, moisture content, and temperature and (b) Scatter plot for prediction result on moisture content [*R*, electrical resistance; MC, moisture content; *T*, temperature; and R^2, coefficient of determination; R^2_c, R^2 for calibration; R^2_p, R^2 for prediction; RMSEC, root mean squared error (RMSE) for calibration; RMSEP, RMSE for prediction]

Prediction model

The relationship between the electrical resistance, MC, and temperature of the (*A*) 1 cm^2 (*l*) 2 cm samples based on the 2P method is presented in Fig. 4a. From the relationship, it is clear that the resistance decreased as the temperature and MC increased. The R^2 of the regression plane across the given data points was 0.986. The LSR model trained with MC and temperature data also demonstrated high performance for predicting MC, with an R^2 of 0.985 (Fig. 4b and Table 3). These results suggest that the LSR model can predict the MC of Japanese larch wood with high precision under the climatic conditions tested.

Table 3. Regression Equation Among Electrical Resistance, Moisture Content, and Temperature, and Prediction Performances of the Regression Model

Sample	Regression Equation	Prediction Results			
		RMSEC	R^2_C	RMSEP	R^2_P
(*A*) 1 cm^2 (*l*) 2 cm	log *R* (MΩ) = 8.630 – 0.036T – 0.358MC	0.257	0.985	0.315	0.985

Face-to-face measurement

Figure 5 shows the electrical resistances measured by the ECF electrodes. The resistance values were divided into two groups according to the end surface area *A* of the sample (Fig. 5), in contrast to those measured by the 2P method.

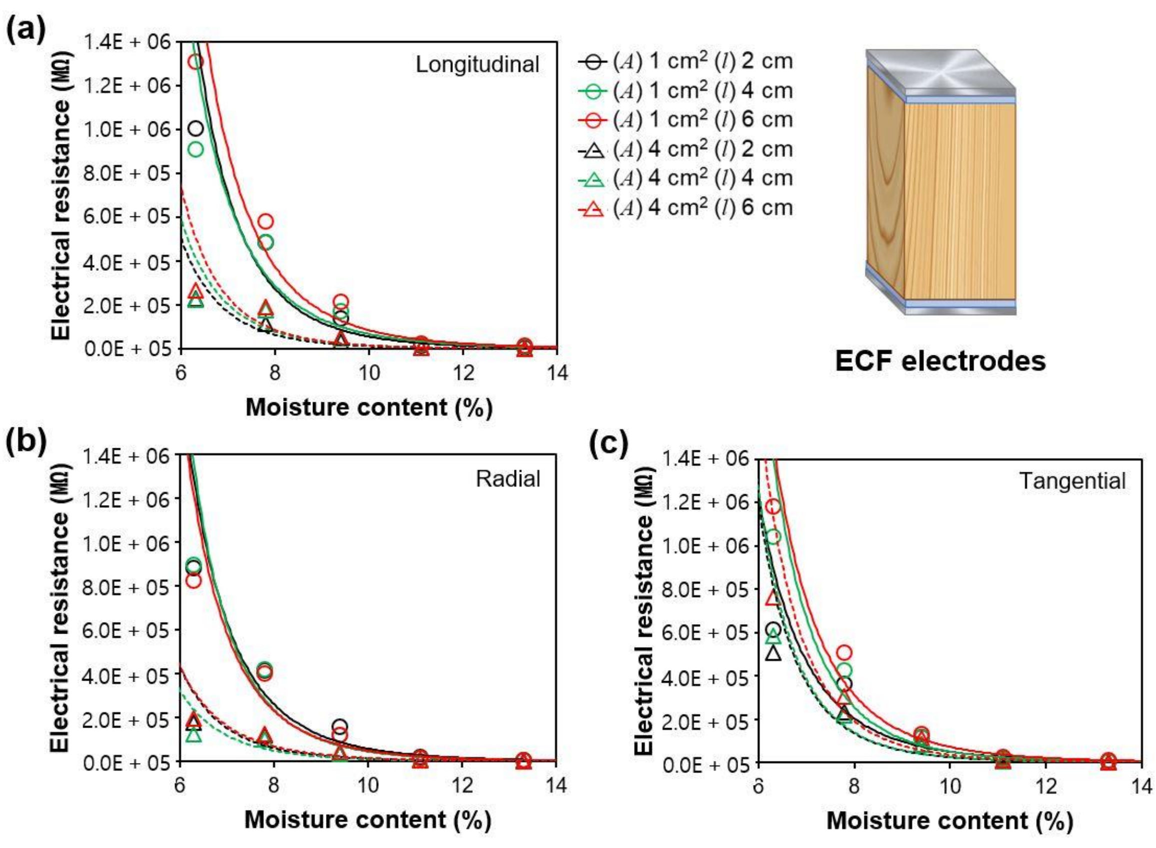

Fig. 5. Electrical resistance in three orthogonal directions, (a) longitudinal, (b) radial, and (c) tangential, measured with electrically conductive fabric electrodes

In the 2P method, there was practically no difference in *A* because only one needle-like electrode was in contact with the end surface, whereas the ECF electrode covered the entire surface; thus, the resistance was substantially different because of the difference in *A*. In the ECF method, a decrease in resistance with increasing *l* was also observed, but its effect was less than that of *A*.

The effect of *A* was observed in all three orthogonal directions, and the difference was obvious in the radial direction with the least effect of *l* (Fig. 5b). This was attributed to the inherent anatomy in the radial direction across annual rings. Latewood (LW) has a higher cell wall ratio and a lower water ratio than earlywood (EW), although it does not make a remarkable difference in EMC (Domec and Gartner 2002). This can lead to anisotropic electrical conductivity between EW and LW. In contrast to the longitudinal and tangential directions in which EW and LW are continuously arranged between the electrodes in the radial direction, the current travels across the EW and LW arranged alternately. Therefore, the electrical anisotropy between EW and LW might have been offset, resulting in a large difference in resistance by *A*.

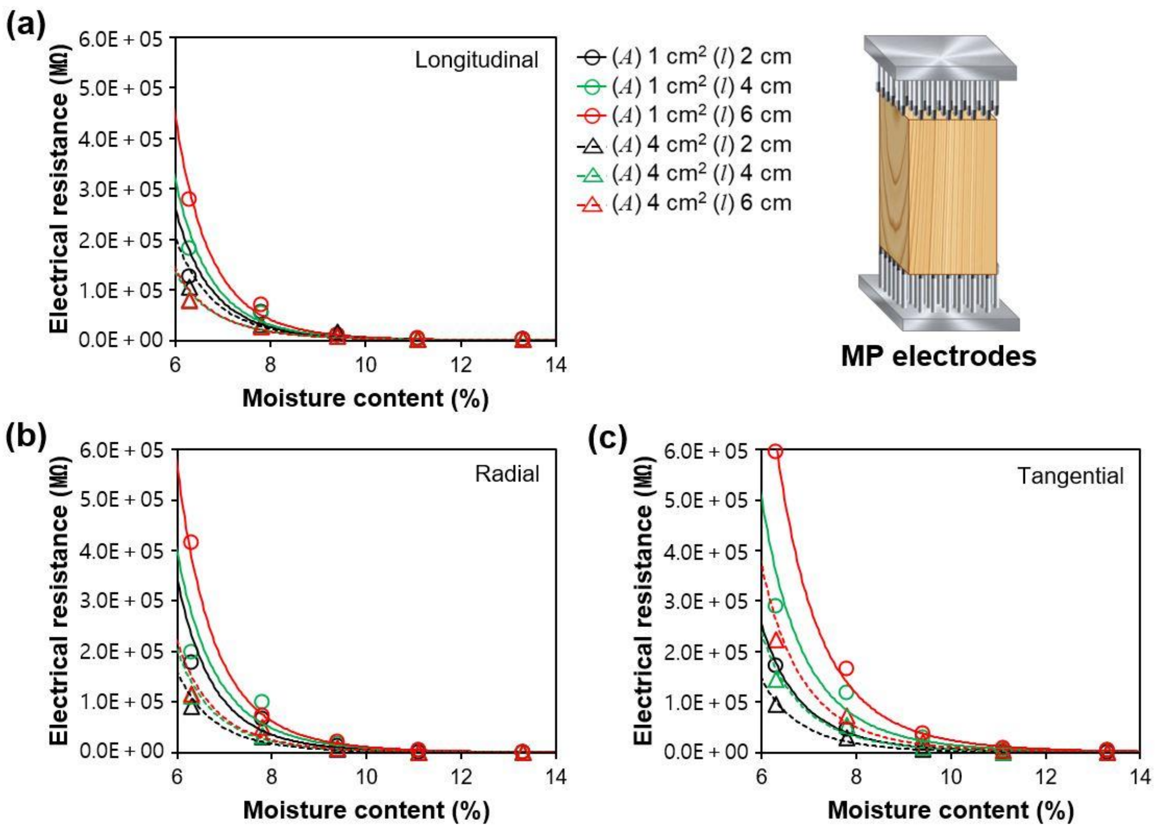

Fig. 6. Electrical resistance in three orthogonal directions, (a) longitudinal, (b) radial, and (c) tangential, measured with multi-pin electrodes

The resistance in the tangential direction was less affected by *A* than in the other directions, but the effect of *l* was larger (Fig. 5c). In addition, the tangential direction exhibited greater resistance than the others. This was attributed to the absence of continuous cell wall structures, such as vessels and rays, in the tangential direction.

The continuity of electrical conduction paths affects the electrical conductivity of the wood (Skaar 1988; Nursultanov *et al*. 2017). From a percolation model established to account for electrical conduction in wood (Zelinka *et al*. 2008), it was reported that the critical moisture fraction required to form a continuous path of capillary water in wood was 16% MC. The EMC range of 5.7 to 13.4%, corresponding to the environmental conditions tested in this study, was below that critical fraction, suggesting that there are no continuous paths for loosely bound or capillary water. In addition, high resistance in the tangential direction implies more path breaks. Zelinka *et al*. (2016) reported that the electrical resistance of the S2 layer decreased more rapidly than that of the middle lamellae with increasing RH, which could explain the anisotropy of electrical resistance by structure direction in terms of ion mobility and path continuity.

Figure 6 shows the resistance of the wood samples measured with MP electrodes in three orthogonal directions at 15 °C. The resistance was influenced by both *A* and *l*, unlike the 2P and ECP methods, which decreased with an increase in *A* and a decrease in *l* in all directions. The resistance was highest in the tangential direction, and those in the longitudinal and radial directions were similar to each other so that the anisotropy due to the structural direction was similar to that of the ECF method.

Resistivity

Electrical resistivity is the intrinsic property of a material that resists the flow of an electric current. In contrast to the electrical resistance shown in Eq. 2, the resistivity has the same value for the same material, regardless of its dimensions. Factors affecting the DC resistivity of wood include MC, temperature, structural orientation, and species. Clark and Williams (1933) reported that the DC resistivity of oven-dried wood was 10^{18} Ω·cm.

The resistivities measured by ECF, MP, and 4PP are presented in Fig. 7. The resistivities of ECF and MP were calculated using Eq. 3 from their electrical resistance values, and the resistivity of 4PP was calculated using Eq. 6 from the current, voltage, and spacing between the electrodes. The difference in resistance in the ECF, which showed a large difference depending on the end surface area *A*, was noticeably reduced as it was converted to resistivity, whereas the difference due to the length *l* was increased (Fig. 7a). Except for the tangential direction, the resistivity of MP showed a large difference due to the sample dimensions, especially *A* (Fig. 7b). These results show that the resistance measured with the ECF and MP electrodes did not increase or decrease in exact proportion to *A* and *l*, as shown in Eq. 2.

In contrast, for the 4PP method, the difference in resistivity between *A* and *l* and the standard deviation between samples with the same dimensions were greatly reduced. The electrical anisotropy induced by the structural direction was reconfirmed by producing larger resistivities in the tangential direction than in the others, and this tendency was also the same for the ECF and MP electrodes. These results suggest that the 4PP method can measure the resistivity of wood more reliably than other electrodes and is a promising tool for evaluating moisture in wood. The potential of the 4PP method for moisture gradient evaluation has also been reported in a study on the resistivity of Douglas fir (Hafsa *et al*. 2021).

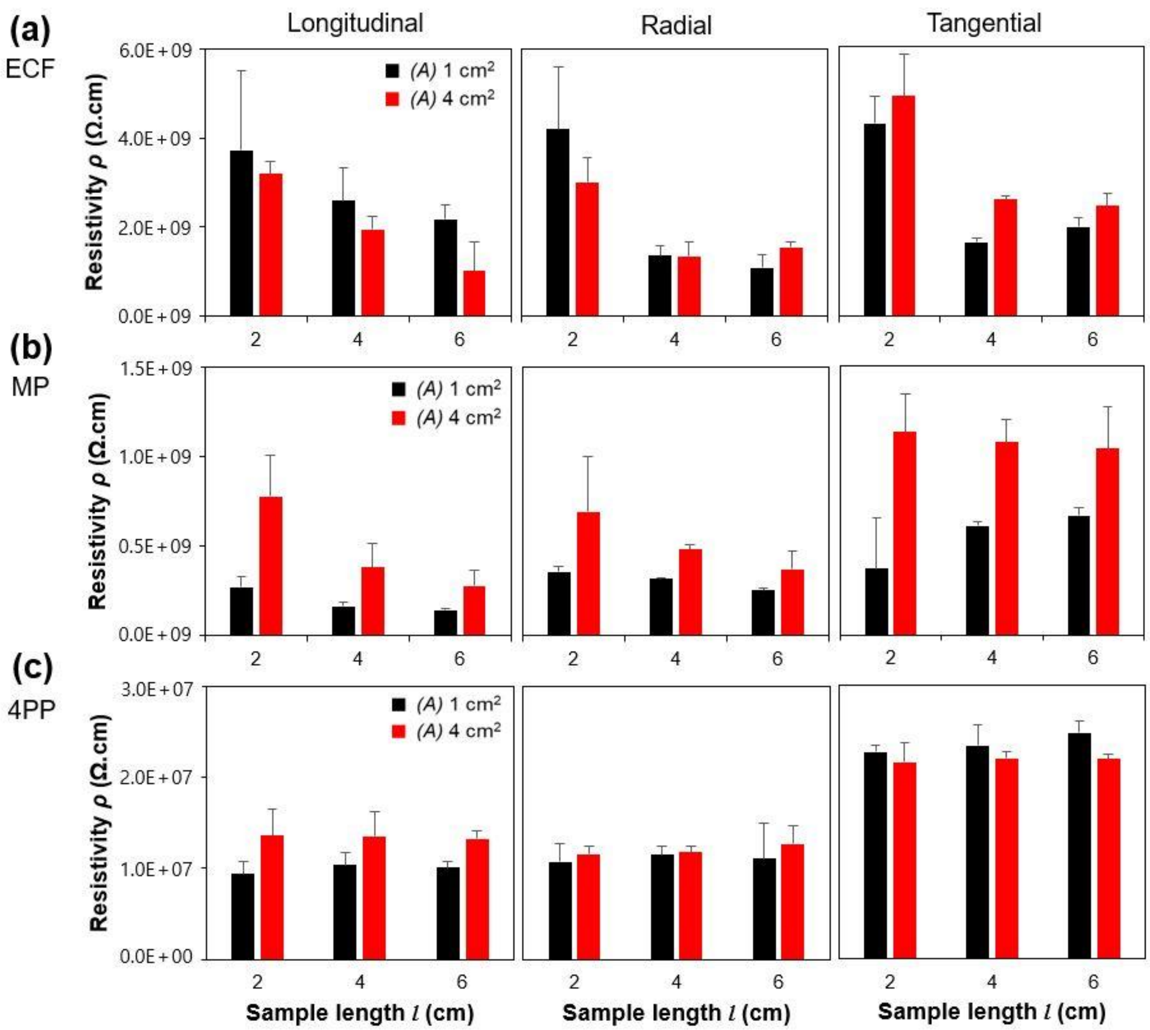

Fig. 7. Electrical resistivity of wood samples conditioned at a temperature of 15 °C with 70% relative humidity measured with (a) electrically conductive fabric, (b) multi-pin, and (c) four-point probe methods [ECF, electrically conductive fabric; MP, multi-pin; 4PP, four-point probe; and *A*, end surface area of the sample in contact with the electrode]

Considerations for Application in Moisture Meters

Compared with the dielectric-based moisture meter, the electrical resistance-based moisture meter has the advantage of determining the moisture gradient of wood by varying the insertion depth of the electrodes, even though precise control of the insertion depth is a challenge. It is necessary to investigate the internal moisture gradient to monitor the drying process of large-diameter logs or the moisture changes of large wood members. For this purpose, the 2P method based on electrical resistance has been widely used. Compared with the 2P method, the ECF and MP electrodes cover a larger area, which may reduce bias due to local measurement, but it is more difficult to install the electrodes into the wood. They can be used as surface electrodes (Moron *et al*. 2016; Li *et al*. 2018), but this is not a validated approach for determining the moisture gradient.

Electrical resistance-based methods, including the 2P method, have practical difficulties in measuring the internal MC of large wood members because the measurable depth completely depends on the length of the electrode. For example, a 2P moisture meter requires the insertion of two electrodes into the wood at the same depth at a certain distance. Therefore, the depth at which the MC can be measured is limited to the length of the electrode. Even if the electrode has a length of 10 to 20 cm or more, it is practically difficult to insert the two electrodes in-line into a large member at a predetermined distance and depth. The anatomical features, such as the spiral grain, which is common in Japanese larch used in this study, make it more difficult.

In this regard, the resistivity-based MC measurement using 4PP is a promising method for application to large wood members. Because micro 4PP operates with only one electrode, there are relatively few technical limitations for installing the electrode inside the wood. For the application of 4PP, it is necessary to discuss efficient electrode configurations and designs. Hafsa *et al*. (2021) investigated three-electrode configurations for 4PP: Wenner alpha, Wenner beta, and Wenner gamma. They reported that the Wenner beta configuration was the most similar to the results of the numerical model with the smallest deviations. The greater the distance between the electrodes, the deeper the injected current flows (Herman 2001). If the electrodes are too far apart, then it is difficult to evaluate the moisture gradient, and four pins cannot be implemented in one probe. This means that each of the four pins must be individually inserted into the wood, making it difficult to place the pins in the intended position deep inside the large wood member, as in the 2P method. Therefore, the 4PP probe needs to be miniaturized.

Several pin-type electrodes have been proposed for efficient MC monitoring (Norberg 2000; Fredriksson *et al*. 2013; Li *et al*. 2018; Hafsa *et al*. 2021). To solve the electrical contact failure between the electrode and the wood caused by repeated shrinkage and swelling of wood during long-term monitoring, screw-type electrodes (Norberg 2000; Otten *et al*. 2017), conductive adhesive injection (Brischke *et al*. 2008; Fredriksson *et al*. 2013), and their combinations (Li *et al*. 2018; Hafsa *et al*. 2021) were designed. For the 4PP used in this study, the contact between the electrode and the drilled inner end surface of the wood was important because the probe had a narrow inter-electrode spacing. If the end surface is even slightly uneven, for example due to drill bit marks, then any one of the four electrodes may not be in contact. To prevent this, it is necessary to adopt a method in which a spring is connected to each electrode, and the electrode moves in and out according to the local shape of the surface.

There are other important considerations for the application of 4PP. This electrode requires a higher voltage, and the electrical signal detection is relatively unstable at low MC. In addition, as shown in Fig. 7, the anisotropic resistivity induced by the structural direction should be considered when measuring the internal MC of large wood, where it is difficult to determine the grain orientation accurately. Therefore, it is necessary to study the electrode configuration to measure the resistivity at a low MC stability and offset the structural anisotropy.

CONCLUSIONS

1. The four-point probe (4PP) method was determined to be a promising approach for measuring relatively uniform resistivity that is not remarkably affected by the sample dimensions. To apply this method as a moisture meter for large wood members, further

investigations under extended conditions, such as various species, equilibrium moisture contents (EMCs), temperatures, and structural orientations, are required.

2. The resistance measured with the conventional two-pin (2P) electrode was less affected by *A* and *l*, and a high R^2 of 0.986 was produced from the least squares regression (LSR) model for predicting the moisture content (MC) (%).
3. The resistances measured with electrically conductive fabric (ECF) and multi-pin (MP) electrodes, the face-to-face measurements, were affected by *A* and *l*. The resistance in the tangential direction was higher than that in the other directions, indicating anisotropy due to the structural direction.

ACKNOWLEDGEMENTS

This study was supported by the Korea Forestry Promotion Institute through the R&D Program for Forest Science Technology, funded by the Korea Forest Service (Project No. 2020224C10-2022-AC02).

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Article submitted: July 13, 2021; Peer review completed: August 21, 2021; Revised version received and accepted: August 31, 2021; Published: September 3, 2021.
DOI: 10.15376/biores.16.4.7040-7055