Effects of Brown-rot Decay on the Electrical Resistance of Wood and its Mechanism

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The objective of this study was to investigate the effect of decay on the electrical resistance (ER) of wood with a high moisture content (> 45%) and to try to determine the mechanism. Poplar wood blocks were exposed to a brown-rot decay fungus (*Gloeophyllum trabeum* (Pers. ex. Fr.) Murr.) for 2 to 12 weeks to obtain different degrees of decay. The ER values of the non decayed and decayed wood at various moisture contents were measured using a voltammetry method and were statistically analyzed. It was found that the ER of the wood blocks decreased with the fungus exposure time. Changes in the ER were quick during the first 2 weeks of exposure, which suggested that it can be used to assess early wood decay. The ER values of the decayed wood at different moisture contents were generally lower than that of the non decayed wood. A large difference (approximately 50 kΩ) was found between them when the wood moisture content was above 45%. Further analysis showed that this was because of the increase in conductive ions in the wood, rather than an increase in the moisture content. These results may be helpful to better detect the internal decay of trees using ER-based methods and could partly explain ER differences in decayed trees.

Keywords: Wood; Non-destructive test (NDT); Brown-rot decay; Electric resistance; Moisture content

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INTRODUCTION

As a non-destructive measurement technique, the method of electric resistance (ER) measurement is advantageous because of convenience and low cost (Yu 2005). It was originally introduced to measure moisture content (MC) of wood by Stamm (1927). Since then it has been used for wood quality evaluation, decay detection, and wood boundary differentiation (Oliva *et al.* 2011; Guyot *et al*. 2013; Martin and Günther 2013; Tamme *et al.* 2014; Wang and Wang 2016).

In recent decades, a variety of ER-based devices have been developed for field tree quality measurement, which include Shigometer, Rotfinder, and Picus TreeTronic (Shigo and Shigo 1974; Oliva *et al*. 2011; Yue *et al*. 2016). During application, it has been found that the electrical properties are affected by various factors, such as the temperature, grain orientation, and testing frequency (Tiitta *et al*. 1999). The ER value at different locations in a tree is also highly variable because of the complex structure of wood and the influence of the factors mentioned above. Guyot *et al.* (2013) found that the ER correlated with the wood MC and density, rather than the electrolyte concentration in a stem cross-section surface by using electrical resistivity tomography. However, a different study showed that the ER correlated with neither the wood MC nor density, but rather the steep increase in the ER at the sapwood–heartwood boundary correlated well

with the decreasing pH and electrolyte concentration (Bieker and Rust 2010). Thus, no identical conclusion has been reached about the factors that influence the ER of trees and wet wood.

Previous studies have shown that the ER in discolored or decayed areas of wood tissue is generally lower than that in sound wood (Tattar *et al.* 1972, 1973; Shigo and Shigo 1974; Weihs *et al*. 1999; Oliva e*t al*. 2011), which makes it a potential technique to detect decay in wood and determine the decay shape and size in a field test (Bertallot *et al*. 2000; Nicolotti *et al*. 2003). An important prerequisite for this is to know what factors cause the decrease in the ER of decayed wood. Concerning this aspect, Martin (2012) systemically reported the effect of anisotropy, MC, and fungal infection on complex ER of wood and found that ER decreased with increasing MC. In the study, wood MC showed a decreasing trend with increasing incubation time; this may be unhelpful to explain the relation between ER and incubation time because it is well known that both MC and decay could cause the decrease in the ER of wood. Thus, it may be necessary to design a new experiment to make MC increase with incubation time and then to comparatively analyze the effect of MC and decay on ER. Additionally, both wood decay and tree decay generally occur at a relatively high MC (> FSP), so the effect of decay on ER in wood should be evaluated within this MC range. However, based on the literature known to the authors, related research is still limited and requires additional laboratory investigation. It is a shortage of portable resistance-based tools developed for field applications.

Thus, the main objective of this study was to investigate the decay effect on the wood ER and try to determine the mechanism. This study also investigated: (i) how the measured ER changes in non decayed and decayed wood with an increasing MC and the difference between them, and (ii) how the MC and measured ER changed with an increasing fungal exposure time.

EXPERIMENTAL

Materials

Forty-eight clear wood blocks (20 mm × 20 mm × 50 mm long) were obtained from the sapwood of freshly-cut logs of a 46-year-old poplar tree. These blocks were numbered and placed in a climate chamber with an equilibrium MC of 12% (GB/T 1935-2009 2009). They were prepared to soak in distilled water and the ER test was conducted at different MCs with clear wood and wood at different decay stages after fungal exposure.

Methods

Electric resistance test method

The ER test instruments included a signal generator (VC2002, Victor Company, Shenzhen, China), oscilloscope (DS1052E, Rigol, Suzhou, China), multimeter (DT9206, Fluke, Everett, USA), two 100-kΩ and 10-kΩ carbon film resistors (R_1 and R_2), and some wire. Based on the authors' previous study, the resistance value of various voltages, waveform and frequency under direct current (DC) and alternating current (AC) were measured at different MC levels. The observed frequency of each waveform ranged from 10 Hz to 20,000 Hz with 5 to 5000 Hz increments. Effects of the current type (DC and AC) and testing voltage on the resistance of wood were examined. Results showed that

voltammetry, with AC using 1000 Hz sine waves, was found to be adapt to measure electrical resistance in wood. Thus, the voltammetry method with the parameters of 5 V and 1000 Hz sine wave signal was used in this study.

During the test, a 2 mm diameter copper electrode was inserted at each end of each wood block with the depth of about 5 mm. The specimen was then placed in the measurement circuit along the wood grain (Fig. 1). Because the resistance of wood is generally above 100 kΩ, inter-connection-type voltammetry was adopted for the wood resistance measurement, which had a better performance than exter-connection-type voltammetry used in a previous study (Bao and Wang 2015). Two 100-kΩ resistors (R_1 and R_2) were used and connected to each side of the wood sample in series (Fig. 1). The average current in the circuit ($\bar{I}$, A) was calculated using the formula below,

$$\bar{I} = \frac{\frac{U_{ab}}{R_1} + \frac{U_{cd}}{R_2}}{2} \quad (1)$$

where U_{ab} and U_{cd} are the voltages (V) of R_1 and R_2, respectively, and U_{bc} is the applied voltage (V) of the wood sample (Wang and Wang 2016).

According to Ohm's law (Zhao 2010), the resistance of a wood sample (R_w) was then calculated by dividing U_{bc} with $\bar{I}$.

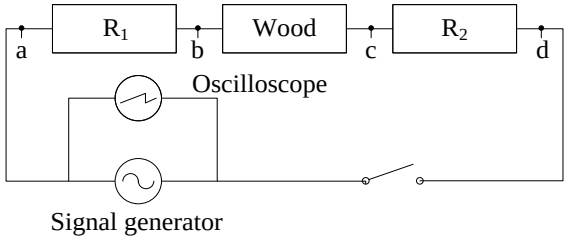

Fig. 1. Circuit diagram for the wood ER measurement

Electric resistance measurement of the non decayed wood

To relate the ER and MC of the non-decayed wood blocks, the ER of each block was tested at different MCs using the voltammetry method. Each wood block was first oven-dried (105 °C) and weighed until it reached a constant weight (m_d, g). The blocks were soaked in distilled water at 10 s intervals and weighed (m_1, g) after absorbing the water from the surface using filter paper. Then, the blocks were connected to a circuit to test the ER. After that, the weight was measured again and recorded as m_2. Based on this, the MCs of each block before (w_1, %) and after (w_2, %) the test could be calculated and the average MC was obtained using the formula below:

$$\bar{w} = \frac{w_1 + w_2}{2} \quad (2)$$

After first measuring the ER and MC, each wood block was soaked again and weighed at regular intervals. Once the MC increased by 10%, the ER test was conducted. The test process was repeated until the maximum MC of the wood blocks was reached and all test were conducted in the laboratory of constant temperature-humidity (20 °C and 65% RH) during the experiment period.

Fungal exposure experiment

Decay chambers were prepared by adding 15 g of poplar sawdust and 8.5 g of corn meal to 150 g of clean river sand (GB/T 13942.1-2009 2009). The mixture was placed in a 500-mL Erlenmeyer flask. Fifty milliliters of a mixture containing 9.4 g of malt extract and 1 g of unrefined cane sugar were added to the sand mixture. Four pieces of poplar (20 mm × 20 mm × 5 mm long) were placed onto the surface of the sand in each flask to serve as feeder strips for the test fungus. The flasks were sterilized by heating them at 121 °C and 0.1 MPa for 60 min and were then allowed to cool.

The test fungus (*Gloeophyllum trabeum* (Pers. ex. Fr.) Murr., Isolate #5.98) was grown on 1.5% potato dextrose agar until it completely covered the medium surface. Five small discs (5-mm diameter) were cut from the edge of the actively growing culture and placed onto the medium surface between the poplar feeder strips. The flasks were covered and incubated at 28 °C and an 80% relative humidity (RH) until the fungus covered the feeder strip surfaces (Zabel and Morrell 1992). The autoclaved test blocks were weighed in a sterile environment and then placed onto the feeder strips (cross-section face down) and the flasks were incubated at 28 °C and an 80% RH for 2 weeks to 12 weeks. The weights were used to calculate the MC of the wood before decay. A total of 18 inoculation flasks and three control flasks were prepared. Each flask contained two wood blocks.

Electric resistance measurement of the decay wood

The effect of fungal attack on the wood ER was assessed at two-week intervals by removing six test samples that were weighed and measured as previously described. Before the test, all of the residual malt extract on the surface of the wood blocks was removed, and the two resistors (R_1 and R_2) were adjusted to 10 kΩ to guarantee an accurate test result because of the reduction in the ER caused by decay (Shigo and Shigo 1974; Oliva *et al*. 2011). The difference between the initial and final weights was used to calculate the MC. According to this procedure, all of the decay blocks were tested at different fungal exposure times and the six control blocks were also removed and tested after the twelfth week.

Energy spectrum analysis

In the laboratory, some wood samples with an area of 8 mm^2 were prepared with a sliding microtome. The samples included the non decayed wood and indoor cultured decayed wood that were from the same blocks for ER test and natural decayed wood that were from the same standing tree. There were six samples of each kind, and they were dried through a graded alcohol series and finally soaked in pentene. The pentene was allowed to evaporate, and the dry block was sputter coated with gold palladium. The blocks were first examined using a Quanta 200 electron microscope (FEI Company, Hillsboro, OR, USA) at an accelerating voltage of 10.0 kV, and then measured using an energy dispersive spectrometer (EDAX Genesis 2000, FEI Company, Hillsboro, OR, USA). The energy spectrum and relative content of the five metal elements K, Ca, Mg, Al, and Na were measured.

RESULTS AND DISCUSSION

Electric Resistance *versus* Moisture Content in the Non decayed Wood

The linear relationship between the ER and MC of the non decayed wood was firstly illustrated in Fig. 2. The data indicated that the ER decreased as the MC increased, but the decrease rate varied with different MC ranges. The decrease rate was faster below a 45% MC. From 6% to 45% MC, the ER decreased from above 700 kΩ to 150 kΩ, which is nearly one fifth of the original value. Above a 45% MC, the ER diminished slowly and the value fluctuated around 60 kΩ.

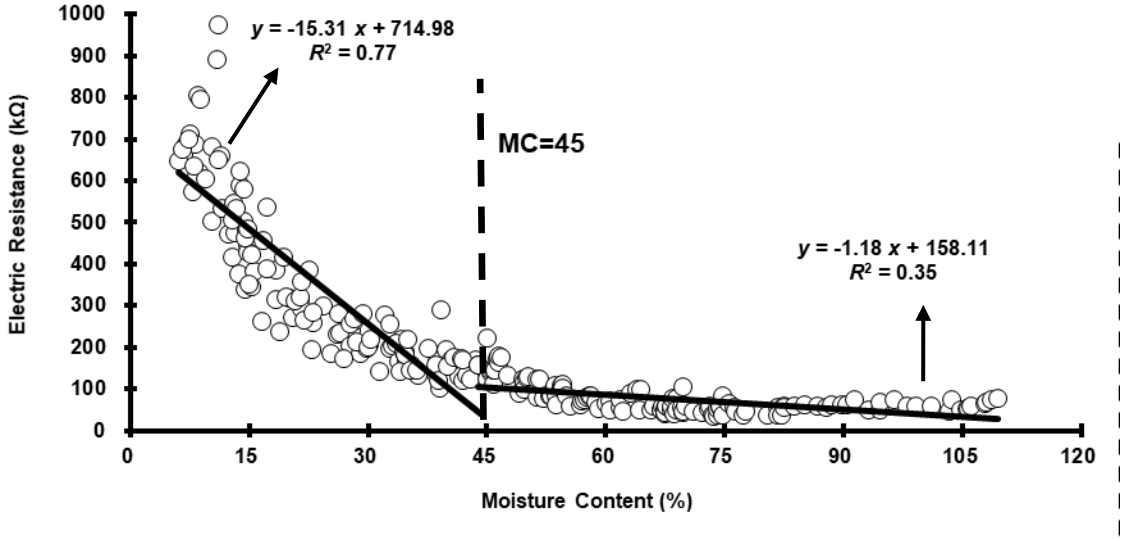

Fig. 2. Linear relationship between the ER and MC in the non decayed wood

The ER–MC relationship was characterized by the segmented linear regression models at two different MC ranges (Fig. 2). Over the range of 6% to 45% MC, the regression analysis using SPSS software showed a strong linear relationship between the ER and MC with a determination coefficient (R^2) of 0.77, which indicated that there was a 14-kΩ decrease in the ER when the MC increased by 1% and that the MC had a significant effect on the ER. When the MC was above 45%, the determination coefficient (R^2) between the ER and MC was only 0.35, which suggested that no significant correlations were found between them and that the ER could be treated as a constant.

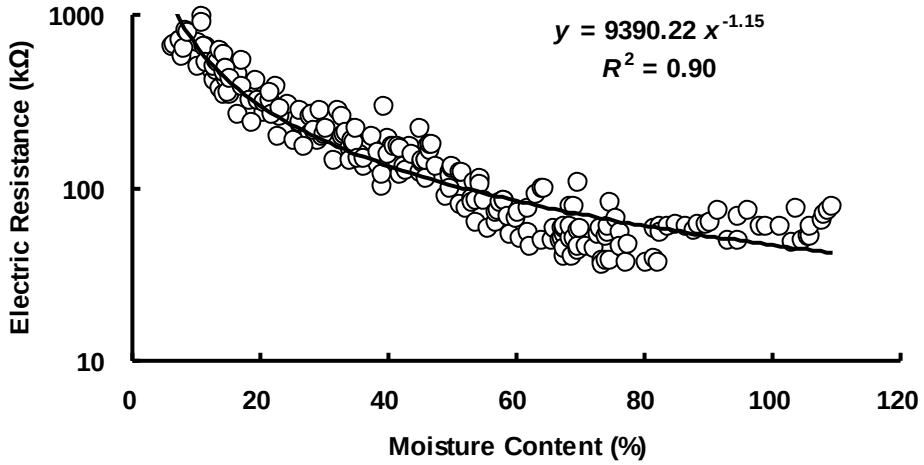

Fig. 3. Power function relationship between the ER and MC in the non decayed wood (Y-axis is shown in log-scale)

For getting more accurate relation between the ER and MC, a power function model was employed to analyze the ER data over the range of 6% to 110% MC (Fig. 3). A very strong correlation was found (R^2= 0.90), which indicated that the power function model could be used to better illustrate the quantitative relation between the ER and MC in the non decayed wood.

Electric Resistance *versus* Moisture Content in the Decayed wood

The ER in the decayed wood samples decreased with the fungus exposure time. For the wood with a MC above 45%, the ER was 75.19 kΩ before decaying (Table 1). After the first 2 weeks of fungal exposure, the ER quickly decreased by 86% to 10.16 kΩ. The ER loss rate slowed after 2 weeks and decreased by 0.47 kΩ per week on average from 2 weeks to 12 weeks. It changed less between 4 weeks and 12 weeks and only decreased by 0.14 kΩ per week. The ER averaged 6.53 kΩ after 4 weeks of fungal exposure and steadily decreased with the incubation time to an average ER of 5.44 kΩ after 12 weeks, except after 6 weeks of fungal exposure. This indicated that the decay time, especially the initial decay period, had a significant effect on the ER of the wood (MC > 45%). The single factor analysis of variance (ANOVA, SPSS software) also found a significant difference ($P < 0.001$, $\alpha = 0.05$) between the ER of the wood before and after decay.

Table 1. Effect of Exposure to *G. trabeum* on the MC and ER of the Chinese Poplar Blocks

Decay Time (weeks)	Number	MC (%)	ER (kΩ)
Before Decay	42	50.08 (1.27)	75.19 (5.98)
Control	6	79.00 (12.39)	33.60 (3.87)
2	6	105.17 (7.94)	10.16 (1.50)
4	6	155.33 (24.73)	6.53 (1.11)
6	6	133.50 (9.77)	7.38 (1.30)
8	6	151.17 (33.29)	6.09 (0.97)
10	6	185.83 (23.57)	5.63 (2.12)
12	6	186.67 (10.33)	5.44 (1.23)

The values in parentheses represent one standard deviation

Also, the MC of the wood samples increased gradually with the fungus exposure time. During the fungal exposure period, it increased steadily after 2 weeks, except after 4 weeks of fungal exposure (Table 1).

After 12 weeks of fungal exposure, the MC increased to approximately 186%, which was almost the same as the MC of the wood immersed in distilled water for 12 weeks in a previous experiment (Bao and Wang 2015). The ANOVA results also showed that a significant difference existed between the wood MC before and after decay ($P < 0.001$, $\alpha = 0.05$).

The change trend of the ER in the decayed wood with increasing MC is shown in Fig. 4. Below a 45% MC, the ER decreased dramatically from 350 kΩ to 25 kΩ with the MC. This phenomenon was similar to what was observed for the non decayed wood. When the MC was above 45%, the ER started to decrease slowly and steadily decreased to an average of 5.44 kΩ at an average MC of 200%. The average ER was kept constant at approximately 10 kΩ as the MC increased from 100% to 200%.

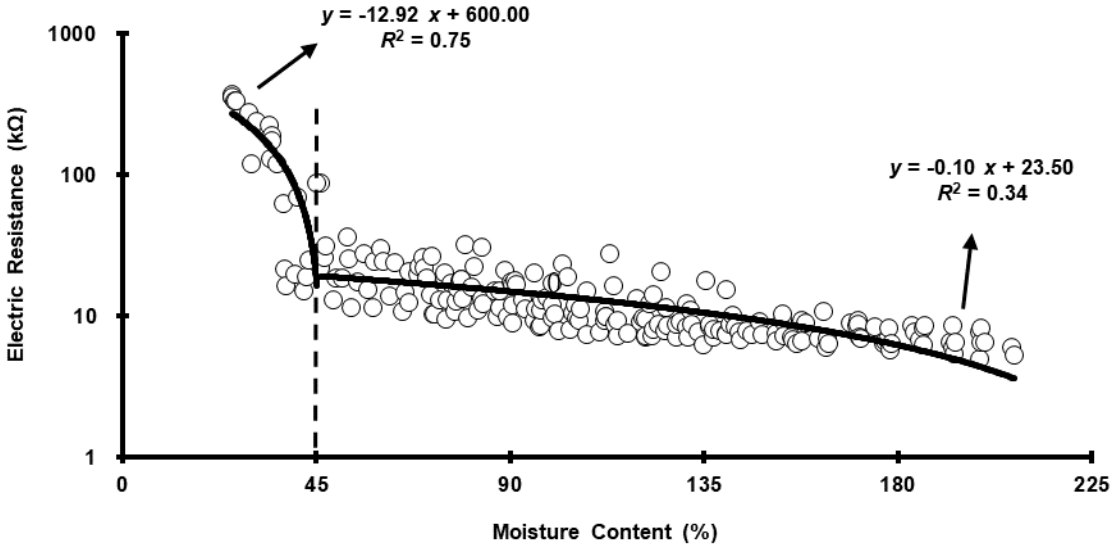

Fig. 4. Relationship between the ER and MC in the decayed wood (Y-axis is shown in log-scale)

Considering the MC ranges, the ER–MC relationship for the decayed wood could also be characterized by the segmented linear regression models at two different MC ranges (Fig. 4). The regression analysis showed that there was a significant relationship between the ER and MC below 45% ($R^2 = 0.75$), which suggested that the ER in the decayed wood was highly dependent on the MC. However, when the MC was above 45%, no significant relationship was found between the ER and MC ($R^2 = 0.34$). Therefore, when the MC of a wood sample remained above 45% before and after decay, it was concluded that a MC increase will not induce a significant reduction in the ER. Knowing that the MC is generally larger than 45% in trees (Nicolotti *et al*. 2003; Guyot *et al*. 2013), this deduction applies to trees as well.

Comparison of the Electric Resistance between the Non decayed and Decayed wood

The difference in the ER between the non-decayed and decayed wood is shown in Fig. 5. As the MC increased, the overall change trends of the ER in both the non decayed and decayed wood were similar. The ER loss rates were initially fast and then slowed. However, there was a large difference in the ER values with different MCs, especially above 45%. When the MC was between 20% and 25%, the ER of the decayed wood was close to that of the non-decayed wood with an average value of approximately 340 kΩ. When the MC was in the range of 40% to 45%, the ER of the decayed wood decreased to 33.6 kΩ, while that of the non decayed block was approximately 153 kΩ. Above a 45% MC, the ER decreased gradually to a constant value of approximately 60 kΩ for the non decayed wood and 10 kΩ for the decayed wood, which was a large difference ($d \approx 50$ kΩ).

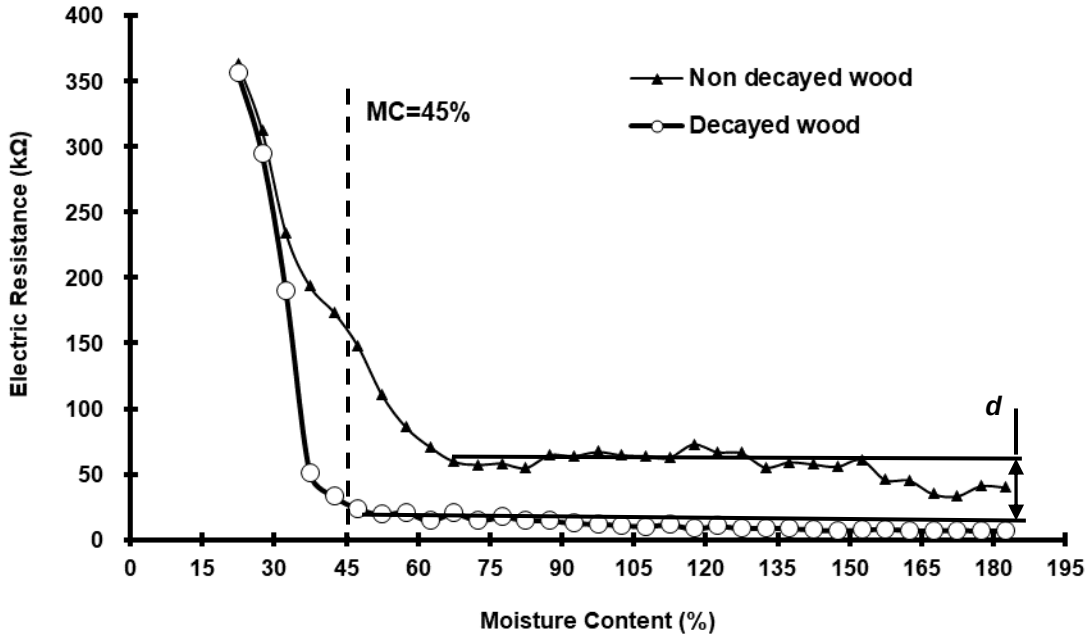

Fig. 5. Comparison of the ER change between the non decayed and decayed wood

Mechanism of the Decay on the Wood Electric Resistance

As described above, the ER of the decayed wood was generally lower than that of the non-decayed wood. When the MC was greater than 45%, there was a large difference between them. The reason for this is unknown and should be studied. Generally, the ER decrease often occurs with a simultaneous MC increase during the wood decay process (Tattar *et al.* 1972; Tattar *et al.* 1973; Shigo and Shigo 1974; Oliva *et al.* 2011). Thus, it was easy to infer that the MC increase might be one of the main reasons for the large difference, but the analysis results showed that this was not true.

When the MC was less than the fiber saturation point (FSP), the MC increase could have caused a reduction in the wood ER. When the MC was greater than the FSP, the wood ER was generally unchanged and could not be affected by the MC, which was shown by the experimental results for the non-decayed wood in this study (Fig. 5). When the MC was greater than 45%, the regression analysis showed that there were poor

correlations between the MC and ER in both the non decayed (Fig. 2, R^2 = 0.35) and decayed wood (Fig. 4, R^2 = 0.34), which suggested that the MC change had only a slight influence on the ER in this situation.

As has been stated, the MC was maintained above 45% for the indoor cultured wood throughout the decaying period (Table 1), so that the MC increase could not induce a dramatic reduction in the ER for the decayed wood. The true mechanism still needed to be discussed. From the previous wood ER equivalent circuit model, the wood ER is equivalent to the combination of different component resistances. When the MC is less than 45%, the wood ER consists of the organic substance ER and bound water (BW) ER. When the MC is greater than 45%, the wood ER is a combination of the ERs in three types of matter, including the free water (FW), organic substances, and BW. Among them, the ER of the BW was higher than that of the FW, so the wood ER mainly depends on the BW, which was established by Brown *et al*. (1963). Moreover, the biggest ER difference between the non decayed and decayed wood occurred over a MC range of the FSP to 45% (Fig. 5). Therefore, it was deduced that fungal exposure caused a large reduction in the ER of the BW and then decreased the wood ER. At this aspect, Brischke *et al*. (2018) did a similar study. They observed the changes in ER of wood caused by fungal decay and found that rot fungus lowered its ER in the hygroscopic range.

To test the above deduction, ionic conduction aspects were explored. Because the process of wood conduction is actually a moving process of free ions, the concentration and flow capacity of free ions in the wood were assumed to have a great influence on the ER (Brown *et al*. 1963; Lin 1965; Lin 1967). Below the FSP, the active groups in the cell walls of the non decayed wood were more easily ionized to become free groups as the BW content increased, which led to the reduction in the ER of the BW and wood. Above the FSP, the BW ER was unchanged, so the ER of the non decayed wood decreased firstly and then almost remained stable. Some data in the study of Zelinka *et al*. (2008) confirmed this result. They proposed a percolation model to describe conducting water at 16% MC percolation threshold and also found that the conductivity remained constant when MC increased to above 63%. In this study, the ER of the non-decayed wood was higher than that of the decayed wood when the MC was greater than 45%. Thus, it was further concluded that there were other conductive ions produced by rot fungi in the BW, in addition to those conducting groups ionized from active groups in the non-crystalline area of the cell wall, which decreased the BW ER and then changed the wood ER.

The relative content of various metal elements in the wood samples were measured and are presented in Table 2. Compared with the non decayed wood, the contents of the five metal elements were higher in both the indoor cultured and natural decayed wood blocks. Among them, K was the most sensitive element. The relative content was 0.50% in the non decayed wood, but was 1.43% in the indoor cultured decayed wood and 3.78% in the natural decayed wood. The relative Ca content also increased from 0.90% before decay to 1.50% and 2.24% after indoor cultured and natural decay, respectively. The changes in the other metal elements Mg, Al, and Na were also significant, but were lower than for K and Ca. The content of these elements in the natural decayed wood was higher than that in the indoor cultured decayed wood, except for the Na and Al elements, which was consistent with previous results (Tattar *et al*. 1972). Oliva *et al*. (2011) also tested the content of some metal elements in the decay area of Norway spruce and Scots pine in central Sweden and found that the K, Ca, Mg, and Mn contents increased, but the Na content did not. Therefore, wood decay can cause the content of metal cations to increase, especially for K and Ca ions.

Table 2. Relative Content of the Metal Elements in the Various Wood Samples

Sample	Mean Relative Content of Metal Element (%)				
	K	Ca	Na	Mg	Al
Non decayed Wood	0.50	0.88	0.14	0.12	0.07
Indoor Cultured Decayed wood	1.43	1.50	0.51	0.46	0.27
Natural Decayed wood	3.78	2.24	0.22	0.49	0.19

The change data for these metal elements supported the conclusion that the ER reduction in the decayed wood (MC > 45%) may be mainly due to an increase in conductive ions, rather than an increase in the MC. The growing of rot fungi in the wood led to an enrichment of conductive cations and reduced the wood ER. Meanwhile, it also caused a water content increase, but water was only a medium for metal ion movement and did not significantly affect the wood ER (MC > 45%). Only when the MC was less than the FSP did water shortage restrict the movement of metal ions, which then affected the wood ER.

CONCLUSIONS

1. The electrical resistance (ER) of the wood blocks decreased with the fungus exposure time at a moisture content (MC) greater than 45%. During the exposure period, the ER quickly decreased by 86% from 75.19 kΩ to 10.16 kΩ in the first 2 weeks and then steadily decreased to an average of 5.44 kΩ after 12 weeks, which suggested that the ER may be used to assess early wood decay.
2. The ER values of the decayed wood at different MCs were generally lower than that of the non-decayed wood, and there was a large difference (approximately 50 kΩ) between them when the MC was above 45%. Through analysis of the effect mechanism of the decay on the wood ER, it was found that this might be due to the increase in the conductive ions in the wood, rather than the increase in the MC.

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