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Abstract: This paper examines how the moisture conditioning method affects the electrical conductance of wood. A widely used dataset was acquired by Stamm in 1929 who used a method of conditioning where water-saturated wood specimens were partially dried, sealed and left for a period of time for moisture to be redistributed before the electrical conductance was measured. However, more recent measurements combined conditioning above saturated salt solutions and pressure plate/pressure membrane techniques to obtain equilibrium moisture contents at constant relative humidity levels in the full moisture range. In this paper, the electrical conductance as a function of moisture content was compared for these two conditioning methods. When the specimens were conditioned to constant relative humidity levels, the data obeyed a percolation model better than when the conditioning procedure by Stamm was used. This was attributed to that Stamm's method gives moisture gradients through the specimen because of sorption hysteresis effects, even though the wood is conditioned to a steady-state moisture content. Equilibration to constant relative humidity levels thus provided more well-defined moisture states and that the data followed a percolation model indicates that the mechanism of electrical conduction in wood does not change, even at high moisture contents.

Keywords: electrical conduction; ionic conduction; moisture content; percolation theory; wood.

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1 Introduction

Wood is an ionic semiconductor whose electrical properties depend upon the moisture content. For ionic conductors and semiconductors, the conductivity, σ (S m^{-1}), is an intrinsic material property that can be described by

$$\sigma = n z \mu \tag{1}$$

where n (m^{-3}) is the number of charge carriers per volume, z (C) is their charge, and μ (m^2 V^{-1} s^{-1}) is their mobility, with the voltage (V) indicating the average speed of charge movement.

In traditional silicon semiconductors, the electrical properties are tuned by adding small amounts of impurities which change the band gap of these electronically conducting materials. In wood, the electrical properties can be tuned by moisture; the conductivity increases by over 10 orders of magnitude as the moisture content changes from a dry to fully water-saturated state (Glass and Zelinka 2010).

For a planar electric field, the conductivity can be calculated from the electrical resistance, R (Ω), through

$$R = \frac{1}{G} = \frac{L}{\sigma A} \tag{2}$$

where L (m) is the length between the electrodes and A (m^2) is the cross-sectional area. The resistance is the reciprocal of the electrical conductance, G (S). The fact that resistance is both easy to measure and a strong function of moisture content has made electrical measurements an important tool in practical wood technological applications. Wood moisture meters are used to estimate the moisture content of lumber through electrical resistance or dielectric (alternating current) methods (James 1963, 1988). Beyond practical applications, the models used to describe conduction in wood help us to understand how moisture affects the wood cell wall.

For many years, the Hearle model was used to describe ionic conduction in wood (Hearle 1953). The Hearle model attributed the change in the conductivity to a change in the number of charge carriers in the wood as a function of moisture content. The number of charge carriers was calculated from an application of Debye-Hückle theory. However, the application of Debye-Hückle theory required *a priori* information about the dielectric constant of the same species as a function of moisture content. Zelinka et al. (2008) have shown that the Hearle model is in fact circular as the dielectric constant is always a function of the electrical resistance through the Kramers-Krönig relations. They instead showed that conduction in wood obeys a percolation phenomenon where the increase in conductivity is related to the increase in mobility of ions rather than the number of charge carriers. This ionic mobility was believed to be related to polymer relaxations in the wood cell walls (Jakes et al. 2013), and it has recently been demonstrated that ion transport occurs in interconnecting pathways of softened amorphous polysaccharides in the cell wall (Jakes 2019; Jakes et al. 2019).

Zelinka et al. (2008) developed a percolation model for electrical conductivity in wood. Physically, the model assumes there are pathways for ions to move through wood. As the wood moisture content is increased, the number and size of the pathways increases. The percolation threshold is the minimum amount of moisture needed to facilitate long range transport of ions. Above the percolation threshold the conductivity can be described by

$$\sigma = \sigma_o^{'}(f - f_c)^z \tag{3}$$

where f (-) is the weight fraction of water in the wood, i.e. the mass of water divided by the total mass, f_c (-) is the weight fraction of water corresponding to the percolation threshold, $\sigma_o^{'}$ (S) is related to the conductivity of the individual pathways and z (-) is the critical exponent related to the fractal dimension of the percolating system. Equation (3) implies that above the percolation threshold the logarithm of the conductivity is linearly related to the logarithm of the adjusted weight fraction of water (f–f_c).

1.1 Effects of moisture conditioning method

The percolation model was used by Zelinka et al. (2008) to fit the data of Stamm (1929) who measured the conductance of wood in the hygroscopic and over-hygroscopic moisture ranges. Conductance data collected by Stamm, according to the methodology described by Stamm (1929), are one of the primary sources of the conductance data in the Wood Handbook (Glass and Zelinka 2010) which is a widely cited reference for the physical properties of wood. While other studies have also measured wood electrical conductance or resistance as a function of moisture content (Brischke et al. 2008; Brischke and Lampen 2014; Davidson 1958; Du et al. 1991; Hiruma 1915; Hasselblatt 1926; James 1961; James 1988; Keylwerth and Noack 1956; Myer and Rees 1926; Nusser 1938; Sharma et al. 1997; Takechi and Inose 1953; Vermaas 1982) the data of Stamm are noteworthy for the wide moisture content range in which the conductance was measured.

The data of Stamm were collected by measuring the conductance of water-saturated specimens as they dried out. Specimens were removed from a container and allowed to dry for 5–10 min and were then placed in a sealed glass weighing bottle for between 15 min and 18 h before the next measurements were made. This procedure was used to let the moisture redistribute within the wood. Stamm (1929) claimed that “Experiments showed that for these small specimens 2 h or so was a sufficient time to hold the specimens under non-drying and non-absorbing conditions in order to insure [sic] any possible adjustment in the distribution of the moisture taking place.” Stamm used disk shaped specimens with a diameter of 10 mm and a thickness of 2–3.5 mm. The conductance as a function of moisture content from Stamm (1929) is presented in Figure 1. Stamm observed that when the logarithm of conductivity was plotted as a function of moisture content, the data exhibited bi-linear behavior. Such behavior is also seen when the dimensional change of wood and the logarithm of mechanical properties of wood are plotted as function of the moisture content (Tiemann 1906; Wilson 1932). The inflection point between the two linear regimes can be found at approximately similar moisture contents for these different properties, which for decades has been interpreted as the fiber saturation point.

In constructing the percolation model, Zelinka et al. (2008) observed that the Stamm data could not be fit with the percolation model at wood moisture contents above 63% (Figure 1). Zelinka et al. (2008) discarded that data and hypothesized that the percolation model may only apply close to the percolation threshold. In a more recent study, Fredriksson et al. (2013) used wire electrodes to examine the electrical conductance of wood in the moisture content range from water-saturation to 14%. In contrast to the moisture conditioning method of Stamm (1929), Fredriksson et al. (2013) equilibrated specimens by the pressure plate/pressure membrane techniques and above saturated salt solutions to obtain well-defined moisture states of the wood specimens throughout the entire range of moisture contents. These data, as well as previously unpublished data collected in a pre-study to Fredriksson et al. (2013) using similar methodology, are compared to the Stamm data in Figure 1. Since it is non-trivial to convert electrical conductance to electrical conductivity when measurements are taken with wire electrodes, the data sets are compared in terms of electrical conductance. At first glance, when plotted as log of conductance as a function of moisture content, both data sets exhibit a similar trend. However, when plotted as log of conductance as a function of adjusted weight fraction of

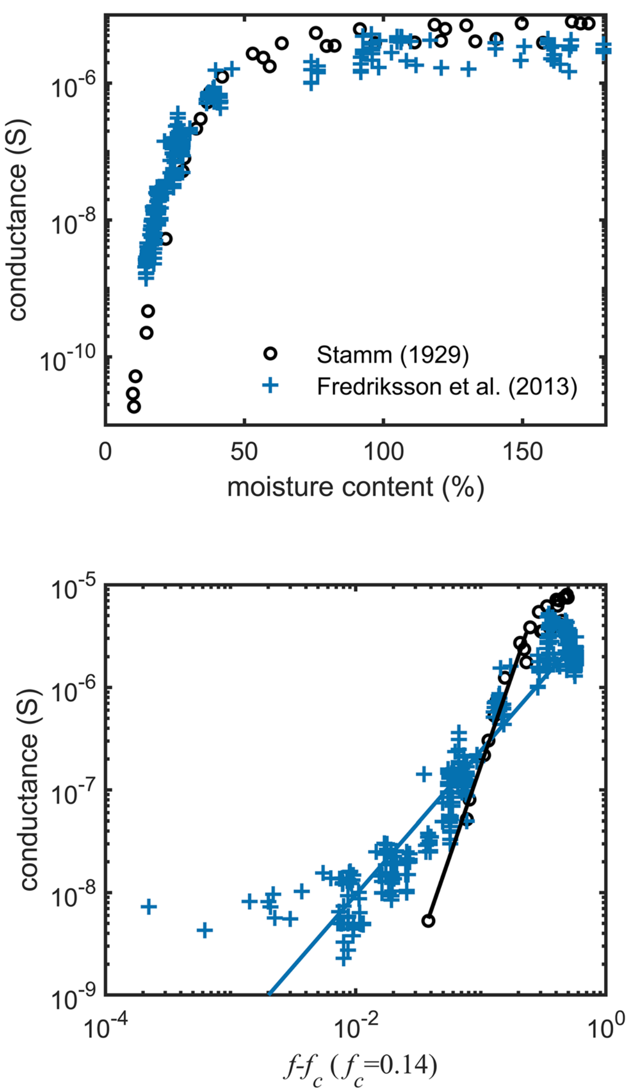

Figure 1: (Top) Data of Fredriksson et al. (2013) and unpublished data from a pre-study to Fredriksson et al. (2013) where the specimens were conditioned to equilibrium by pressure plate/pressure membrane techniques and saturated salt solutions prior to the conductance measurements (+). Data collected after conditioning by partial drying by Stamm (1929) (O). The moisture content is given as mass of water in relation to the dry mass of the wood. (Bottom) The same data, but as a function of adjusted weight fraction of water, see Eq. 3.

water (see Equation (3)), the Stamm data exhibits a discontinuity at high moisture contents while the data of Fredriksson et al. fits better with the percolation model at high moisture contents. These differences between the data of Fredriksson et al. (2013) and Stamm (1929) naturally raise questions about the true behavior of electrical conductance of wood in the over-hygroscopic region and how the moisture conditioning method might affect this.

In this paper, the electrical conductance as a function of moisture content was examined, specifically how the method used to condition the specimens affects the conductance data as well as the conformity with the percolation model. To accomplish these objectives, specimens from the study by Fredriksson et al. (2013) were reconditioned using the methods described by Stamm (1929), whose data has been used as the basis for the percolation model. In this way, the influence of other potential experimental variables such as specimen geometry and wood species is minimized and a comparison between conditioning methods can be conducted. Additional pressure plate data were also collected to provide more data for the electrical conductance of wood at high moisture contents.

2 Materials and methods

2.1 Re-conditioning of specimens from Fredriksson et al. (2013) using the method by Stamm (1929)

Six specimens ($30 \times 20 \times 10$ mm^3, 10 mm in the longitudinal direction) of mature heartwood of Norway spruce (*Picea abies* (L.) Karst.) with moisture content sensors fastened with electrically conductive adhesive as described by Fredriksson et al. (2013) were used. The sensors were positioned in the middle of each specimen with a 10 mm distance between them. That is, the sensors were inserted at a depth of 5 mm and the distance from the sensor to the other edges of the specimen was 10 mm. The electrical conductance as function of moisture content was determined using the procedure described by Stamm (1929) to the maximum extent possible. Stamm (1929) saturated his specimens by placing them in water until they sank, and the six specimens in the present study were thus placed in deionized water inside a glass container. However, after a week, the specimens had still not sunk. Therefore, in order to make the specimens saturated to approximately the same degree as in Stamm's experiments, the glass container with the specimens in water, was placed under vacuum (about 40 mbar) for 1 h. This procedure was repeated four times during the following week until the specimens finally sunk. The wet mass was determined, and the electrical conductance of each specimen was measured using the conductance logger described by Fredriksson et al. (2013). The specimens were then dried for 5–10 min in the laboratory in which the climate was 20 °C and 30–35% relative humidity (RH), and were then placed in a sealed PMMA box, see Fredriksson and Lindgren (2013), with the moisture content logger connected to the specimens. Since the box was sealed, there were no air movements inside the box. After at least 2 h in the box, the specimens were disconnected from the logger and the mass of each specimen was determined. The same procedure was then repeated, i.e. the box was opened so that the specimens were dried in lab climate for 5–10 min, followed by sealing the box for at least 2 h until the mass was taken again. This procedure was used for about 10 days. However, since the decrease in moisture content was small between two mass determinations, the drying time was increased to 15–30 min until the moisture content reached about 40–50% where drying times of 5–10 min were used again. These measurements continued for 57 days in total during which 78 measurements were taken and the moisture content decreased from about 170–180% to about 15%. The specimens were finally dried at 105 °C for

24 h and the total dry mass, m_{dry} (g), was determined. The moisture content, ω (g g^{-1}), was then determined as:

$$\omega = \frac{m - m_{dry}}{m_{dry} - m_{sensor}} \quad (4)$$

where m (g) is the total mass of each specimen after each conditioning and redistribution period and m_{sensor} (g) is the mass of the moisture content sensor.

2.2 Additional measurements for pressure plate conditioned specimens

To get additional data for pressure plate conditioned specimens, the six specimens used in the experiment described above, as well as three additional specimens, were vacuum saturated with water and conditioned using the pressure plate technique at two pressures, 1.4 and 0.6 bar, using the procedure described by Fredriksson et al. (2013). After nine months, the pressure was released and the specimens were transported to a glove box connected to a humidity generator, see Fredriksson et al. (2013). The mass of each specimen and the electrical conductance were then determined with the specimens inside the glovebox. The moisture content was finally determined according to Equation (4) . In the study by Fredriksson et al. (2013), specimens were split after the experiments to ensure the quality of the electrically conductive adhesive. In some cases, the gluing was considered insufficient and data for these specimens were not included, see Fredriksson et al. (2013) for details.

3 Results and discussion

3.1 Electrical conductance as function of moisture content

Figure 2 shows the new conductance data collected after partial drying (Stamm's conditioning method), data obtained in the present study after pressure plate conditioning, and data from Fredriksson et al. (2013) as well as unpublished data from a pre-study to Fredriksson et al. (2013). Both data sets from Fredriksson et al. (2013) (pre-study and published data) were collected after conditioning by the pressure plate/pressure membrane techniques and above saturated salt solutions. At first glance, both the partial drying data and the data collected after conditioning at constant RH levels appeared to have a similar bi-linear behavior where the conductance increased rapidly with increasing moisture content below 40% and then increased at a slower rate above this point. Higher conductance values were, however, observed in the over-hygroscopic moisture range for the specimens that were conditioned using the pressure plate/membrane techniques.

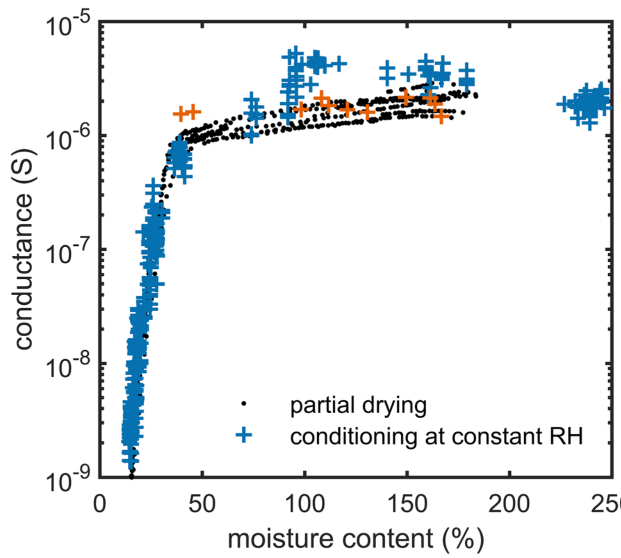

Figure 2: Conductance as a function of moisture content for specimens conditioned at constant RH using pressure plate, pressure membrane and saturated salt solutions (+) and those taken after partial drying (∘). The data obtained after conditioning to constant RH include the original measurements of Fredriksson et al. (2013) and data from a pre-study to the same paper (blue +) as well as new measurements on pressure plate conditioned specimens performed in the present study (red +). The moisture content is given as mass of water in relation to the dry mass of the wood.

3.2 Fit to percolation model

The left column (a) in Figure 3 shows the same data as in Figure 2, but as conductance as a function of weight fraction of water above the percolation threshold, i.e. as Zelinka et al. (2008) did to fit the percolation model. Zelinka et al. (2008) originally took the percolation threshold, f_c, as 0.14, which corresponds to a wood moisture content of 16.3%. This choice was based on radioactive tracer measurements of Lin (1965). However, recent work has shown that the percolation threshold may be lower for certain ions (Zelinka et al. 2015) and therefore several values of f_c were used. Figure 3 shows that the data obtained after partial drying was not linear and it is therefore not possible to fit this data to the percolation model. However, the data obtained by conditioning to constant RH levels by pressure plate/membrane and saturated salt solutions appeared to fit a linear model in the entire moisture range, at least to a higher extent than for the data obtained by partial drying. Therefore, an investigation on which value of f_c that gave the best fit and the goodness of this fit was performed. The best fit was obtained when using $f_c = 0.13444$, which gave an R^2 of 0.94. Also f_c values of 0.11 and 0.12 gave R^2 close to 0.94 while $f_c = 0.14$ gave a lower R^2

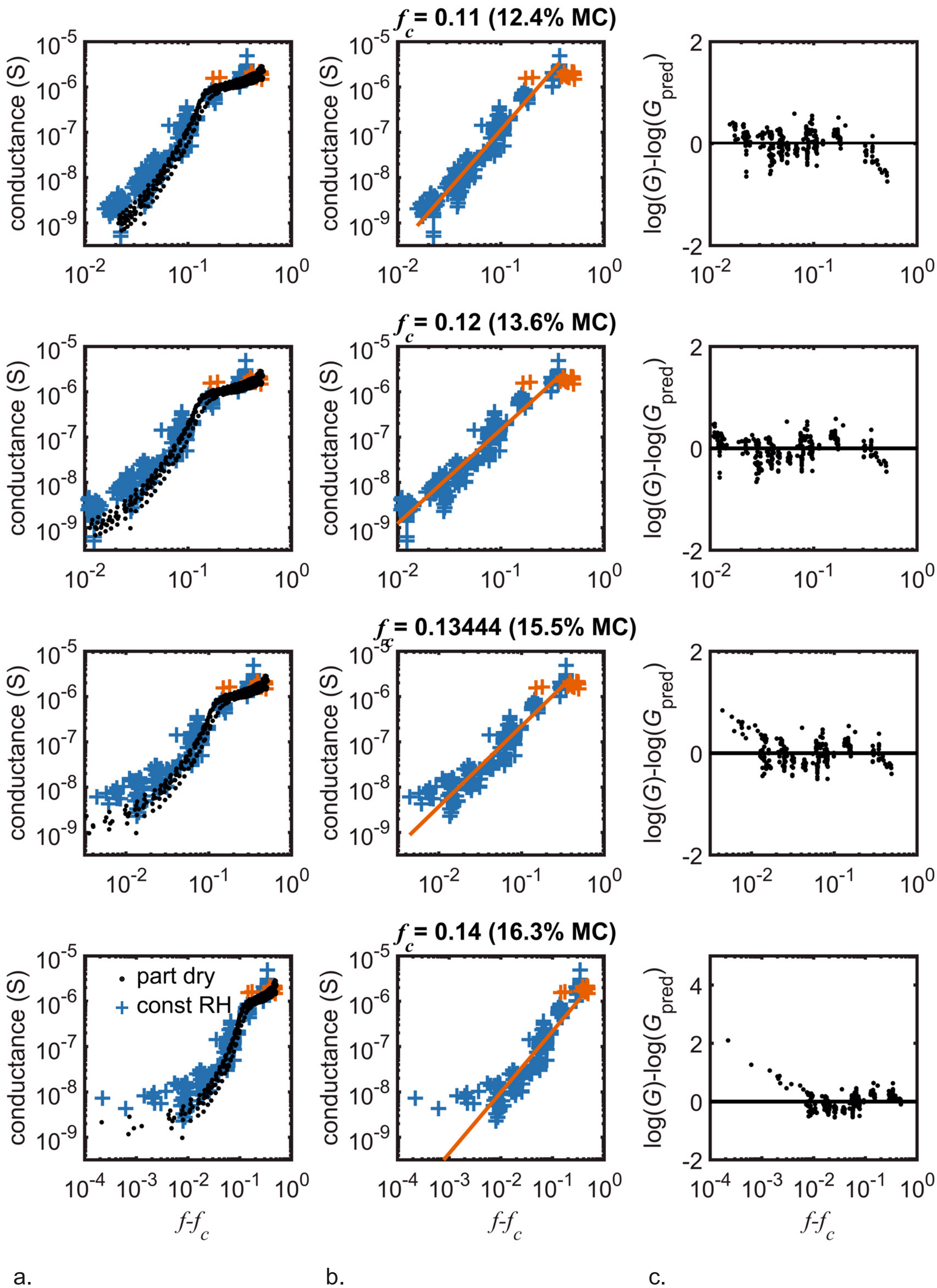

Figure 3: The right column shows conductance as a function of adjusted weight fraction of water (see Eq.3) for four different values of f_c. Data collected after conditioning to constant RH by pressure plate, pressure membrane, and saturated salt solutions (+) appear linear over the whole range of moisture contents (MC) whereas those measurements taken under after partial drying (◦) exhibit a bilinear behavior. The middle and right columns show linear fits to the data collected after conditioning at constant RH and the residuals, respectively.

of 0.91. Figure 3b and c show the fit to the data and the residuals, respectively, for the value of f_c that gave the best fit as well as lower and higher values as indicated in the figures. Since the data was found to fit well in the entire moisture range, this suggests that the mechanism of conduction does not change even as the amount of capillary water becomes significant at high moisture contents.

3.3 Influence of conditioning method of the measured electrical conductance

For the specimens conditioned by partial drying, measurements were performed on the same specimens dried to different moisture contents (in total six specimens), while for the specimens conditioned by pressure plate/pressure membrane/saturated salt solutions each specimen was only conditioned to one or two moisture contents. For the former case, the data points are thus dependent while for the latter case they are not. It is therefore difficult to evaluate if there are statistically significant differences between the two conditioning methods. However, since the specimens used in the partial drying experiment in the present study were the exact same specimens as were conditioned to three different climates in Fredriksson et al. (2013), these data can be used to compare influence of conditioning method. Also, six of the specimens that were conditioned by the pressure plate method in the present study were the same specimens that were conditioned using partial drying. For these specimens it is therefore possible to compare the influence of conditioning method directly at similar moisture contents. In Figure 4a the data obtained after conditioning by partial drying and data obtained after conditioning above saturated salt solutions are compared for the exact same specimens. It is clear from Figure 4a that the conductance measured after partial drying was lower than when the specimens were conditioned to similar moisture contents above saturated salt solutions. However, although Figures 2 and 3 indicate that the conductance was higher at high moisture contents when specimens were conditioned by pressure plate compared to partial drying, this difference between conditioning methods was less clear in Figure 4b when comparing individual specimens. For three specimens, the conductance was higher after pressure plate conditioning, while for the remaining three specimens, the conductance was similar or lower after pressure plate conditioning. The difference between conditioning methods was thus less clear at high moisture contents than at lower moisture contents.

3.4 Potential differences in moisture states between the conditioning methods

The data in Figures 3 and 4a point towards that the electrical conductance differed between the two conditioning strategies, even at the same moisture content. A likely reason for this is that the strategies yield different moisture states. Figure 5 illustrates the RH and moisture content distributions obtained by the partial drying method. Here, the outer part of the water-saturated specimen was initially conditioned to laboratory climate, i.e. lower than 100% RH. As a result, the overall moisture content of the specimen is decreased by evaporation, but the moisture content in the outer part of the specimen decreases more than in the inner parts. When the evaporation is stopped by sealing the specimen, the moisture redistributes within the specimen until reaching equilibrium. For the inner parts of the specimen, this equilibrium state is approached by desorption from water-saturation as in the pressure plate conditioned specimens. However, the outer parts of the specimen approach equilibrium by absorption as the moisture content increases in these parts during moisture

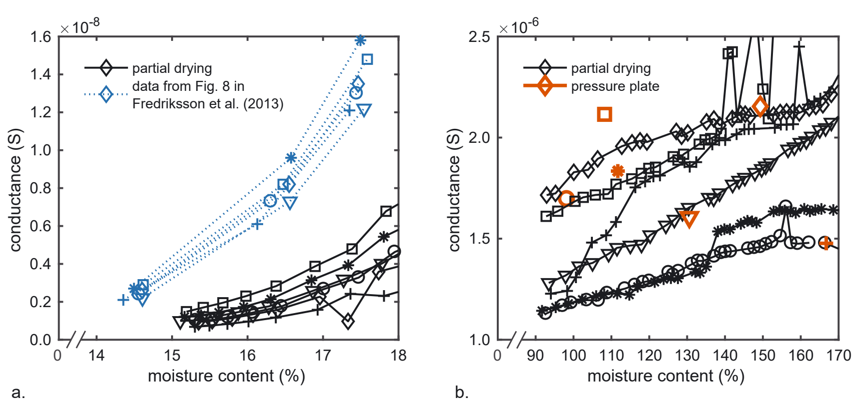

Figure 4: a. Data obtained after partial drying in the present study (black) and the data for the exact same specimens from Figure 8 in Fredriksson et al. (2013), but obtained after conditioning above saturated salt solutions. b. Data obtained after partial drying (black) and data obtained after conditioning the same specimens by pressure plate (red). For both a and b, the same symbol indicates the same specimen. The moisture content is given as mass of water in relation to the dry mass of the wood.

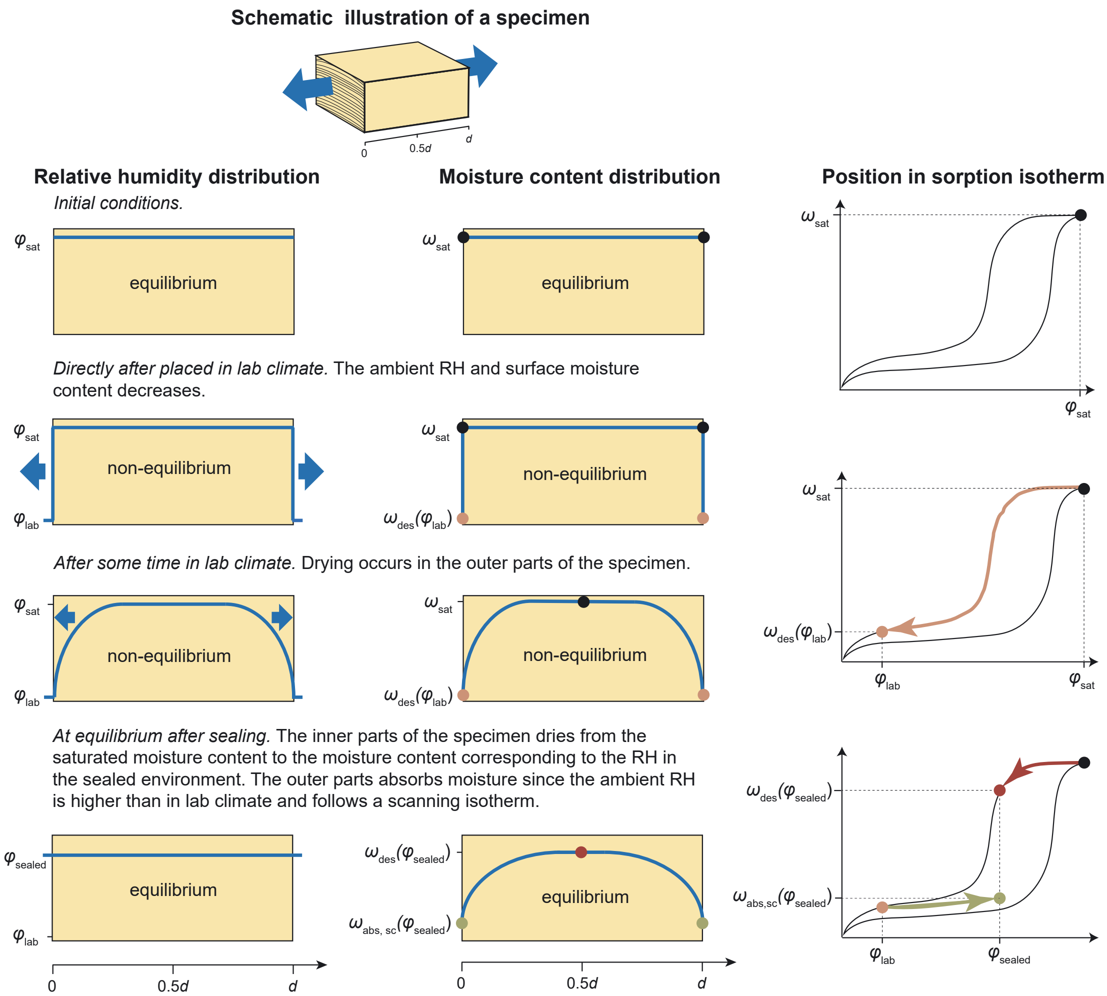

Figure 5: Schematic illustration of relative humidity (φ) and moisture content (ω) distribution within a wood specimen using a conditioning procedure where the moisture is redistributed after stepwise drying. The arrows in the sorption isotherms show the changes in moisture content at the surface and the middle of the specimens.

re-distribution. Since the desorption and absorption isotherms of wood only coincide in the fully water-saturated and dried states (Fredriksson and Thybring 2019), a phenomenon known as sorption hysteresis, the outer parts of the specimen will reach a lower moisture content than the inner parts when equilibrium is obtained. The result is that specimens conditioned by partial drying will contain moisture gradients even in the equilibrated condition. On the other hand, conditioning by the pressure plate/pressure membrane technique (at high humidity levels) or by saturated salt solutions (at lower humidity levels), ensures that all parts of the specimens approach equilibrium with the surrounding environment by desorption from the fully water-saturated state or by absorption from dry state. The result is a uniform distribution of both RH and moisture content within the specimens provided that the equilibration time is long enough. Although there are observations of moisture content gradients in specimens conditioned with pressure plate/pressure membrane measurements, they were attributed to lack of equilibrium (Cloutier and Fortin 1991; Cloutier et al. 1995), i.e. too short equilibration times. Because of the long equilibration times used both in the present study and by Fredriksson et al. (2013), the moisture content distribution was most probably uniform in this case. At least, any moisture content gradients should be small and thus negligible compared to the gradients present when using partial drying as conditioning method.

The presence of moisture gradients within wood affects the electrical conductance (Stamm 1927). Thus, for wood with a specific average moisture content, the conductance is not equal between an even and uneven moisture distribution. The reason is the logarithmic dependency of the conductance with moisture content. If the

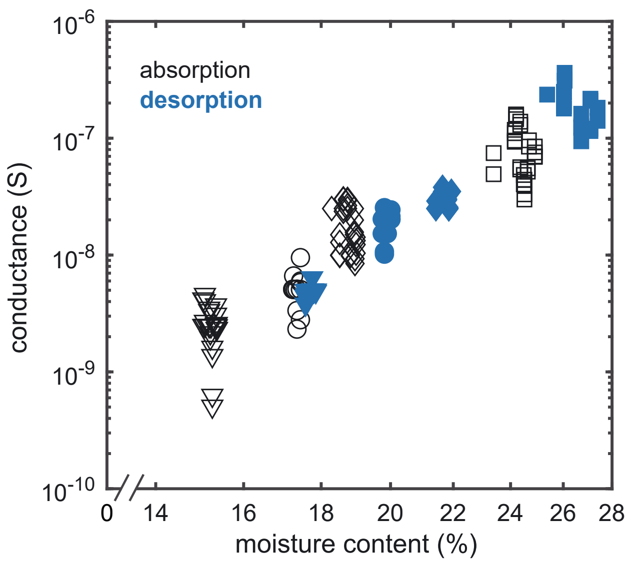

Figure 6: Data from pre-study to Fredriksson et al. (2013) which included data collected after conditioning above saturated salt solutions in both absorption and desorption at the same relative humidity levels. Black unfilled symbols are absorption data, blue filled symbols are desorption data. The same symbol indicates the same relative humidity level: 75% (triangle), 82% (circle), 85% (diamond) and 95% (square). The moisture content is given as mass of water in relation to the dry mass of the wood.

moisture gradient is parallel to the electric current, the conductance is lower than expected based on the average moisture content, whereas the conductance is higher than expected if the moisture gradient is perpendicular to the electric current (Niklewski 2018). In this study, the partially dried specimens should have higher moisture content in their inner core than closer to the bulk surfaces, see Figure 5. It is, however, difficult to predict in advance how this moisture distribution with gradients in 3D will affect the electric current between the wire electrodes. Nonetheless, it is clear that the partial drying method results in moisture gradients significant enough to affect the determined electrical conductance. Since the sorption hysteresis is larger in the over-hygroscopic range, it is, however, somewhat surprising that larger difference between conditioning methods were seen at lower moisture contents than at higher moisture contents.

It should, however, be noted that conditioning in absorption or desorption itself does not affect the electrical conductance in any other way than that different moisture content are obtained. Due to sorption hysteresis, the same RH yields different moisture contents which in turn results in a difference in electrical conductance. This is illustrated in Figure 6 where data from the pre-study to Fredriksson et al. (2013) obtained after conditioning in both desorption and absorption in the hygroscopic range is shown. The same RH level resulted, as expected, in different moisture contents, but the same relationship between electrical conductance and moisture content was obtained. It is thus only a problem when sorption hysteresis causes differences in moisture content within a specimen which is the case when using partial drying as conditioning method.

4 Conclusions

Moisture conditioning by partial drying and subsequent moisture re-distribution does not produce well-defined moisture states in wood. The moisture gradients within the specimen obtained using this method affected the measured electrical conductance. The conductance data obtained for specimens conditioned to equilibrium to constant RH levels fitted the percolation model better than when conductance data for partially dried specimens were used. Therefore, it is possible that the mechanism of electrical conductance in wood as function of moisture content does not change with significant amounts of capillary water present in the wood.

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