ELECTRICAL MEASUREMENT OF MOISTURE CONTENT IN POROUS BUILDING MATERIALS

Measurement of moisture content

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Abstract

The moisture content (MC) of porous building materials is often estimated via measurement of the resistance between two electrodes inserted into the material. The most common material to which this technique is applicable is wood. In general, the MC reading obtained is affected by several internal and external factors, some of which are seldom taken into consideration in practice. The paper exemplifies some of the most important factors involved in the determination of MC. The background to the various expressions relating the electrical resistance to MC, temperature, etc., are reviewed particularly for wood.

Keywords: Electrical measurement, resistance, geometry, electrode configuration, moisture content, porous materials, wood

1 Introduction

Several common building materials are porous or even hygroscopic, e.g. solid wood and wood-based products, plasterboard, concrete, autoclaved aerated concrete, rendering, coatings, etc. The performance of these materials is in many respects related to their moisture content (MC). This quantity is defined as the ratio of the weight of water to the weight of dry material. Estimate of MC in wood is most often made by measuring the resistance between two electrodes driven into the material. In principle, the same technique can be used with almost any porous or hygroscopic material. Traditionally, however, wood has been the most typical material to which resistance methods have been applied. This is partly because wood is relatively soft and electrodes are fairly easy to install at an arbitrary depth. Another reason is that the variation in resistance between different wood species or different samples is much smaller than that caused, for example, by relatively small changes in MC.
Various factors affect the measurement of resistance and they can be divided into at least three categories, namely, those involving:

- the size and geometry of the measured object in relation to that of the electrodes and also their configuration
- the interaction of the material (and the electrodes) with the surrounding climate
- the intrinsic properties of the material

The consequences of the first category are very often given by the instrument and electrodes used, but may to some extent be related to the skill of the operator. Of great importance in this context is also the understanding of the two concepts: resistance and resistivity. The second category involves environmental factors such as temperature and MC and the presence of thermal and moisture gradients in the material. The third category, finally, comprises e.g. the presence of conducting ions, the nature of the pore structure and the density of the material. In the end, the integrated actions of all these factors will affect the measured resistivity that in turn is frequently used for estimating the MC.

This paper presents the general principles and theoretical considerations for estimating, by resistance measurements, MC of porous and hygroscopic materials in general. Semi-empirical expressions will be shown that relate resistance to MC, temperature and some other factors that are specific to the materials considered. In particular, the effects of some of the factors mentioned will be exemplified using laboratory data obtained for wood.

2 Observations

A common observation made in the context of measuring MC in wood using pin- or nail-type electrodes is that the distance between the electrodes seems to be of very little importance to the obtained reading. It does not matter much if the electrodes are a few centimetres apart or if several meters separate them, provided that the MC is the same all over. The main reason for this result is that the resistance exerted by the bulk wood between the electrodes, even when mounted at very long distances from each other, is small compared with the resistance that arises closer to the electrodes. In Figure 1, \( R_{C_1} \) and \( R_{C_2} \) are associated with the wood/electrode interface and \( R_w \) with the volume resistance of wood (James 1994). However, it is not correct to consider \( R_{C_1} \) and \( R_{C_2} \) as regular contact resistances comparable to the situation when oxides are present on metallic surfaces. In this case, there is no physical barrier limiting the transfer of current but the resistance rather arises because of geometrical reasons, as will be further discussed below. In the presence of moisture gradients also large differences between \( R_{C_1} \) and \( R_{C_2} \) would be anticipated. The obtained moisture reading results from the total resistance in the electric circuit. Consequently, the electrode that is situated in the driest part of the wood will be decisive for the MC reading. This also means that the actual MC will always be underestimated when gradients are present.
In the case of electric moisture meters, MC is related to the resistance or conductance obtained for the given electrode configuration. Normally, this is not a problem as the calibration is valid for the dedicated electrodes when inserted into a sample volume that may be considered infinite, i.e. a situation that may be illustrated in Figure 1. On the other hand, serious deviations in the estimates of MC may be expected if electrodes having different geometries are used with the same reading instrument without correcting for, primarily, the difference in cross-sectional area of the electrodes. Deviations are also expected to occur for essentially one- and two-dimensional wood samples or if the overall size of the sample is small, as a consequence of the narrowing of the electric field (Grahn 1997). In this case, the distance between the electrodes will also come into effect.

3  Theory

3.1 Resistance and resistivity

The resistivity $\rho$ and conductivity $\sigma$ are intrinsic material properties in contrast to the resistance $R$ and conductance $G$, respectively, which are also dependent on the geometry of the conducting medium. It is essential for the understanding of the phenomena described previously to be aware of the difference between resistance and resistivity and their reciprocals, respectively. For a conducting medium with constant cross-sectional area $A$ and length $L$, the resistance is:

$$ R = \rho \frac{L}{A} = \frac{L}{\sigma A} = \frac{1}{G} \quad (1) $$

Fig. 1: Schematic showing the apparent distribution of electric resistance across two wood moisture electrodes (James 1994)
Equation 1 is applicable only if the cross-sectional area of the wood sample is the same as that of the electrode. The quantity L/A is generally referred to as the cell constant for the particular electrode configuration.

If the cross-sectional area varies along the length L, the resistance is given approximately by:

$$R = \rho \int_0^L \frac{dL}{A(L)}$$  \hspace{1cm} (2)

Equation 2 reveals the effect of geometry of the conducting path on the resistance between the electrodes, as was discussed earlier. The dominating contribution to the integral (= the cell constant) would come from parts of the wood that involve small cross-sectional areas, i.e. the two wood/electrode interfaces when pin-type electrodes are used.

For more exact formulations of resistance, Laplace’s equation must be solved subject to appropriate boundary conditions:

$$\Delta V(x, y, z) = 0$$  \hspace{1cm} (3)

where V is the electric potential. The influence of the actual geometry on the apparent resistance may also be studied by experiments using an electrolytic tank (Grahn 1997). If the electrolyte in the tank has the same size and geometry as the wood sample it may be used as a model for studying the effects of electrode configuration, sample thickness etc., on the distribution of the electric field and thereby the resistance across the electrodes.

### 3.2 Influence of temperature and moisture content

The decreasing resistivity of wood and other ionic conductors with increasing temperature was observed by Clark and Williams (1933):

$$\log \rho = A + \frac{B}{T}$$  \hspace{1cm} (4)

where T is the absolute temperature and A and B constants at a constant MC. Equation 4 is essentially the logarithmic version of Arrhenius’ well-known equation.

Another common relationship, originally proposed by Stamm (1927), expresses the effect of wood MC on resistivity at a constant temperature:

$$\log \rho = C + D \cdot \log M$$  \hspace{1cm} (5)

where M is the moisture content and C and D constants at a constant temperature. This expression is utilised by most wood moisture meters and has been found to work satisfactorily within the typical range of MC where electric moisture meters are used, i.e. 7 - 30%.

The simultaneous effects of temperature and MC on the resistivity can be expressed in one single equation by superimposing Equations 4 and 5 (Norberg
1998a):

\[ \log \rho = A + B \cdot \log M + \frac{C}{T} \]  \hspace{1cm} (6)

or from the practical point of view:

\[ \log M = A + B \cdot \log \rho + \frac{C}{T} \]  \hspace{1cm} (7)

By taking the antilogarithm of Equation 7 the following expression is obtained:

\[ M(\rho, T) = 10^{(A + B \cdot \log \rho + C/T)} = 10^A \cdot \rho^B \cdot 10^{C/T} \]  \hspace{1cm} (8)

Equations 6 - 8 are applicable to a sample of any porous material for which the resistivity is depending mainly on the moisture content. The validity of this expression must also be restricted to a certain moisture content interval where the moisture may be considered bound to the structure in a certain way. For wood, the fibre saturation point is often defined as the moisture content at which the cell walls are saturated with bound water with no free water in the lumens. Above this point, typically around 30% MC, the resistivity decreases much less with increasing MC than it does below, the fibre saturation point.

Many moisture meters are not equipped with facilities that enable direct compensation for temperature in the way suggested by Equation 8. Often the meter follows Equation 5 and the reading has to be manually corrected for the difference between the actual temperature and the calibration temperature. A useful relationship in this context may be obtained by taking the derivative of Equation 8 with respect to T:

\[ \frac{\partial M}{\partial T} = -\frac{M \cdot \ln 10 \cdot C}{T^2} = -K_T \frac{M}{T^2} \]  \hspace{1cm} (9)

Equation 9 shows that the effect of temperature increases in the negative direction with increasing MC and with decreasing temperature. This is also illustrated in Figure 2 using limited data for European oak from the study by Norberg (1998b). As an example, assume that a moisture meter, calibrated at 20°C, results in an MC of 18% at a wood temperature of 10°C. The temperature correction estimated from Figure 2 at 18% MC and 10°C is -0.155% per °C or +1.5% MC for the -10°C difference, and thus the true MC is 19.5%.

When conducting measurements of resistance or resistivity in order to estimate the MC of e.g. wood, it is important to consider the possible risk that the electrodes and the temperature probe affect the conditions at the measuring spots by altering the temperature there. The conduction of heat to and from the measuring spots via the electrodes and the connecting leads should therefore be minimised by proper design and by keeping the size of heat conducting parts as small as possible. These precautions are particularly important to long-term measurements outdoors where the variations in temperature and radiation
conditions are large over time.

![Graph showing the influence of moisture content on the change in MC per degree change in temperature for European oak as measured with resistance-type moisture meter.]

**Fig. 2:** The influence of MC on the apparent change in MC per degree change in temperature for European oak as measured with resistance-type moisture meter

### 3.3 Intrinsic properties

Very little work seems to exist regarding the effect of dry density on the resistivity of wood. The influence of density is generally considered weak but with a negative correlation with resistivity as reviewed by e.g. Keylwerth and Noack (1956), Lin (1967), and Vermaas (1982). Recently, on the other hand, the effect of dry density of wood was found to explain a great deal of the observed variance of a given data set (Norberg 1998b). An *ad hoc* adaptation was made by simply adding a linear term representing the dry density of wood to Equation 6, resulting in:

$$ \log \rho = C_1 + C_2 \cdot \log M + \frac{C_3}{T} + C_4 \cdot d_{gw} $$

(10)

A similar formula was also developed by Du et al. (1991), but the background work has never been published.

There are two reasons why the dry density should be considered in relation to resistivity. First, a denser material would imply more cell-wall substance per unit volume and, secondly, higher contents of extractives should also involve a higher concentration of conducting species in the cell walls. Further improvement of Equation 10, with regard to the density term, is possible by assuming a very simple structural model for wood, see Figure 3.
According to Siau (1984) the resistivity of wood in the longitudinal direction is:

$$\rho = \frac{\rho^*}{1 - a^2}$$  \hspace{1cm} (11)

where $\rho$ is the longitudinal resistivity of bulk wood, $\rho^*$ is the longitudinal resistivity of cell-wall substance and $1-a^2$ the fraction of cell-wall substance per unit volume of wood. Similarly, the dry density of bulk wood $d_{dw}$ may be expressed in terms of the dry density of the cell-wall substance $d^*_dw$:

$$d_{dw} = d^*_dw \left(1 - a^2\right)$$ \hspace{1cm} (12)

By combining Equations 11 and 12 the geometrical term can be eliminated and the following expression is obtained:

$$\rho = \frac{\rho^* \cdot d^*_dw}{d_{dw}}$$ \hspace{1cm} (13)

If $\rho^*$ and $d^*_dw$ are considered constant then Equation 13 may be further simplified to:

$$\rho = \frac{C^*}{d_{dw}}$$ \hspace{1cm} (14)

Equation 10 can be modified by substituting the ad hoc part of it, involving the dry density, with the expression given by Equation 14:

$$\log \rho = C_1 + C_2 \cdot \log M + \frac{C_3}{T} + C_4 \cdot \log d_{dw}$$ \hspace{1cm} (15)

In order to conform to the particular experimental conditions prevailing in the study by Norberg (1998b), Equation 15 can also be written with MC as the
dependent variable and substituting current i (nA) for resistivity:

\[
\log M = A + B \cdot \log i + \frac{C}{T} + D \cdot \log d_{dw} \tag{16}
\]

A renewed regression analysis of the previous data using Equation 16 was made and the result is summarised in Tables 1 and 2.

Table 1: Result of regression analysis using Equation 16 on data for 12 specimens conditioned at 8 different combinations of relative humidity and temperature. Input data from Norberg (1998b)

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Regression coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Coefficient</td>
<td>-1.08</td>
</tr>
<tr>
<td>Standard error of coefficient</td>
<td>0.0720</td>
</tr>
<tr>
<td>t-value</td>
<td>-15.0</td>
</tr>
</tbody>
</table>

Table 2: Regression results for the total estimate in addition to the data given in Table 1

<table>
<thead>
<tr>
<th>R²</th>
<th>Standard error of log M estimate</th>
<th>F-value</th>
<th>Degrees of freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.89</td>
<td>0.0161</td>
<td>241</td>
<td>92</td>
</tr>
</tbody>
</table>

The analysis presented in Tables 1 and 2 shows that Equation 16 provides a slightly better fit than did Equation 10 as given by Norberg (1998b). The significance of the coefficients and of the total regression equation can be tested according to t- and F-statistics, respectively. The critical t- and F-values tabulated for 92 degrees of freedom and an arbitrary significance level of 0.005 are 2.63 and 19.5, respectively. Comparison with the data in Tables 1 and 2 shows that all of the coefficients and the regression equation as such are highly significant.

4 Discussion and conclusions

The present paper discusses the various factors affecting measurement of MC of porous materials in general and of wood in particular. The cell constant for the electrode configuration applied influences all measurements of resistance in electrolytes. Many investigators, as it appears from the studied literature, neglect this important fact. Thus, to enable comparison between results originating from
different types of equipment, estimates of MC in building materials should be correlated to resistivity rather than resistance.

The effects of excitation voltage, AC or DC, and its duration, on polarisation phenomena have not been considered in this paper. If the measurement of resistivity aims at estimating the MC, then making a rapid DC excitation during fractions of a millisecond with reversal of the polarity, should eliminate the possible effects of polarisation. In this way, any capacitance associated with the material/electrode interface would be eliminated and only the resistivity of the electrolyte in the material will contribute to the result.

Equation 7 relates the electrically determined MC to resistivity and temperature. This expression is generic to ionic conductors and should be applicable to most porous and hygroscopic materials, at least within a certain range of MC where the conduction of charges follows the same mechanism. Further improvement of Equation 7 in relation to moisture measurements in wood has been accomplished by taking into account the dry density of wood (Equation 16). This was done using a simple model of the basic wood-cell structure enabling the resistivity to be expressed as a function of the dry density.

Similar models, based on the actual pore structure, could be developed for other porous materials, e.g. concrete and autoclaved aerated concrete. An additional complication with cementitious materials, such as concrete, is the fact that the pozzolanic reactions are expected to continue indefinitely and gradually alter the pore structure and thereby the resistivity (Whittington et al. 1981; Hanson and Hanson 1983; Hughes et al. 1985). This would require a time dependent factor when describing the resistivity.

Recently, work has started that will eventually make possible a description of the pore structure of autoclaved aerated concrete and renderings in conjunction with resistance-type measurements of MC under field conditions (Kus and Norberg 1999).

5 References


