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Application of Time-domain Reflectometry Method for Measuring Moisture Content in Porous Building Materials

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Abstract: The Time Domain Reflectometry (TDR) method can be generally classified as a dielectric method for moisture measurement, which is based on an analysis of the behavior of dielectrics in a time-varying electric field and consists in the measurement of permittivity of moist porous media. It is commonly used for moisture measurements in loose materials. In this study, an application of the TDR method for measuring moisture content in porous building materials is presented. In the calibration process, several different homogenization techniques, among them formulas proposed by Dobson *et al.*, de Loor, Boettcher, Polder and van Santen and Lichtenecker, as well as some empirical formulas developed for various types of soils are applied. The results are compared with the empirical calibration function determined by the gravimetric method. On the basis of this analysis, suitable mixing formulas are identified and recommendations for their practical application are formulated.

Key words: Moisture content, building materials, TDR method, calibration formulas, homogenization techniques

INTRODUCTION

The Time Domain Reflectometry (TDR) method in its original version from 1930s was developed for cable testing. Therefore, it was suitable for investigation of conducting materials only where the electrical properties were usually well known. Later, a straightforward modification of the method appeared, using quite opposite way of data evaluation. The principle of this modification consisted in using the information on the spatial location of the reflection point. If this location was known, the propagation velocity of the waves in the material could be calculated which could then be utilized for determination of the electrical properties.

The fact that liquids were the first materials used in measuring dielectric properties by TDR was not a coincidence. They were homogeneous and could achieve a very good contact with the measuring cell. In 1980s the application range of the method was spread to several other fields of research. A fast development of the TDR technology was initiated in soil science where the method found an increasing use in soil moisture measurement (Topp *et al.*, 1980). Since 1990s TDR already could be considered a well-established technique that was widely used in tens of scientific laboratories. However, its application for measurement of the electrical properties of liquids and loose or soft solid materials was still dominant.

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During the last couple of years the number of ISI references of TDR measurements was stabilized at approximately 120-130 per year and its increase was not as dramatic as during 1990s. Besides the well-established measurements on traditionally analyzed materials mentioned before, some additional applications appeared. For instance, TDR was used for the dielectric characterization of coals (Fornies-Marquina *et al.*, 2003), compact building materials (Pavlik *et al.*, 2002; Wansom *et al.*, 2006), compact rock materials (Cerepi, 2004; Sass, 2005), foods and agricultural materials (Miura *et al.*, 2003; Nelson, 2005) or human skin (Hayashi *et al.*, 2005).

Therefore, the current state of the TDR measuring technology can be characterized as very advanced but its development is far from completed. Application of TDR for measuring moisture content in porous building materials belongs still to the challenges in this respect.

In the design of the experimental setup for measuring moisture content in porous building materials using TDR method, the main problem to be solved is the installation of probes into the specimens, which have quite different structure than for instance liquids or soils. Therefore, the experimental setup commonly used for soils is to be changed significantly. For instance, the methods for building materials sample preparation that are quite different compared to soils lead to the necessity to replace the cylindrical geometry of the experiment used in soil science by rectangular geometry. Also, the problem of avoiding air gaps between the needle probes and the sample is much more difficult to solve than for soils. An attempt to improve the experimental setup according to these requirements was done couple of years ago by Pavlik *et al.* (2002). This study will follow similar directions in that respect but for somewhat different porous building material, namely cellular concrete.

The TDR method makes possible to determine directly the travel time of the launched electromagnetic impulse in a moist porous material and to calculate the relative permittivity of the material using this travel time. However, the method itself is not able to relate directly the relative permittivity of the mixture to the moisture content. This is probably the weakest point in TDR data interpretation, nowadays. The relation between the water content and relative permittivity of moist porous materials is determined mostly by empirical formulas such as those by Topp *et al.* (1980) or Malicki *et al.* (1996) because they allow quick and efficient determination of water content. However, it was indicated by Pavlik *et al.* (2005) that the methods for calculation of moisture content from measured relative permittivity used in soil science may not be applicable for building materials in general and verification of conversion functions by a reference method may be necessary case by case.

In this study, the relations between the water content and relative permittivity of porous building materials will be constructed using homogenization techniques and verified using empirical calibration. These techniques are relatively common in constructing electric and magnetic field mixing models in various fields of research but for the interpretation of TDR data for moist porous building materials they were not used yet.

The main objective of this study is to achieve improvements in the application of the TDR method for measuring moisture content in porous building materials. The experimental results will contribute to the knowledge of the dielectric behavior of moist porous building materials and to the improvements in using dielectric mixing formulas for determination of moisture content on the basis of measured relative permittivities of moist materials.

MATERIALS AND METHODS

The Time-Domain Reflectometry (TDR) Method: Principles and Devices

The TDR method can be generally classified as a dielectric method, based on an analysis of the behavior of dielectrics in a time-varying electric field and consists in the measurement of permittivity of moist porous media. The determination of moisture content using the permittivity measurements is based on the fact that the static relative permittivity of pure water is equal to approximately 80 at 20°C, while for most dry building materials it ranges from 2 to 6.

The permittivity of materials is strongly affected by the orientation of molecules in the electric field. This characteristic is high for water in gaseous and liquid phase, but is significantly lower for water bound to a material by various sorption forces, which makes the rendition of water molecules more difficult. This feature makes it possible to distinguish between the particular types of bond of water to the material using the permittivity but on the other hand, it results in the dependence of the sensitivity of moisture measurements on the amount of water in the material. The relative permittivity of water bonded in a monomolecular layer is approximately 3.1, but for further layers it increases relatively fast. Therefore, the dependence of relative permittivity on moisture content is generally characterized by a more or less gradual change at the transition from a monomolecular to a polymolecular layer. Consequently, the methods of moisture measurements based on the determination of changes of relative permittivity have lower sensitivity in the range of low moisture where is their application rather limited.

The principle of TDR device consists in launching of electromagnetic waves and the amplitude measurement of the reflections of waves together with the time intervals between launching the waves and detecting the reflections. The fundamental element in any TDR equipment used for the determination of moisture content in porous materials is a device to observe the electromagnetic pulse echo in time domain. The method application originates from the application of electric cable tester. The measuring device usually consists of four main components: a step or needle pulse generator, a coaxial cable wave guide, a sampler and an oscilloscope to register or visualize the trace of echo.

The pulse generator produces the electromagnetic wave that propagates through the measured media. The Fourier transform of an electrical pulse consists of sine waves covering a large frequency range but dependent on the shape of pulse. The highest frequency present in the pulse depends on its slew rate. This means that step pulse and needle pulse can be used equivalently if their rise time is comparable.

A very important part of TDR equipment is the probes. Rods of the probes are the signal conductors. There are a lot of probe constructions available for TDR measurements. They generally differ in shape, material and number of rods but general idea is that TDR probe is an extension of the coaxial cable with specified geometry. For instance, Topp *et al.* (1980) used a coaxial cell in a direct (but much larger) extension of the coaxial cable. Nissen and Moldrup (1995) described a three-rod coaxial probe, where the shield of the coaxial cable was replaced by two metal rods of the same length as the conductor.

The TDR probe itself is conductively connected to the coaxial cable in such a way that the cable is open ended and the probe forms this open end. In principle, the coaxial cable and the probe differ not only in the shape but also in a type of dielectric material. While the cable has usually polyethylene as a dielectric, the measured material serves as a dielectric of the probe. While the cable dielectric is nearly ideal, measured moist material usually contains dissolved salts and therefore conducting current appears. This is, however, not disturbing the measurement because of the high frequency of the pulse.

The sampler detects the electromagnetic waves launched by the pulse generator and transmitted through the coaxial cable and TDR probe system. TDR meter consists of two main components, a high precision timing device and a high precision voltmeter. When the electromagnetic waves launched by the generator are detected by the sampler, the sampler measures the voltage between the shield and the conductor at a certain time interval. The set of data obtained consists of voltage as a function of time when the transmitted pulse echo comes back to the device.

The coaxial cable connects the step-pulse generator and the sampler. The shield of the coaxial cable is connected to earth and its electric potential is 0 V. The electromagnetic waves produced by the step- or needle-pulse generator are launched into the coaxial cable with a voltage drop of several tenths of a volt between the conductor and the shield.

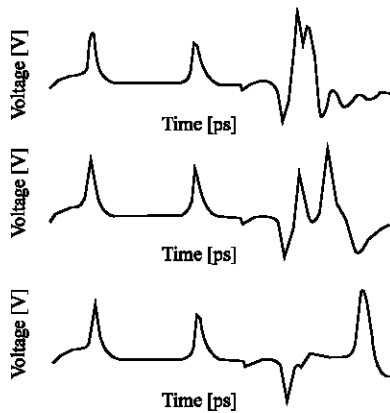


Fig. 1: TDR reflectograms depending on water contents. Upper reflectogram indicates dry porous material, middle reflectogram shows intermediate states and final reflectogram shows TDR trace for water

The evaluation of data obtained by a tester is based on the following basic principles. Any change of impedance in the cable-probe system causes a partial or total reflection of the pulse. Therefore, one reflection will be on the cable/probe interface, where the dielectric is suddenly changed and therefore the impedance must also be changed, while the second reflection is on the open end of the probe, where the impedance tends towards free space impedance and the wave is reflected in phase.

Reflected pulses can be either in phase with the incident pulse, which happens in the case when the electromagnetic waves pass an increase in impedance, or in counter phase, when a decrease of impedance is met.

The digital oscilloscope displays the measurements of voltage in time obtained by the sampler on a liquid crystal display, or the data in a digital form can be directly sent to a PC and displayed there. This generates a curve called the trace. The trace is flat with the exception of places where it meets disturbances around the conduit. These disturbances change the impedance and partial reflection or lose of the signal.

Figure 1 presents TDR oscilloscope traces for three media with different water content (relative permittivity). The upper one shows trace of completely dry medium. Two first left peaks define time scale, used for tool control. They are constant and are the result of intentional placing of conduit with determined characteristics and length. Subsequent two peaks are the result of changes of impedance because of changing the media-the beginning of the probe and the end of the probe. In dry material where the relative permittivity is very low the time of signal propagation is very short, which results in very short distance between peaks.

The middle trace in Fig. 1 indicates a material partially saturated with water (majority of typical porous media). Increase of relative permittivity causes decrease of velocity of propagation of the electromagnetic signal, which results in increase of time of propagation. Bottom trace indicates water, which relative permittivity has the highest value.

Time/velocity of pulse propagation depends on the apparent relative permittivity of the porous material, which can be expressed using the following formula:

$$\epsilon = \left(\frac{ct_p}{2L} \right)^2 \quad (1)$$

where ϵ is the relative permittivity of the porous medium, c the velocity of light ($3 \cdot 10^8$ m/s), t_p the time of pulse propagation along the probe rods measured by TDR meter and L the length of the rod inserted into a measured porous medium. Knowing the relative permittivity of a moist porous material, the water content in the material can be identified.

Application of the TDR Method for Measuring Moisture Content in Cellular Concrete

In the experimental work in this study, the cable tester LOM/RS/6/mps produced by Easy Test was used which is based on the TDR technology with sin²-like needle pulse having rise-time of about 200 ps. It is computer aided instrument (Malicki and Skierucha, 1989) originally designed for measurements of soil moisture. The built-in computer serves for controlling TDR needle-pulse circuitry action, recording TDR voltage-versus time traces and calculating the pulse propagation time along particular TDR probe rods and the relative permittivity of measured material.

A two-rod miniprobe LP/ms (Easy Test) was used for the determination of moisture content that was designed by Malicki *et al.* (1992). The sensor is made of two 53 mm long parallel stainless steel rods, having 0.8 mm in diameter and separated by 5 mm (Fig. 2). The probe cable length from the sensor to the multiplexer is 1 m and cable feeder length from the multiplexer to LOM is 3 m. The sphere of influence was determined with the help of a simple experiment. The probe was fixed in the beaker and during the measurement, there was added water step by step. From the measured data (relative permittivity in dependence on water level) there was found out that the sphere of influence creates the cylinder having diameter about 7 mm and height about 60 mm, circumference around the rods of sensor. The accuracy of moisture content reading given by producer is $\pm 2\%$ of displayed water content.

Measurements were done on Ytong cellular concrete samples. The cellular concrete blocks were provided by Ytong Germany. They were produced in the Ytong factory in Laussig as a special series. The experiment was done on 20 samples having dimensions of 40×40×100 mm.

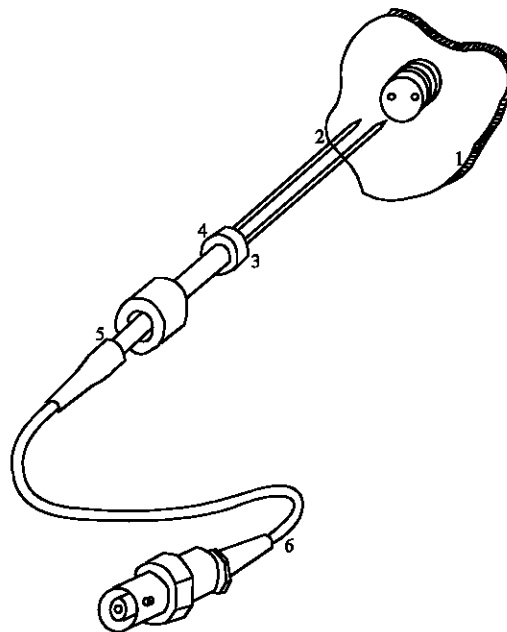


Fig. 2: Scheme of LP/ms minihygroscopy probe, 1: is rods guide, 2: rods, 3: bonding body, 4: clamp nut, 5: shrinkable tube, 6: BNC connector

Table 1: Basic properties of cellular concrete

Total open porosity (m ³ /m ³)	0.77
Bulk density (kg m ⁻³)	480
Matrix density (kg m ⁻³)	2060
Saturation moisture content (kg m ⁻³)	768

At first, two parallel holes having the same dimensions as the sensor rods were bored into each sample. Then, the sensors were placed into the samples and sealed by silicon gel. The samples were partially saturated by water and insulated to prevent water evaporation. The relative permittivity of wet samples was then continuously monitored until the measured values reached the constant value. Then, the experiment was interrupted, sensors removed from the samples and moisture content in the samples was determined using gravimetric method. Finally, the measured values of permittivity were assigned to the gravimetric moisture content.

As the application of homogenization techniques and empirical functions for evaluation of moisture content from measured relative permittivity assumes the knowledge of material properties, the measurement of porosity, bulk density and matrix density were carried out as well. The measurements were done on the vacuum saturation principle. The results are given in Table 1.

Determination of the Moisture Content Using the Measured Relative Permittivity

There are three basic approaches to the determination of moisture content from measured relative permittivity. The first possibility is utilization of empirical conversion functions generalized for a certain class of materials, which, however, are always limited to specific groups of materials only, for which they were proposed. The second possibility is application of dielectric mixing models, which assumes knowledge of the relative permittivities of the material matrix, water, air and other parameters, that can not be measured directly but have to be determined by empirical calibration of the model. The third method for evaluation of moisture content from measured relative permittivity consists in empirical calibration for the particular material using a reference method, such as the gravimetric method. This method is the most reliable until now but the most time consuming one.

In this study, the empirical calibration was done using the gravimetric method as described in the previous section. The empirical calibration curve was then used for the assessment of two other empirical conversion functions frequently used in soil science and of several calibration functions based on dielectric mixing models.

Empirical Conversion Functions

The conversion functions proposed by Topp *et al.* (1980) and Malicki *et al.* (1996) were used. The Topp's third-order polynomial relation, which is expressed by the equation

$$\theta = -5.3 \cdot 10^{-2} + 2.92 \cdot 10^{-2} \cdot \epsilon_{\text{eff}} - 5.5 \cdot 10^{-4} \cdot \epsilon_{\text{eff}}^2 + 4.3 \cdot 10^{-6} \cdot \epsilon_{\text{eff}}^3 \quad (2)$$

where ϵ_{eff} is the relative permittivity and θ the moisture content in the porous body [m³/m³], had for the originally studied materials standard error of estimate 0.0468 and was proposed for materials having the bulk density close to 1500 kg m⁻³.

The normalized conversion function proposed by Malicki *et al.* (1996) is considered presently by many authors as universal for different types of materials. The Malicki's function

$$\theta = \frac{\sqrt{\epsilon_{\text{eff}}} - 0.819 + 0.168 \cdot \rho - 0.159 \cdot \rho^2}{7.17 + 1.18 \cdot \rho} \quad (3)$$

where ρ is the bulk density of dry material, had for the originally studied materials standard error of estimate 0.0269.

Dielectric Mixing Models-Homogenization Techniques

In terms of homogenization, a porous material can be considered as a mixture of three phases, namely solid, liquid and gaseous phase. For the cellular concrete, the solid phase is formed by fine-grained siliceous sand, burned lime, cement and aluminum powder. Liquid phase is represented by water and gaseous phase by air. In the case of dry material, only the solid and gaseous phases are considered. The volumetric fraction of air in porous body is given by the measured total open porosity. In case of penetration of water, part of the porous space is filled by water. For the evaluation of relative permittivity of the whole material, the permittivities of the particular constituents forming the porous body have to be known. In our case, the relative permittivity of matrix of cellular concrete ϵ_s was determined on the basis of the measurement of relative permittivity of dry samples ϵ_{eff} . From the known ϵ_{eff} the ϵ_s value was calculated using the Rayleigh formula (Rayleigh, 1892).

$$\frac{\epsilon_{eff} - 1}{\epsilon_{eff} + 2} = f_s \left(\frac{\epsilon_s - 1}{\epsilon_s + 2} \right) + f_a \left(\frac{\epsilon_a - 1}{\epsilon_a + 2} \right) \tag{4}$$

where f_s and f_a are volumetric fractions of solid and air in the material, ϵ_a the relative permittivity of air (1.0).

The first dielectric mixing model analyzed in this paper was the 4-phase α -model proposed by Dobson *et al.* (1985) expressed in the following formula:

$$\theta = \frac{\epsilon_{eff}^\alpha - \theta_{bw} (\epsilon_{bw}^\alpha - \epsilon_{fw}^\alpha) - (1 - \Psi) \epsilon_s^\alpha - \Psi \epsilon_a^\alpha}{\epsilon_{fw}^\alpha - \epsilon_a^\alpha} \tag{5}$$

where ϵ_{eff} is the measured value of relative permittivity of the porous medium, θ the moisture content in the porous body [m^3/m^3], θ_{bw} the amount of water bonded on porous walls, ϵ_{bw} the relative permittivity of bonded water (3.1), ϵ_{fw} the relative permittivity of free water (79 at 20°C), ϵ_s the relative permittivity of air, Ψ the total open porosity (0.77) determined using vacuum water saturation test and α is an empirical parameter.

The Maxwell-de Loor mixing model (De Loor, 1968) was the second formula which was tested for the application with the studied material. The Maxwell-de Loor model is expressed by equation

$$\theta = \frac{3(\epsilon_s - \epsilon_{eff}) + 2\theta_{bw} (\epsilon_{bw} - \epsilon_{fw}) + 2\Psi(\epsilon_a - \epsilon_s)}{\epsilon_{eff} \left(\frac{\epsilon_s}{\epsilon_{fw}} - \frac{\epsilon_s}{\epsilon_a} \right) + 2(\epsilon_a - \epsilon_{fw})} + \frac{\epsilon_{eff} \theta_{bw} \left(\frac{\epsilon_s}{\epsilon_{fw}} - \frac{\epsilon_s}{\epsilon_{bw}} \right) - \epsilon_{eff} \Psi \left(\frac{\epsilon_s}{\epsilon_a} - 1 \right)}{\epsilon_{eff} \left(\frac{\epsilon_s}{\epsilon_{fw}} - \frac{\epsilon_s}{\epsilon_a} \right) + 2(\epsilon_a - \epsilon_{fw})} \tag{6}$$

Another tested homogenization technique was the model proposed by Boettcher (1952) given by the relation

$$\frac{\epsilon_{eff} - 1}{\epsilon_{eff} + 2\epsilon_{eff}} = f_a \left(\frac{\epsilon_a - 1}{\epsilon_a + 2\epsilon_{eff}} \right) + f_w \left(\frac{\epsilon_w - 1}{\epsilon_w + 2\epsilon_{eff}} \right) + f_s \left(\frac{\epsilon_s - 1}{\epsilon_s + 2\epsilon_{eff}} \right) \tag{7}$$

Three Bruggeman-type homogenization formulas proposed by Polder and van Santen (1946) were employed as well. The first of them, the original one, is valid for spherical inclusions, the second assumes acicular orientation of inclusions and the third was derived for their board orientation. The applied mixing formulas are described in the following equations, respectively,

$$\epsilon_{\text{eff}} = \epsilon_s + \sum f_j (\epsilon_j - \epsilon_s) \cdot \frac{3\epsilon_{\text{eff}}}{2\epsilon_{\text{eff}} + \epsilon_j} \quad (8)$$

$$\epsilon_{\text{eff}} = \epsilon_s + \sum f_j (\epsilon_j - \epsilon_s) \cdot \frac{5\epsilon_{\text{eff}} + \epsilon_j}{3\epsilon_{\text{eff}} + 3\epsilon_j} \quad (9)$$

$$\epsilon_{\text{eff}} = \epsilon_s + \sum f_j (\lambda_j - \lambda_M) \cdot \frac{2\epsilon_j + \epsilon_{\text{eff}}}{3\epsilon_j} \quad (10)$$

In Eq. 8-10, f_j is the volumetric fraction of air or water, ϵ_j is the relative permittivity of air or water.

According to Wiener (1912), for any multi-phase composite one can write the lower

$$\epsilon_{\text{eff}} = \frac{1}{\frac{f_1}{\epsilon_1} + \frac{f_2}{\epsilon_2} + \frac{f_3}{\epsilon_3}} \quad (11)$$

and upper

$$\epsilon_{\text{eff}} = f_1 \epsilon_1 + f_2 \epsilon_2 + f_3 \epsilon_3 \quad (12)$$

bounds of its effective permittivity function. This means that the effective permittivity function, ϵ , for a given physical system, in a sense, lies between these bounds. The upper bound for this effective permittivity function is reached in a system consisting of plane-parallel layers disposed along the field. The lower bound is reached in a similar system, but with the layers perpendicular to the field. In this work, the Wiener's bounds are used for verification of obtained results.

Finally, the Lichtenecker's equation (Lichtenecker, 1926) for the effective permittivity function is considered. Lichtenecker assumed that the effective permittivity function of the considered composite satisfied the following equation

$$\epsilon_{\text{eff}}^k = f_1 \epsilon_1^k + f_2 \epsilon_2^k + f_3 \epsilon_3^k \quad (13)$$

where the parameter k varies within the $[-1, 1]$ range. Thus, the extreme values of k index correspond to the Wiener's boundary values. The parameter k may be considered as describing a transition from anisotropy at $k = -1.0$ to anisotropy at $k = 1.0$. However, the Lichtenecker's equation may be also applied for isotropic composites. Note also that Eq. 13 is consistent with some other approximations (Looyenga, 1965, with $k = 1/3$).

RESULTS AND DISCUSSION

Figure 3 shows the results of empirical calibration of the moisture content vs. relative permittivity relation for cellular concrete. The measured results are smoothed by polynomial expression that can be considered as an empirical calibration curve having $R^2 = 0.9913$.

Figure 4 presents the results obtained from application of Topp's and Malicki's empirical conversion functions. For the clarity of results, the Wiener's bounds of effective relative permittivity function are given as well. We can see that results of Topp's curve are systematically higher than those

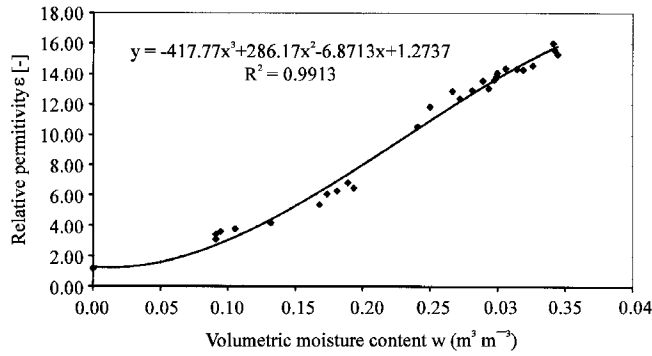


Fig. 3: Empirical calibration curve of cellular concrete

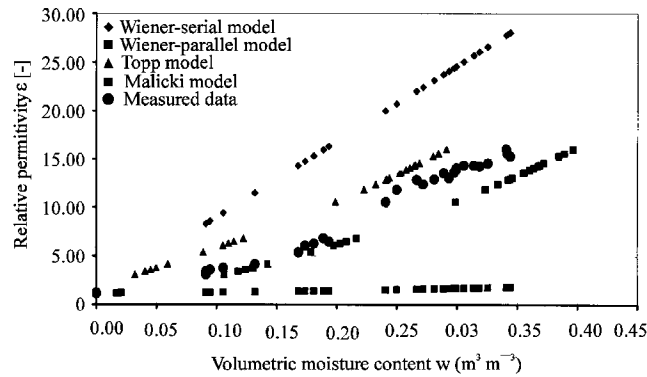


Fig. 4: Moisture dependent relative permittivity calculated by two empirical models used in soil science

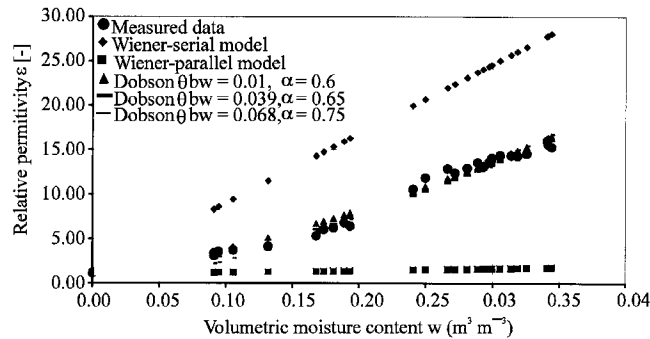


Fig. 5: Moisture dependent relative permittivity calculated by Dobson 4-phase α -model

measured. Relatively good agreement is observed for Malicki's function in lower moisture content up to $0.20 m^3/m^3$. For higher moisture content, the Malicki's function failed as well. This is, however, not very surprising result. The empirical and semi-empirical formulas for evaluation of moisture content from measured relative permittivity designed for application in soil science cannot be universal. As most soils exhibit a very low hygroscopicity, the application of soil-science formulas particularly for hygroscopic building materials is not straightforward and should always be done with care.

Figure 5 shows characteristic results obtained by the application of the Dobson 4-phase α -model for different values of the empirical parameter α and different values of the amount of bound water θ_{bw} .

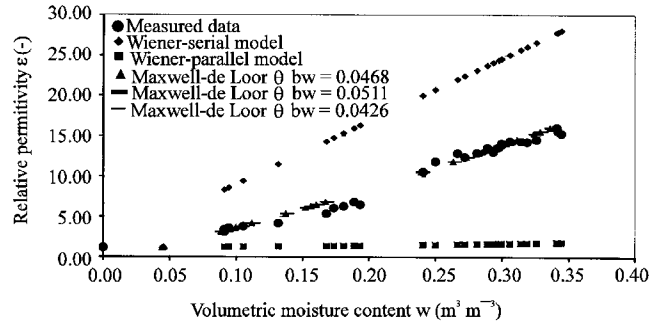


Fig. 6: Moisture dependent relative permittivity calculated by Maxwell-de Looor model

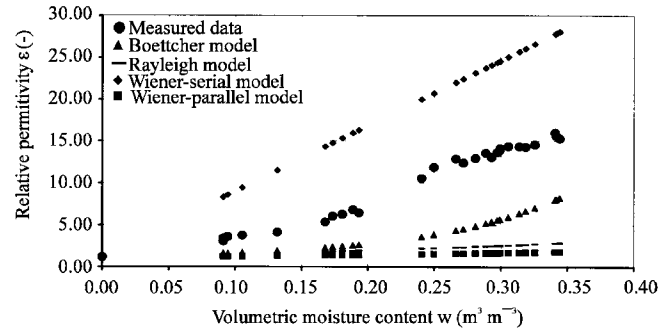


Fig. 7: Moisture dependent relative permittivity calculated by Boettcher and Rayleigh mixing formulas

The presented data were obtained by optimization using a least square procedure. θ_{bw} values were the chosen parameters in this procedure, α parameters were fitted according to the gravimetric data. The first two values of θ_{bw} in Fig. 5 correspond to the sorption-isotherm data for 30% RH and 97% RH which can be considered as effective limiting values in the hygroscopic moisture range, the third value is characteristic for the very beginning of the overhygroscopic moisture range. The results in Fig. 5 show that the sensitivity of the Dobson model to the choice of ϵ_{bw} values was in the studied range very low and a very good coincidence with gravimetric data was achieved in all three characteristic cases which were investigated. However, it should be noted that the application of this model assumes knowledge of the amount of bound water and calibration procedure using reference method, e.g., gravimetric method.

For the Maxwell-de Looor mixing model the best agreement with the gravimetric data was achieved for θ_{bw} values close to the maximum hygroscopic moisture content. The results presented in Fig. 6 show three examples of successful approximations which can illustrate that the sensitivity of the model to minor changes of θ_{bw} was not very high.

Moisture dependent relative permittivity calculated by Boettcher and Rayleigh mixing formulas is given in Fig. 7. These models apparently failed for the studied material, the main reason being probably the lack of free parameters.

Figure 8 shows the results of relative permittivity calculations using three Polder and van Santen Bruggeman-type mixing formulas. The best results were achieved using the model with needle inclusions. The agreement was slightly worse than in the case of Dobson and Maxwell-de Looor models but taking into account that the model does not contain any free parameters it can be highly rated as well.

The application of Lichtenecker's equation which is presented in Fig. 9 showed similar results as Dobson model. The optimal value of the k parameter which describes a specific microgeometry

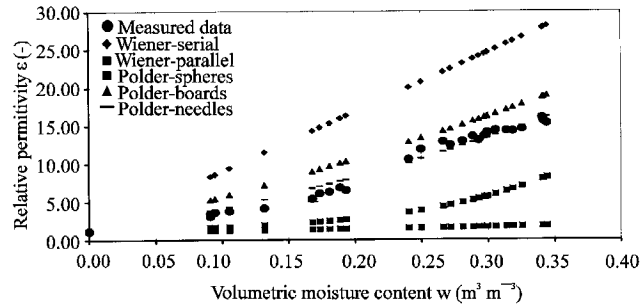


Fig. 8: Moisture dependent relative permittivity calculated by Polder and van Santen models

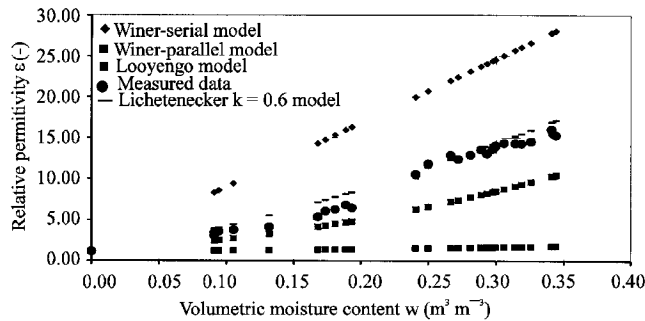


Fig. 9: Moisture dependent relative permittivity calculated by Lichtenecker's equation

(topology) of a material was roughly the same as the α value in the Dobson model. This is not very surprising result because the Dobson model was apparently derived on the basis of Lichtenecker's equation. The slightly better agreement with experimental data achieved for the Dobson model compared to the original Lichtenecker's formula can be attributed to the second free parameter in the Dobson model which is the amount of bound water.

CONCLUSIONS

The experiments and calculations performed in this paper can be considered as further step towards regular application of TDR technique for monitoring moisture content in building materials. The main finding was that methods for calculation of moisture content from measured relative permittivity commonly used in soil science are not applicable for building materials in general. However, the application range of some of the methods can be extended to a wider class of materials relatively easily. The most successful results were achieved for the application of Dobson *et al.* (1985) and Maxwell-de Loor (De Loor, 1968) formulas which contain the amount of bound water as free parameter. This seems to be a critical factor for building materials which -contrary to most soils-often contain a considerable amount of hygroscopic moisture. However, it should be noted that the experimental work in this study was done on just one characteristic building material so that at the current state of research these results cannot be generalized yet. Experiments for other types of building materials are needed and further testing of various conversion functions and mixing formulas by a reference method is necessary case by case. In future work the main focus will be on looking for more general empirical conversion functions and on application of more sophisticated dielectric mixing formulas for specific groups of building materials.

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