

DETERMINATION OF LIQUID WATER DIFFUSIVITY OF BUILDING MATERIALS USING TDR METHOD

MATÚŠ HOLÚBEK, PETER MATIAŠOVSKÝ

The objective of this study is an application of time domain reflectometry (TDR) in determination of liquid water diffusivity of porous building materials. We chose the lime-cement perlite plaster to study the applicability of TDR method for continuous measurements of non-stationary water transport processes. The study includes determination of the relation between the equilibrium moisture content and the relative permittivity of a material (calibration curve) and its comparison to physical, empirical and mixing effective permittivity models. Depending on various probe placement techniques different calibration curves were obtained. Their comparison enabled the evaluation of the quality of contact between probe and material.

The moisture profiles measured during water uptake experiment provided a basis for the determination of the moisture diffusivity. Boltzmann transformation was used to obtain the diffusivity function. Taking the error analysis of TDR method into account the proper methodology for determination of the diffusivity was proposed.

Keywords: diffusivity, moisture content profiles, time domain reflectometry, uncertainty

1. Introduction

The time domain reflectometry (TDR) method enables the instantaneous monitoring of moisture transport in porous materials. The correct measurement is conditioned by estimating the proper relative permittivity-moisture content dependence (the calibration function). At non-stationary transport regimes the water diffusivity can be calculated from the measured moisture content profiles.

At the beginning, the TDR method was used for the relative permittivity measurements to define the moisture content in soils (Topp, 1980; Mojid, 1998). The permittivity-moisture content calibration curve was found to be a polynomial function of the third order.

Afterward, the TDR method was applied to determine the electric conductivity from the signal attenuation (Dalton, 1984).

By means of the electric conductivity measurements we can estimate the concentration of salts in soils and some authors applied this method to monitor the transport of salt solutions (Kachanoski, 1992, Risler, 1996).

The relationship between moisture content and relative permittivity which could describe the most of mineral soils was derived in (Topp, 1980). Afterwards, studies concerning the moisture

content depending on the loam (Persson, M., 2000) and minerals proportion (Cosenza, 2004), organic substances and porosity or soil density (Malicki, 1996) and density of soluble salts (Persson, 2000; Dalton, 1992; Nadler, 1999) were published.

Studies (Sobczuk, 2005; Suchorab, 2009; Pavlik, 2007; Mihulka, 2008; Hansen, 2002) deal with measuring the empirical calibration curves for some of building porous materials (calcium-silicate and aerated concrete). Several research teams (Plagge, 2006; Pavlik, 2005; Sawiski, 2002) have investigated an application of TDR method to monitoring the time-dependent moisture content profiles in building materials during transient regimes.

Nowadays, the TDR is the attested and well established method for measuring the moisture content in soils and building materials, including the volumetric electric conductivity and the method is applicable in laboratories as well as in-situ.

A simultaneous measurement of the moisture content across the specimen at non-stationary transport processes with precise determination of time and location of a probe is the basic advantage of TDR method.

2. Principal description of time domain reflectometry method

The selectivity of measured physical quantity is a key feature of the TDR method. As the permittivity of a porous material markedly depends on the moisture content the calibration curve is not sensitive to another factor.

Concerning the dielectric moisture content measurements in porous materials the polar structure of water is an important feature of its molecules. The water molecule has a permanent dipole moment. The polarity of the water molecules is the reason of a significantly higher relative permittivity of water ($\epsilon_{rw} = 81$) in comparison to the relative permittivity of the solid phase of porous building material ($\epsilon_{rs} = 4 - 5$).

The relative permittivity of the moist porous material therefore depends strongly on its moisture content, and the dielectric measurements of moist porous building materials can be based on the relative permittivity measurement.

The moist building material represents an electrically conducting material which assumes the properties of dielectric and conductor together.

Generally, the relative permittivity is a complex quantity:

$$\epsilon_r = \epsilon_r' - i \left(\epsilon_r'' + \frac{\sigma}{\omega \epsilon_0} \right) \quad (1)$$

where the term in brackets is the imaginary part of the complex relative permittivity, ϵ_r' is the real part, ϵ_r'' is the negligible contribution of dielectric losses connected with dielectric polarization (mutual friction of permanent and induced dipoles), σ is the electric conductivity of moist material, ϵ_0 is the permittivity of vacuum, ω is the angular frequency of external electric field equal to $\omega = 2 \pi f$, where f is the frequency of electric field.

The real part ϵ_r' depends solely on the moisture content and on the density ρ of the dry porous material. The imaginary part depends on the frequency of electric field f , the electric conductivity of the material σ (moisture content dependent quantity) and the concentration of salts in a material. The bigger imaginary part of the complex permittivity, the more noticeable conducting characteristics the material has, and the losses grow. If the frequency of electric field is sufficiently high, the

imaginary part of the complex permittivity is negligible. If the frequency increases, the polarizing current becomes dominant in comparison to the conducting current. Therefore, the alternating electric field applied in the probe perceives the porous material as a dielectric and the measurement turns to be selective.

When the measurement of moisture content in porous material is realized by means of TDR method, the typical value of electric conductivity is $1 \text{ S}\cdot\text{m}^{-1}$ and the electric field of a frequency higher than 1 GHz must be used.

The TDR method, well known as a radar method, is based on energizing a voltage pulse (which spreads along the transmission line) and recording the time intervals between the occurrences of the partial reflections caused by change in material impedance.

The electric voltage impulse consists of infinite series of harmonic waves with various frequencies. The edge of rising impulse composes of the harmonic waves of highest frequency from the package. They define the maximum frequency, f_{\max} , of the interval, and also the impulse rising time (Strickland, 1970):

$$t_r = 0.35 \cdot f_{\max}^{-1} \quad (2)$$

Equation (2) enables to determine the minimal frequency f_{\min} of alternating electric voltage which has to be used in order to minimize the non-selective feature in measuring the moisture content of given material by means of the dielectric method (Topp, 1980).

$$\lg(f_{\min}) = 8.87 + 1.06 \cdot \lg \sigma \quad (3)$$

f_{\min} defines the lower boundary of the frequency package the electromagnetic impulse used in TDR method is composed of. The upper boundary of the frequency package can be determined from the impulse rise time.

The relative permittivity can be estimated by measuring the velocity v of electromagnetic impulse propagation in the material of interest using following equation:

$$v = \frac{c}{\sqrt{\mu_r \varepsilon_r}} \quad (4)$$

where c is the velocity of light (electromagnetic waves) in the vacuum, μ_r is the relative permeability.

The relative permeability of moist dielectric material μ_r is approximately equal to 1. Transforming the equation (4) we obtain the formula for the refractive index of given medium (Malicki, 1989):

$$\sqrt{\varepsilon_r} = \frac{c}{v} = \frac{c}{2L} t \quad (5)$$

where L represents the length of sensor rods (Fig. 1), t is the time needed for an impulse to travel the double length of sensor rods $2L$.

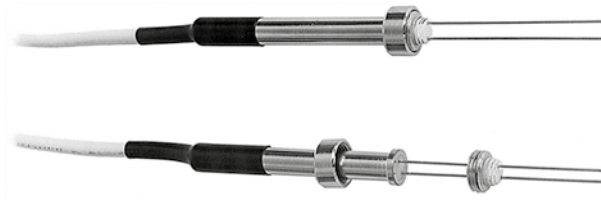


Figure 1. Schematic description of TDR probe (Skierucha, 2004)

3. Calibration curve of lime-cement perlite plaster

3.1 overview of relations used for calibration curves

Knowledge of a calibration curve describing the permittivity-moisture content dependence is crucial for the material moisture content estimation by TDR method. Nowadays widely used is the function proposed by (Malicki et al. 1996) belonging to the class of empirical calibration functions. This function was proposed for soils and it is predefined in our TDR apparatus:

$$w = \frac{\sqrt{\varepsilon_r} - 0.819 - 0.168 \cdot \rho - 0.159 \cdot \rho^2}{7.17 + 1.18 \cdot \rho} \quad (6)$$

where ρ (g.cm⁻¹) is the bulk density of a dry material.

Another class of models is presented by so-called mixing models. The effective permittivity of a multiphase composite cannot pass the so-called Wiener bounds. The Wiener bounds for serial (Eq. 7) and parallel (Eq. 8) arrangements of components are determined by relative permittivity and portions f of particular components (Wiener, 1912):

$$\varepsilon_r = f_1 \varepsilon_{r1} + f_2 \varepsilon_{r2} + f_3 \varepsilon_{r3} \quad (7)$$

$$\varepsilon_r = \frac{1}{\frac{f_1}{\varepsilon_{r1}} + \frac{f_2}{\varepsilon_{r2}} + \frac{f_3}{\varepsilon_{r3}}} \quad (8)$$

The Lichtenecker equation (Lichtenecker, 1926):

$$\varepsilon_r^k = f_1 \varepsilon_{r1}^k + f_2 \varepsilon_{r2}^k + f_3 \varepsilon_{r3}^k \quad (9)$$

or:

$$\varepsilon_r = \left((1 - \phi) \cdot \varepsilon_{rs}^k + (\phi - w) \cdot \varepsilon_{ra}^k + w \cdot \varepsilon_{rw}^k \right)^{\frac{1}{k}} \quad (10)$$

is a generalized form of Wiener formulae. Indices s , a , w represent the solid, air and water phase respectively, f is the porosity and w is the volumetric water content in Equation (10). The value of parameter k can reach the values from -1 up to 1 .

Another mixing model was presented by Rayleigh (Rayleigh, 1892). It describes the material as a continuous phase (solid matrix), which contains randomly distributed spherical particles of air and water.

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \sum_{j=1}^3 f_j \left(\frac{\varepsilon_{rj} - 1}{\varepsilon_{rj} + 2} \right) \quad (11)$$

3.2 Calibration of TDR probes immersed into fresh lime cement mixture

Five specially manufactured specimens of the lime-cement plaster of a cylindrical geometry had the radius $r = 0.023$ m and the height $h = 0.12$ m. The bulk density of the material was 600 kg/m^3 and the porosity was $0.67 \text{ m}^3/\text{m}^3$. The measuring probes were fixed horizontally through openings in a vertical plastic cover and glued in the position of specimen axis. A sophisticated system of the specimens closing in the airtight plastic containers provided stable moisture conditions during conditioning the specimens.

After the fixation of probes the specimens were kept three days in moulds then they were demoulded and matured for a week under laboratory conditions. Then they were placed into the CO_2 incubator to mature. Afterwards all specimens were placed into a drier at 40°C temperature to be prepared for experiments.

The moisture content interval (from $w = 0 \text{ kg/kg}$ to capillary moisture content $w_{\text{cap}} = 0.63 \text{ kg/kg}$) was divided into ten parts by the values of moisture content chosen for calibration measurements. The relative permittivity of a dry and capillary saturated material was determined as the average of the measurements performed on five specimens. Afterwards each of five specimens was conditioned to different equilibrium moisture contents (within range $0 - 0.32 \text{ kg/kg}$) during four days. After a gradual determination of the relative permittivity

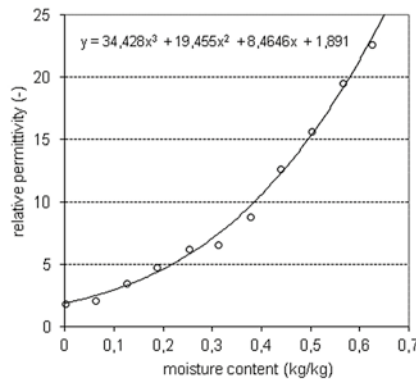


Figure 2. Calibration curve $\varepsilon(w)$ of lime-cement perlite plaster in case of probes immersed into fresh mixture

by TDR method and the consequent equilibrium moisture contents by the gravimetric method we moisturised all specimens to another higher equilibrium contents (within range 0.32 – 0.63 kg/kg) and stabilized them during the same period. This way we have got the 11 various moisture content points for determination of the calibration curve. A stabilization of the specimens moisture content until the equilibrium was provided by continuous monitoring of the relative permittivity in five minute intervals. The obtained moisture content – relative permittivity dependence is in Figure 2. The calibration curve was approximated by the polynomial of the third order.

3.3 Comparison of calibration curve and models

We compared the obtained calibration curve for the lime-cement perlite plaster to the following models: Wiener – Eqs. (7, 8), Lichtenecker – Eq. (9), Malicki – Eq. (6) and Rayleigh – Eq. (11). The calibration curve for the plaster in the case of perfect probes-material contact has the form:

$$\varepsilon = 34.428.w^3 + 19.455.w^2 + 8.4646.w + 1.891 \quad (12)$$

In Figure 3 the Wiener curves for serial and parallel model delimited the borders within which the real curve must be found. The Lichtenecker model with exponent $k = 0.5$ was the closest to the results of the measurement. The physical model of Rayleigh did not give a real shape. In general, the theoretical models have limited applicability for specific group of materials only. The calibration curve of Malicki model used primarily in soil science undervalued the measurement within the whole moisture content range. The comparison

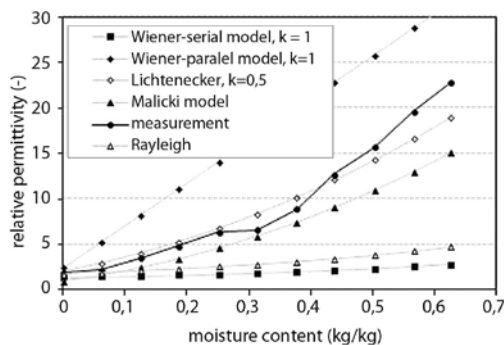


Figure 3. Calibration curve of lime-cement perlite plaster

of the calibration curve to models revealed that in order to obtain reliable estimate of moisture content by TDR it is inevitable to assign an individual calibration curve for particular material of interest.

3.4 Comparison of calibration curves obtained with various probe placement techniques

Similarly as in other contact measuring methods, also in case of TDR it is necessary and decisive concerning the preciseness and applicability of the method to solve the problem of the contact of a probe with tested material.

Wagner et al. (2007) made the simulations of a belt TDR probe measurement, first having the perfect contact with a soil and in further simulations considering gaps of various thicknesses between the sensor and the soil. The simulations showed dramatic underestimation or overestimation of the measured moisture content even in the case of 0.25 mm thick gap around the probe filled in with air or water respectively. Changing the gap thickness and content the shape of electromagnetic field was changed, and so the effective volume too. Therefore we verified experimentally the influence of contact quality on the measured relative permittivity. The perfect contact was provided by embedding the probes into the fresh plaster mixture.

The less tight contacts were realised by drilling the holes with 0.6 mm and 0.8 mm diameters in the cylindrical specimens with a consequential inserting of 0.8 mm thick probe rods. To enable a better comparison the measurements were realised at the same degrees of saturation as in the case of perfect contact. The equilibrium values are shown in Figure 4.

All measured data showed decreasing the values of relative permittivity due to a weaker contact. With increasing the moisture content the differences between the calibration curves increased. The reason for such differences was the presence of air in the contacts which influenced the shape of the electromagnetic field and so the effective volume from which the probe acquires the information about the moist material.

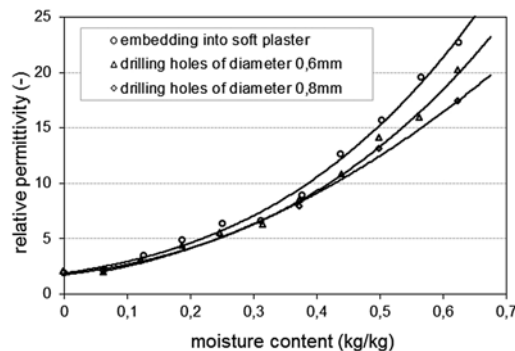


Figure 4. Comparison of the contact quality influence to the relative permittivity measurement at various moisture contents

Our measurements confirmed the significant influence of the probes placement way on the relative permittivity value and its importance during experiments. In general the realisation of a contact can be arbitrary, however at the used methodology it is then necessary for a given material to fulfil strictly a reproducible way of probes placement during all measurements.

4. Determination of liquid water diffusivity

4.1 Water uptake experiment

Monitoring the time development of water absorption in the measuring specimen under the conditions of the one-dimensional capillary suction allows us to determine the moisture content profiles and the liquid water diffusivity. The suction process was realised by experiment of free water uptake in the prismatic specimen.

A prism of the plaster with dimensions of 0.12 x 0.05 x 0.36 m was manufactured by a procedure described in part 3.3.1. The water suction was realised through the bottom surface of the area 0.12 x 0.05 m². During the specimen casting ten TDR probes were fixed in the specimen perpendicularly to its vertical axis. The first probe was placed in distance 0.030 m from the bottom of the prism and the distances between all neighbouring probes were 0.03 m (Fig. 5). The probes embedding into fresh plaster mixture provided a good contact between the specimen and the material.

Before the water uptake experiment the specimen was dried at 40°C temperature. In order to provide an approximately isothermal suction the specimen was kept at laboratory temperature and protected against the water vapour adsorption from the ambient air. The vertical walls of the specimen were protected by epoxy film in order to prevent the surface evaporation during the experiment.

During the experiment besides the moisture content profiles at particular probe positions the time course of cumulative inflow was measured. From the cumulative inflow-square root dependence the water absorption coefficient $A = 0.51 \text{ kg/m}^2 \cdot \text{s}^{0.5}$ and capillary moisture content 0.63 kg/kg were determined. The linear



Figure 5. Photograph of water uptake experiment

relationship between cumulative inflow and square root of time indicates that the analysed material is homogeneous.

4.2 Boltzmann transformation

To determine the moisture diffusivity D_w we used Boltzmann transformation l applied on moisture content profiles during the water uptake (Crank, 1975):

$$\lambda = x \cdot t^{-1/2} \tag{13}$$

The liquid water diffusivity can be determined from one-dimensional isothermal differential liquid water transfer equation:

$$\frac{\partial w}{\partial t} = \frac{\partial}{\partial x} \cdot \left(D(w) \cdot \frac{\partial w}{\partial x} \right) \quad (14)$$

For initial conditions ($w = w_0$ at $x > 0$ at $t = 0$) and boundary conditions ($w = w_b$ at $x = 0$ and $t > 0$), the non-linear partial differential equation (14), after application of Boltzmann transformation (13), can be reduced to an ordinary differential equation.

$$-\frac{\lambda}{2} \frac{\partial w}{\partial \lambda} = \frac{\partial}{\partial \lambda} \cdot \left(D(w) \cdot \frac{\partial w}{\partial \lambda} \right) \quad (15)$$

If the mentioned Boltzmann-conditions are fulfilled (constant boundary moisture content applied to the semi-infinite homogeneous medium that is initially at uniform moisture content w_0), all the measured moisture content profiles should fall on a single λ - w profile. The integration of equation (15) offers the liquid water diffusivity given by the expression (Crank, 1975):

$$D(w) = -\frac{1}{2} \cdot \frac{\int_{w_0}^w \lambda dw}{\frac{\partial w}{\partial \lambda}} \quad (16)$$

4.3 Determination of l - w profiles

Applying the Boltzmann transformation on the measured moisture profiles (Fig. 6) the l - w profiles for the water uptake was constructed (Fig. 7). The positions of the particular probes on the horizontal axis are defined from the bottom of the specimen. In the figure a wide scatter band is apparent.

A reason of this scatter can be found in several factors:

- The accuracy of moisture content measurement by TDR device.
- The quality of contact between TDR probes and tested material.
- The preciseness of the probes position determination and realisation of parallel position of planes, defined by rods of each probe.
- The heterogeneity of the porous building material.

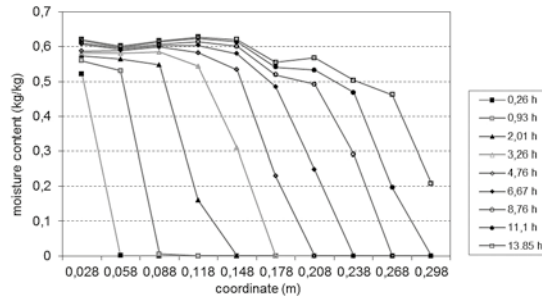


Figure 6. Measured moisture content profiles during first water uptake

4.4 Calculation of liquid water diffusivity

We calculated $l-w$ profiles and corresponding liquid water diffusivity according to the following methodology:

1. The moisture content profiles for single probes were converted by Boltzmann transformation – Equation (13). Apart from thin boundary layer, situated on bottom surface which is in hydraulic contact with water, the transformed moisture content profiles tend to join to single $l-w$ profile with continual band of random scatter (Fig. 7).
2. The boundary moisture content at $l = 0$ was treated by taking it equal to the capillary moisture content. The moisture contents smaller than the critical moisture content (0.16 kg/kg) were not taken into consideration.
3. a) The scattered data were eliminated by the smoothing based on the selection of $l-w$ data pairs in order to maintain the basic shape of characteristic curve and the water absorption coefficient value determined by uptake test (Carmeliet et al. 2004). The procedure resulted in determination of the idealised $l-w$ profile (Fig. 7).
 b) By integration of particular $l-w$ profiles the water absorption coefficients were determined and compared with the absorption coefficient obtained by the uptake test. The profile, the absorption coefficient of which was identical with or close to the uptake test value, was chosen as the representative one.

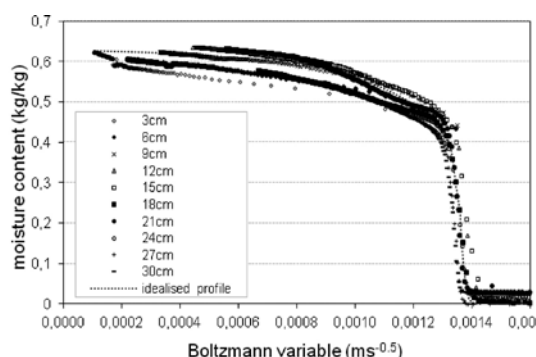


Figure 7. $l-w$ profiles for single probes and idealised profile

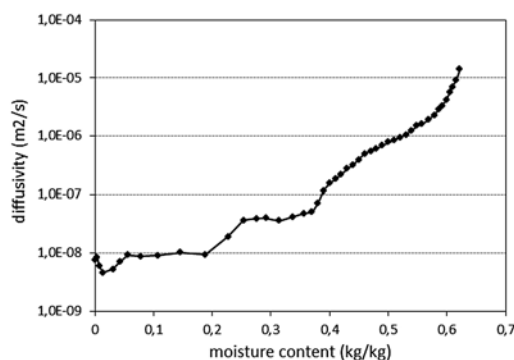


Figure 8. Diffusivity determined from idealised profile

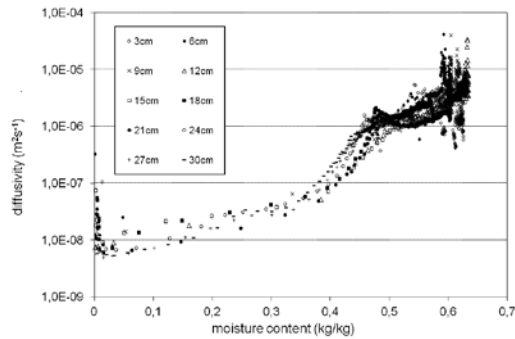


Figure 9. Scatter of diffusivity determined for single probes

4. a) The diffusivity was calculated from the idealised $l-w$ profile (Fig. 8).
 b) The diffusivity was calculated from profiles (Fig. 9).
5. The liquid water diffusivities (Fig. 8 and 9) were calculated from $l-w$ profiles numerically according to Equation (15). The values for the moisture content bigger than capillary moisture content (0.63 kg/kg) and smaller than critical moisture content (0.16 kg/kg) determined from drying test were excluded.

5. Error analysis and accuracy of TDR method

The error analysis of TDR method gives us the complex view on the method applicability for liquid water diffusivity determination. The moisture content interval within which the TDR can be applied reliably is important to know. Therefore we analysed the uncertainty of moisture content determination together with the uncertainty of Boltzmann transformation. Then the $\lambda-w$ profile determination uncertainty was analysed. As a result the theoretical error analysis of diffusivity determined from the idealized $\lambda-w$ profile and the error analysis of diffusivities determined from the particular single real $\lambda-w$ profiles were carried out.

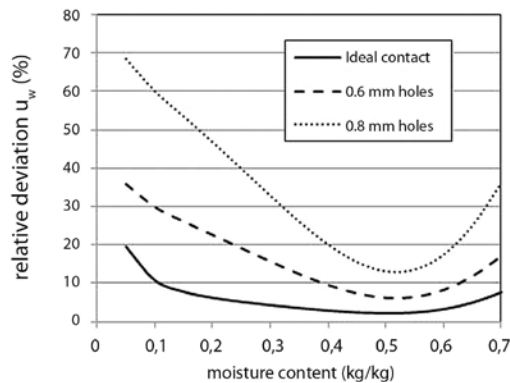


Figure 10. Relative uncertainty of moisture content determination

5.1 Uncertainty of moisture content determination

The uncertainty of moisture content determination u_w is related with the shape of calibration curve and the uncertainty of relative permittivity measurement u_ε . The error u_w was calculated by the expression:

$$u_w = \left[\frac{dw}{d\varepsilon} \right]_{w'} \cdot u_\varepsilon \quad (17)$$

in which the derivative was determined from the analytical expression of the calibration curve approximation. Uncertainty u_ε was defined by the accuracy of measured relative permittivity values for dry ($\varepsilon_r = 1.5$, $u_\varepsilon = 0.1$) and capillary saturated plaster ($\varepsilon_r = 23$, $u_\varepsilon = 1$) and the assumption of a linear dependence $u_w = 0.04 + e/23.9$.

The uncertainty of moisture content determination caused by the probe-material contact quality was treated by the same procedure and $u_\varepsilon = 0.05$ for dry material and $u_\varepsilon = 2.55$ or 5.37 for capillary saturated material in case of 0.6 mm or 0.8 mm thick holes respectively were taken into consideration. The obtained uncertainties of moisture content determination in relative form are compared in Figure 10.

5.2 Uncertainty of Boltzmann transformation

For the evaluation of λ - w profile scatter we have to specify the uncertainty u_l of Boltzmann transformation. The total uncertainty of l determination is calculated according to the expression:

$$u_\lambda = \sqrt{\left(\left[\frac{d\lambda}{dx} \right]_{x',t'}^2 \cdot u_x \right) + \left(\left[\frac{d\lambda}{dt} \right]_{x',t'}^2 \cdot u_t \right)} \quad (18)$$

The uncertainty of probe location was supposed approximately $u_x = 0.002$ m. As the time is measured with a high accuracy its contribution to the total error can be neglected and the resulting uncertainty is $u_l = 0.002/t^{0.5}$.

The high uncertainty at the early stages of suction (Fig. 11 – left) practically means the high uncertainty of the data obtained by the near surface probes (Fig. 11 – right) recording the moisture content increase as first.

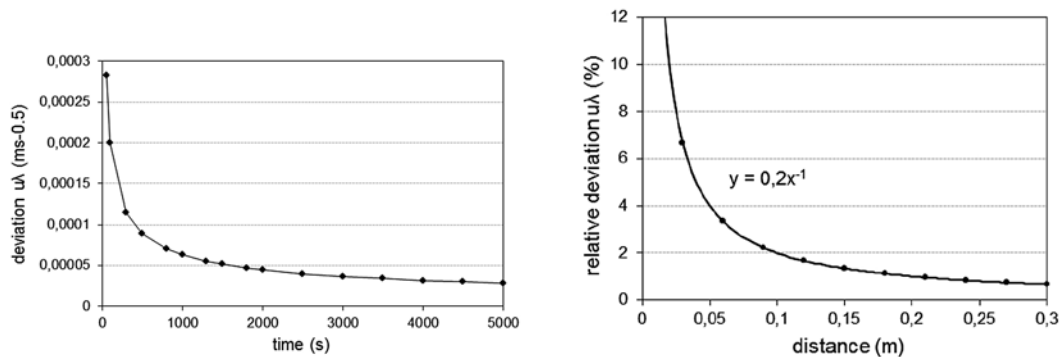


Figure 11. Uncertainty of Boltzmann transformation as function of time – left or function of probe position – right

5.3 Theoretical uncertainty of λ - w profile and diffusivity

We analyzed the upper and lower scatter envelope curves for the idealised λ - w profile which was considered to be the optimum mean curve for all probes. Thus we were able to compare the influence of particular probes position to the λ - w profile scatter.

The upper or lower scatter envelope curves were determined by a combination of the positive or negative uncertainties u_w and u_λ for each of the probe positions. The u_w uncertainties were considered for the case of ideal probe contact, that means they were given by the measurement accuracy only. The scatter envelope curves of λ - w profiles for the near surface – 3 cm (probe 1) and the core – 15 cm (probe 5) positions are plotted in Figure 12.

Due to the uncertainty of probe position determination u_x , by which the Boltzmann transformation is defined, a wide scatter of λ - w profile (horizontal shift of the profile in interval from $0.0010 \text{ m}\cdot\text{s}^{-0.5}$ to $0.0014 \text{ m}\cdot\text{s}^{-0.5}$ for λ coordinate, or up to 0.55 kg/kg for w coordinate) for the first two or three probes from the suction surface is evident (Fig. 12 – left). With increasing distance of probe from specimen suction surface the λ - w profile dispersion decreasing within the mentioned interval can be observed. The uncertainty of the λ - w profile determination due to uncertainty of probe position has practically a small influence on the diffusivity determination error (Fig. 13) as in practice the first near surface probes measure only in a high moisture contents range. The near surface probes measure only parts of the λ - w profiles.

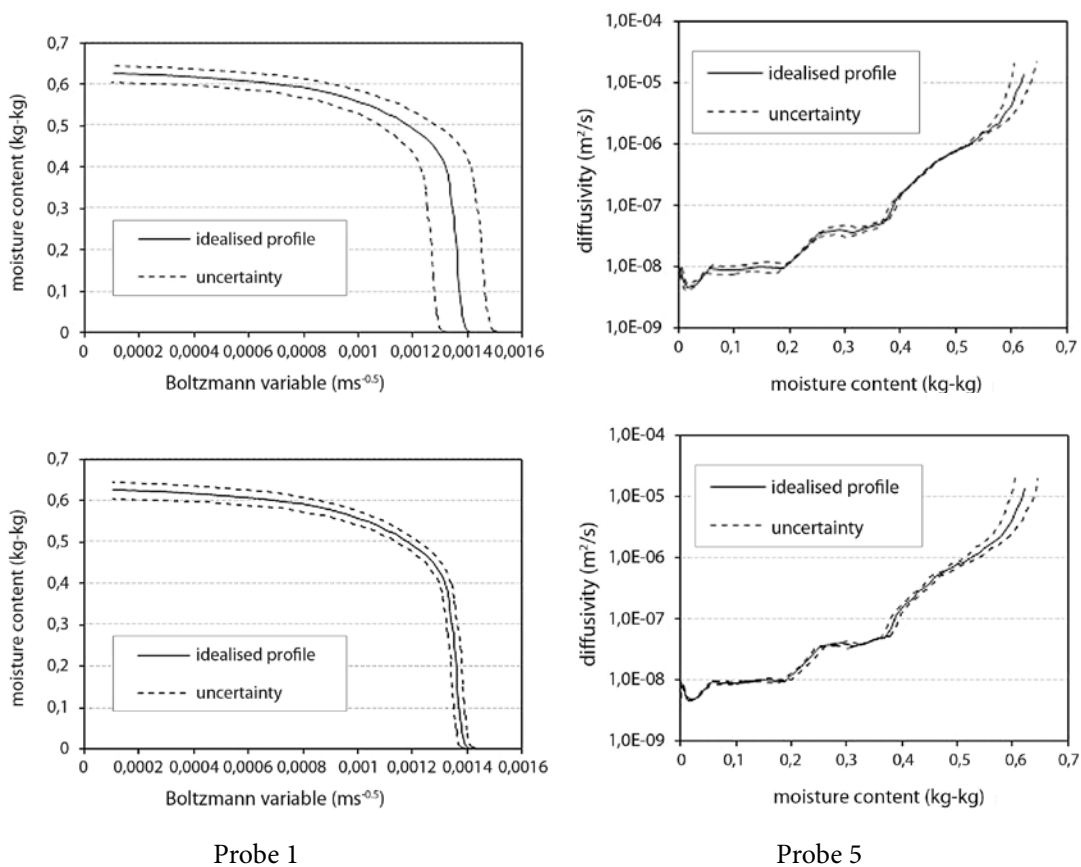


Figure 12. Idealized λ - w profile and diffusivity. Upper and lower scatter envelope curves for near surface (1) and core (5) probe positions

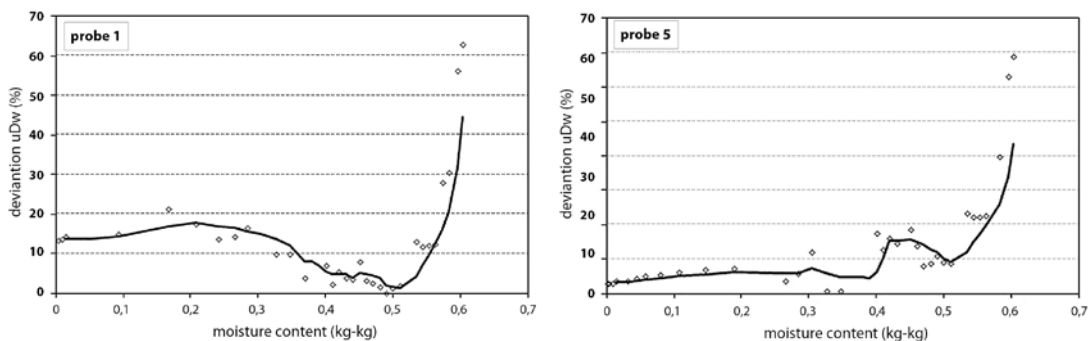


Figure 13. Relative uncertainty of liquid water diffusivity calculated for near surface (1) and core (5) probe positions

More significant is the sensitivity of the diffusivity determination to the uncertainty of the λ - w profile at high moisture contents (more than $0.55 \text{ kg}\cdot\text{kg}^{-1}$) caused by the uncertainty of moisture content determination independently on the probe position when the λ - w profile has a small steep slope, which causes the sensitivity of diffusivity calculation on the derivative of moisture content with respect to Boltzmann coordinate (Eq. 16). The calculated diffusivity values can differ by one order of magnitude due to this uncertainty (Fig. 13).

5.4 Real uncertainty of λ - w profiles and diffusivities determined for particular probe positions

We calculated the uncertainty of diffusivity obtained from the real λ - w profiles belonging to particular probes (Fig. 9). The uncertainty was calculated from the difference between upper and lower scatter envelope curves of all λ - w profiles shown in Figure 14 – left. The obtained diffusivity uncertainty (Fig. 14 – right) is significantly higher than the theoretical one caused by measurement accuracy (Fig. 13).

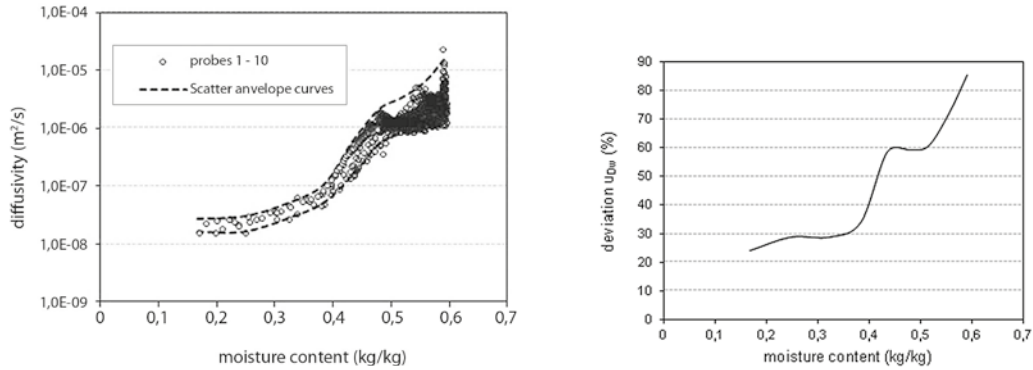


Figure 14. Relative deviation of liquid water diffusivity – right calculated from its scatter envelope curves given by all probes – left

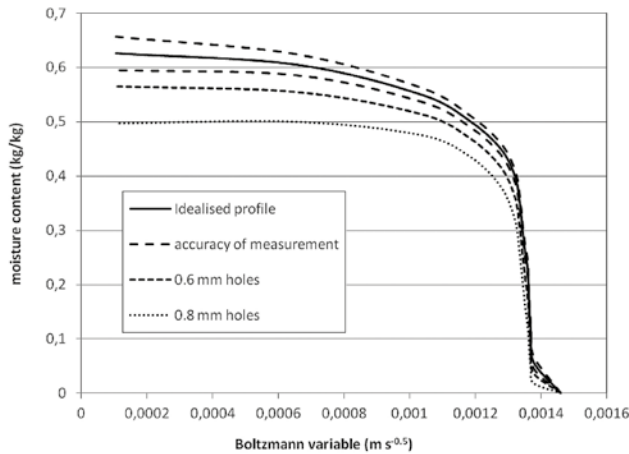


Figure 15. Scatter of λ - w profile caused by moisture content determination uncertainty

The real λ - w profiles scatter band has a trend similar to the theoretical case described in previous part – it is again getting wider with increasing moisture content. The comparison of particular λ - w profiles (Fig. 7) belonging to single probes shows small coincidence and it is difficult to find the λ - w profile common to all particular probes in this case.

If we compare particular probes more in detail the profiles determined for the near surface probes 1, 2 and 9, 10 give the lowest moisture content values and differ apparently from the profiles determined for the core probes 3, 4, 5 which give the highest values of moisture content.

If the scatter of particular λ - w profiles is compared with the scatter caused by theoretical moisture content determination uncertainty (Fig. 15) we see that the near surface profiles correspond to the imperfect contact whilst the other profiles scatter within the accuracy of measurement (Fig. 16).

According to the procedure described in part 4.4 the representative profile was selected from particular profiles by comparison of their water absorption coefficient values A . The water absorption coefficient is calculated

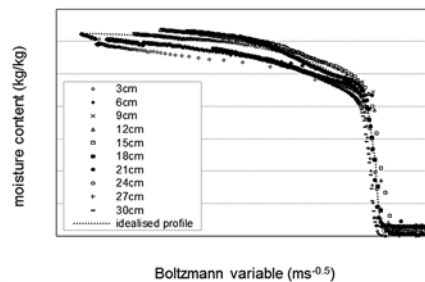


Figure 16. Scatter of λ - w profile caused by moisture content determination uncertainty in comparison with measured profiles

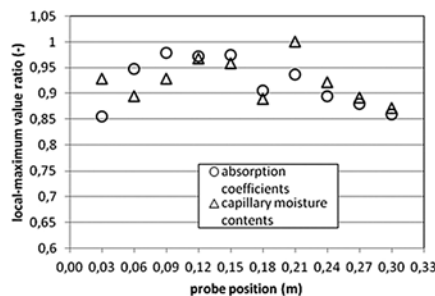


Figure 17. Local-maximum value ratios of absorption coefficients and capillary moisture contents for particular probes

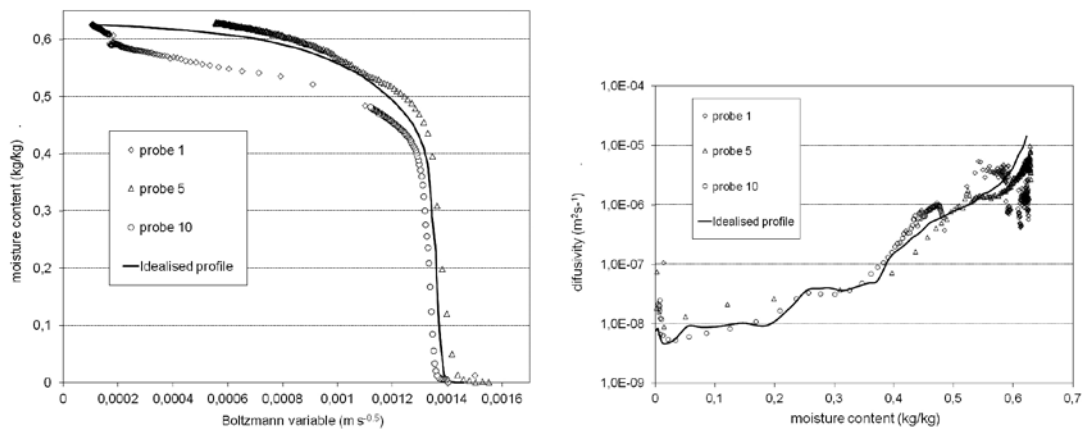


Figure 18. Comparison of λ - w profiles – left and diffusivities –right determined for near surface (1, 10) and core (5) probes

as the λ - w profile integral and the absorption coefficients calculated from particular λ - w profiles should equal to the water absorption coefficient determined from water uptake experiment as it represents the value characteristic for the whole specimen. We evaluated particular profiles according to their water absorption coefficients comparing them with the value of $0.51 \text{ kg/m}^2 \cdot \text{s}^{0.5}$ determined from the uptake experiment. The best 98 % correspondence between the integral and measurement was obtained for the core probes in comparison with the 86 % correspondence obtained for the near surface probes (Fig. 17). The probes 3, 4 and 5 located close to the middle of the specimen give the λ - w profiles which can be selected as the representative ones whilst the results given by the other probes are not acceptable. The variation of probe-specimen A -value ratios along the specimen is asymmetric and it is corresponding to the variation of the measured local-maximum capillary moisture content ratios which indicates that it is related to the probe-material contact quality decrease.

The requirement of the identity of measured and calculated water absorption coefficients looks to be a suitable criterion of the representative λ - w profile selection. Theoretically for determination of the proper representative λ - w profile we need to select only one correct probe scanning the whole moisture contents interval but the other probes give us the information on the position of this probe. In Figure 18 – left there is a comparison of the representative core (probe 5) and idealised λ - w profiles. Their shapes show a good similarity in comparison with the near surface profiles (probes 1 and 10).

As we already mentioned in part 4.1 there is no reason to interpret the observed differences among particular λ - w profiles by the coordinate dependence of diffusivity due to heterogeneity of the material.

The real λ - w profiles scatter lies within the limits of measurement accuracy and imperfect contact error (Fig. 16). The possibility of contact error occurrence in spite of the supposed perfect contact quality can be explained only by the presence of small cracks or air voids in the material. Their presence represents the contact quality decrease and the underestimation of measured values of relative permittivity mainly at high moisture contents (Fig. 4). Equally the contact quality could be decreased due to shrinkage – swelling processes during maturing and conditioning of the specimen and the uptake experiment. The result is that each of the probes gives its specific independent λ - w profile which is a function of the local contact quality and consequent systematic measurement error.

To keep the objectivity, we have to remark that our analysis does not take into account the uncertainty of derivation and integral in Equation (15). Theirs precise determination has a great impact to the resultant diffusivity. The uncertainty of derivation is hard to define and it is primarily dependent on a numerical method used.

6. Analysis

We defined three sources of the uncertainty of diffusivity determination by TDR method: the moisture content determination error given by the measurement accuracy and the measuring probe-material contact quality and the x -coordinate determination error. The moisture content determination accuracy and the moisture content determination error caused by probe-material contact quality, are increasing with the moisture content. The mentioned uncertainties together with the x -coordinate determination error influence the uncertainty of Boltzmann transformation which is increasing with x -coordinate decrease. Consequently the λ - w profile uncertainty determination is dependent on a simultaneous influence of moisture content and λ value determination errors. Finally, the resulting diffusivity which is calculated as the ratio of integral and derivative of λ - w profile is sensitive to the uncertainty of the derivative.

We analysed the influence of moisture content measurement accuracy and x -coordinate determination error to the determination of liquid water diffusivity in porous building material with the use of TDR method. The influence of moisture content and x -coordinate determination error to the determination of diffusivity is strong at high moisture contents and represents 70 % error in comparison with 5 % error at low moisture contents in case of all measuring probe locations and at the low moisture contents is significant for the probes placed close to the specimen suction surface (15 % error). Particular probe positions give different λ - w profile ranges. Each of them is specific for certain λ - w interval.

The analysis of moisture content measurements uncertainty indicates a significant influence of the probe-material contact quality deterioration during the maturing, conditioning and water suction process. We can suppose that in the material layers with higher moisture induced deformations the quality of contact decreases. The analysis of the measurements results shows the scatter of λ - w profiles given by particular probes significant at high moisture contents and the resulting uncertainty of diffusivity determination is reaching 100 % level.

A comparison of λ - w profiles given by particular probes shows their uncertainty caused by a different contact quality of core and near surface probes. According to a criterion of the identity of water absorption coefficients A determined by integration of the single probe λ - w profiles and by suction test, the probes located in core layers give the maximum absorption coefficient values and representative profile which is similar to the idealised profile. The observed λ - w profile scatter band is given by a systematic error due to contact quality deterioration.

6. Conclusions

Time domain reflectometry was adopted as the credible moisture content measuring method to determine the liquid water diffusivity. We applied TDR method in determination of the diffusivity of lime-cement perlite plaster. On the plaster we analysed the influence of the quality of probe-material contacts realised by various placement techniques to the measured relative permittivity. The calibration curve for the analysed plaster was compared to empirical, physical and mixing models and Lichtenecker model gave the best fit of the measured dependence moisture content relative permittivity dependence. TDR was used in continual long-term measurement of moisture profiles under the water

absorption conditions during free water uptake experiment. The Boltzmann transformation enables merging the moisture profiles into $l-w$ profiles band from which the diffusivity of the plaster can be determined. Considering the processing of measured data and methodology of the diffusivity computing the error analysis of diffusivity determination from TDR measurements was made. A great uncertainty of the diffusivity determined for moisture contents close to the capillary moisture content was explained by the uncertainty of moisture content measurement. Significant differences of $\lambda-w$ profiles for particular probes were observed for the core and near surface layers of the specimen. According to the requirement of the identity of the measured water absorption coefficient and the water absorption coefficient calculated as $\lambda-w$ profile integral the data given by near surface probes were excluded and only the core probes were used in the representative $\lambda-w$ profile selection.

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