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A COMPARISON OF CAPACITANCE AND TDR TECHNIQUES FOR DETERMINATION OF MOISTURE PROFILES IN BUILDING MATERIALS*

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Abstract. Comparison of time-domain reflectometry and capacitance methods for determination of moisture content in porous building materials is presented in the paper. Basic principles of compared methods are given, including their calibration process. On the basis of measured moisture profiles, the application of the methods in the engineering practice is discussed.

Keywords: moisture content, time-domain reflectometry, capacitance method

INTRODUCTION

Many instances of damage to buildings are caused by water penetrating into parts of the buildings, for instance through leaks of the foundation or the facade. Increasing moisture content can lead to the violation of proper function of building structures and, in the final stage, can cause irreversible damage to the structure. Therefore, monitoring of moisture content fields in threatened buildings belongs among the most actual topics of building physics.

There are currently various methods for the determination of moisture content in porous materials, and various moisture meters, because water in all its phases possesses many anomalous properties which also affect the properties of porous materials. Basically, the measuring methods are classified in two groups: direct methods, based on removal of water from a material (by drying or extraction), and indirect methods which determine the amount of water in specimens on the basis

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of measuring another physical quantity (e.g. permittivity, electrical conductivity, absorption of high-frequency energy, radiation energy, ultrasound velocity, etc.) having a clear relation to the amount of water in the material under examination.

In this paper, two dielectric methods for measuring moisture content in building materials are presented. The first of them is a typical capacitance method, the second method is the time-domain reflectometry (TDR) technique.

DIELECTRIC METHODS APPLIED FOR MOISTURE MEASUREMENT

Dielectric methods for the determination of moisture content are based on an analysis of the behaviour of dielectrics in a time-varying electric field and consist in the measurement of permittivity of moist porous media [1]. 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^{o}C, while for most dry building materials it ranges from 2 to 6. The permittivity of materials is strongly affected by the orientation capacity of molecules in the electric field. This characteristic is high for water in gaseous and liquid phase, but it is significantly lower for water bound to a material by various sorption forces, which makes the orientation 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 2.5, but for further layers it increases relatively fast. Therefore, the dependence of relative permittivity on the moisture content is generally characterized by an abrupt change at the transition from a monomolecular to a polymolecular layer. Consequently, the methods of moisture measurement based on the determination of changes of relative permittivity have low sensitivity in the range of low moistures, and their application is rather limited.

Based on the frequency of the applied electric field, the dielectric methods can be divided into two groups: capacitance methods and microwave methods. Capacitance methods are employed in the range of lower frequencies, typically from 100 kHz to 100 MHz. The permittivity is determined using a capacitor, usually with the measured material as its dielectric. The measuring capacitor usually has either a simple plate form (for measuring solid materials) or consists of two coaxial cylinders (for measuring loose or granular materials). Microwave methods differ from the capacitance methods principally only in the applied frequency of the power supply. In the spectrum of electromagnetic waves, microwaves occupy the frequency range of 1 GHz to 100 GHz, i.e. the range of dm to mm waves. Their wavelength is comparable with the dimensions of the electric elements, such as capacitors or resistors, and so capacitance methods cannot be employed. Also, for the signal transmission, coaxial cables or waveguides are employed instead of the usual wires. Moisture measurements are performed in a relatively narrow range of microwaves between 2 GHz and 12 GHz. The main reason is that in this range the microwave technology is the most advanced, as most common radars work in this frequency range. The microwave techniques are generally believed to be more precise and more reliable than the capacitance methods, mainly because they are much less affected by the presence of salts in water. However, they use more sophisticated technology for the detection of either reflected or transmitted waves and their calibration is usually more difficult.

The first of the methods for moisture content measurement applied in this paper was a typical capacitance method. The capacitance moisture meter used in the measurements (see [2]) was equipped with electrodes in the shape of two parallel plates with the dimensions of 20 x 40 mm. The device was built on the basis of determination of impedance change and worked in the frequency range of 250 - 350 kHz. The moisture meter reading was proportional to the capacity of the measuring capacitor (its dielectric was the investigated material). The calibration curve was determined for each sample. The final moisture profile was used for that purpose, which was determined by the gravimetric method as well. The sample was cut to pieces 1 cm wide, and the data on the measuring device were assigned to the moisture content of the particular 1 cm segments determined by the gravimetric method. The accuracy of moisture content readings was according to the analysis in [2] 15%.

The second method used for moisture measurements was the time-domain reflectometry (TDR) technique that presents a specific methodology among the microwave impulse techniques. A device based on the TDR principle (see e.g. [3]) launches electromagnetic waves to the sensors placed into the measured material and then measures the amplitudes (time interval t_s) of the reflected waves together with the time intervals between launching the waves and detecting the reflections. Since the length of the probe l_p is known from previous calibration [4], the velocity of the electromagnetic waves in the probes is equal to

$$v = \frac{2l_p}{t_s} \tag{1}$$

From the basic theory of electromagnetism, the velocity of electromagnetic waves propagation in nonmagnetic materials can be expressed as

$$v = \frac{c}{\sqrt{\varepsilon_r}}, \tag{2}$$

where c is the velocity of electromagnetic waves in vacuum, ε_r the complex relative permitivity of the material, including the real and imaginary parts. In TDR experiments, the imaginary part of the complex relative permittivity is neglected, therefore the measured value of permittivity is called the apparent value of permittivity and denoted as $\varepsilon_{r,\,a}$,

$$\varepsilon_{r,a} = \left[\frac{ct_s}{2l_p}\right]. \tag{3}$$

The fundamental element in any TDR equipment used for the determination of moisture content in porous materials is a metallic cable tester. This usually consists of four main components: a step-pulse generator, a coaxial cable, a sampler and an oscilloscope.

The step-pulse generator produces the electromagnetic waves. The electric part of the electromagnetic waves consists of sine waves covering a large frequency range, but which frequencies the step-pulse generator produces is not arbitrary. If a sine wave is superimposed on harmonic sine waves, where the highest frequency tends towards infinity, the result will be a perfect periodic square wave. This is what happens in the step-pulse generator. The periodic square wave is commonly called the "voltage step".

In the experimental work in this paper, we used the cable tester LOM/RS/6/ mps Easy Test, Poland, which is based on the TDR technology with sin2-like needle pulse having rise-time of about 200 ps. It is a computer aided instrument [5], 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 dielectric constant of measured material.

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-pulse generator are launched into the conductor in the coaxial cable with a voltage drop of several tenths of a volt between the conductor and the shield.

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 only in the type of dielectric. While the cable has usually polyethylene as a dielectric, the dielectric of the probe is the measured porous material. The connection between TDR probes and cable tester LOM is realized by a second level multiplexer which allows to connect up to six TDR probes.

The sampler detects the electromagnetic waves launched by the step-pulse generator and transmitted by the coaxial cable-TDR probe system. It generally 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 starts to measure 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.

The oscilloscope displays the simultaneous measurements of time and voltage 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 evaluation of data obtained by the cable 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 waves. 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 infinity and the wave is reflected in phase.

The reflected waves are superimposed on the waves transmitted from the metallic cable tester. The voltmeter in the sampler detects a change in the voltage between the conductor and the shield, and the timing device in the sampler registers the time interval between the start of the transmission of the waves and the detection of the reflection. Reflected waves can be either in phase with the incoming waves, which happens in the case when the electromagnetic waves meet an increase in impedance, or in counter phase, when a decrease of impedance is met.

A variety of TDR probes of different shapes and types have been designed so far. In this paper, we used a two-rod miniprobe LP/ms (Easy Test) for the determination of instantaneous moisture profiles that was designed by Malicki *et al.* [6]. This probe is designed for monitoring changes in water and salt distribution in the material. The sensor is made of two 53 mm long parallel stainless steel rods, having 0.8 mm in diameter and separated by 5 mm. 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 (dielectric constant in dependence on water level) there was found out that the sphere of influence creates the cylinder having a diameter of about 7 mm and a height of about 60 mm, circumference around the rods of sensor. The accuracy of moisture content reading is ± 2% of displayed water content.

EXPERIMENTAL RESULTS

In the experimental work, rod-shaped AAC samples with the dimensions of 20 x 40 x 290 mm were used for the capacitance method and 70 x 50 x 330 mm for the TDR method. PVC thermal shrink-wrap was employed for water and vapour proof insulation on the lateral sides to assure 1-D water transport and perfectly plain surface. The initially dry specimens were put in contact with water in vertical direction and moisture profiles were determined in 10 chosen time intervals. Before application of TDR sensors, the calibration for every probe was done using the known dielectric constants of water and benzene. Calibration of capacitance sensor was performed as given above. Sixteen LP/m probes were installed into each sample into holes bored beforehand. The probes were fixed and water and water vapour insulated with technical plasticine. Both experiments were done in air-conditioned laboratory at 23±1°C and 30±2% of relative humidity. The determination of the material water content θ by means of TDR method, from the measured dielectric constant, $\varepsilon_{r,a}$, was done using the conversion function proposed by Malicki et al. [6].

The moisture profiles determined by the capacitance method and TDR method are presented in Figure 1 in Boltzmann form. Clearly, the data conform well to the Boltzmann transformation conditions because they are reduced into one curve with a reasonably narrow error bar.

The measured results show that both the compared methods are well applicable for the determination of moisture content in porous buildings materials. The differences between measured moisture profiles are within the range of measuring errors of the applied techniques.

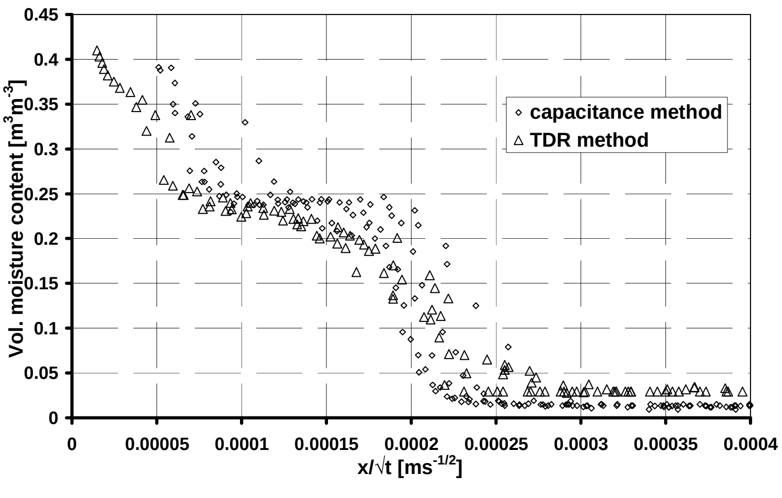

Fig. 1. Moisture profiles of AAC measured by capacitance and TDR methods

CONCLUSIONS

1. Although both the analyzed methods were found suitable for application with building materials in laboratory conditions, it is necessary to point out some of their specific limitations.

2. For the applications in technical practice, e.g. for in-situ moisture content monitoring, the TDR method seems to find a wider use than the capacitance method. The main reason is its measuring frequencies in the range of GHz, which can eliminate to a certain extent the influence of ionic conductivity of the dielectric (measured material). The accuracy of the capacitance method, due to its frequency range in kHz, is very limited in the case of moisture measurement in structures with a higher salt content.

3. In future measurements it is also necessary to take into account the effect of temperature on the accuracy of both methods, because the changes of permittivity due to the change of moisture are of the same order as the changes due to the change of temperature. Therefore, either temperature has to be maintained constant during the measurements or temperature compensation has to be included.

4. An important limitation for the use of presented methods is that they cannot be applied for conducting materials or materials containing conducting particles (e.g. reinforced concrete), because the effect of the conductivity of the matrix on permittivity is higher than that due to the water content. The dielectric loss due to the conductivity depends mainly on that dimensions of the conducting part which is parallel to the direction of the wave propagation. If the conducting parts are positioned perpendicular to the direction of wave propagation, the measurements may not be affected in a significant way.

REFERENCES

1. **Černý R., Rovnaníková P.:** Transport Processes in Concrete. (London: Spon Press, Taylor & Francis Group), 2002.
2. **Semerák P., Černý R.:** A capacitance method for measuring moisture content of building materials (in Czech). Stavební obzor, 6, 102-103, 1997.
3. **Nissen H. H., Moldrup P.:** Theoretical background for the TDR methodology. SP Report No. 11. (Lyngby: Danish Institute of Plant and Soil Science), 9-23, 1995.
4. **Plagge R., Roth C.H., Renger M.:** Dielectric soil water content determination using time-domain reflectometry (TDR). In: A. Kraszewski (ed.), Proc. of Second Workshop on Electromagnetic Wave Interaction with Water and Moist Substances at the 1996. IEEE Microwave Theory and Techniques Society International Microwave Symposium in San Francisco, 59-62, 1996.
5. **Malicki M. A., Skierucha W. M.:** A manually controlled TDR soil moisture meter operating with 300 ps rise-time needle pulse. Irrigation Science, 0, 153-163, 1989.
6. **Malicki M. A., Plagge R., Renger M., Walczak R. T.:** Application of time-domain reflecto-metry (TDR) soil moisture miniprobe for the determination of unsaturated soil water characteristics from undisturbed soil cores. Irrigation Science, 13, 65-72, 1992.

PORÓWNANIE METODY POJEMNOŚCIOWEJ ORAZ TDR W ZASTOSOWANIU DO OKREŚLANIA PROFILI WILGOTNOŚCI MATERIAŁÓW BUDOWLANYCH

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S t r e s z c z e n i e: W pracy przedstawiono porównanie metod reflektometrii czasowej oraz metod pojemnościowych w zastosowaniu do określania wilgotności porowatych materiałów budowlanych. Podano podstawowe zasady porównywanych metod, włącznie z procesem kalibracji. Na podstawie zmierzonych profili wilgotności omówiono zagadnienia zastosowania prezentowanych metod w praktyce inżynieryjnej.

S ł o w a k l u c z o w e: wilgotność, reflektometria czasowa, metoda kapacytancyjna