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Application of TDR measurement technology for construction materials in semi-scale experiments**

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Abstract. Application of TDR (Time-Domain Reflectometry) measurement technology for the investigation of hygric performance for construction materials in the conditions of a semi-scale experiment is presented. Two-needle TDR sensors are used for long term monitoring of moisture fields.

Keywords: moisture content, two-needle TDR sensors, semi-scale experiments, construction materials

INTRODUCTION

There are two basic approaches to the investigation of the hygrothermal function of a building envelope representing a multi-layered system of porous construction materials. The first possibility is to experimentally determine the thermal and hygric parameters of the particular materials applied in the tested building structure under laboratory conditions. These material parameters should be determined with relation to the moisture content and temperature in the whole range of their usage in technical practice. From these basic material tests we obtain the necessary data for the subsequent process of computational analysis of the tested building structure, where it can be exposed to real climatic conditions. The second way to describe the hygrothermal behaviour of the whole building structure is to measure the thermal and hygric field variables directly in the tested construction. The measurements can be applied directly on a real building or on so-called test houses. Field measurements on the construction site make it possible to monitor the hygrothermal performance of a particular envelope, to test the effectiveness of hygric and thermal insulation systems in real conditions, and to validate and calibrate physical models of water and heat transport in construction materials and components.

However, both the given approaches have some substantial disadvantages which have to be taken into account in a practical application. Application of computational simulations is limited by the exact determination of material parameters in dependence on moisture content and temperature, which is not an always practicable task. The next limitation consists in the faintnesses of computer codes, especially in the assessment of empirical parameters, *eg* in the determination of interface transport resistance. Therefore, computer simulations should be employed only in the first step of designing new building systems for the estimation of demanded properties of particular materials involved in the designed structure. The application of temperature and moisture fields monitoring on building site will certainly always remain the final and decisive stage of testing the performance of building envelopes. Nevertheless, this solution should be considered as a final step, when all principal problems have already been solved and the risk of failure is minimal, because the costs of building a special test house are quite high and using private buildings for testing purposes might result in difficult problems if the designed solutions do not work as expected.

In this work, a specially designed semi-scale device for the assessment of hygrothermal performance of building envelopes is described. The design of a semi-scale experiment presents a logical bridge filling the gap between the laboratory measurements of hygrothermal properties and full-scale test house measurements of field variables of

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heat and moisture transport. A semi-scale measuring system for the determination of temperature and moisture fields was designed in such a way that it simulates conditions which are as close as possible to the real conditions on a construction site, but it still maintains its laboratory character, so that expenses can be kept considerably lower compared to a real test house.

SEMI-SCALE TECHNOLOGY: BASIC PRINCIPLES

Concerning the basic arrangement of the experiment, a system of two climatic chambers imposing conditions of differentiated climate to a sample of building envelope system with the real thicknesses of all its components looks like a logical solution. This arrangement is commonly employed in similar systems designed in other laboratories. Another problem is, what field variables are measured. In real test houses and in the semi-scale systems employed in most of other laboratories, usually only temperature and moisture fields are measured (Rode *et al.*, 1993; Zheng *et al.*, 1999). On the other hand, advanced laboratory systems (Černý and Rovnaníková, 2002; Malicki *et al.*, 1992; Plagge *et al.*, 1990) can measure simultaneously temperature, water content, relative humidity, capillary pressure and salinity during a single experiment and obtain point-wise given profiles of these quantities within a material sample.

Temperature and moisture content can certainly be considered as principal quantities from the point of view of the hygrothermal performance of a building envelope. However, while temperature measurement in a series of points within a material sample is very common and does not present any problems, it should be noted that point-wise moisture measurement within a building envelope is not an easy task. Simple methods, such as those based on pin electrode resistance measurements, for instance (Rode *et al.*, 1993; Geving and Uvslokk, 2000), may not be a suitable solution for long-term measurements, because variations in surface resistance of the probes during the experiment and possible appearance of salt solutions in the measured envelope system can harm the measuring accuracy in a very significant way. Therefore, more precise and more reliable methods should be employed. One of prospective solutions in this respect can be the application of the time-domain reflectometry (TDR) method (Malicki *et al.*, 1992; Nissen and Moldrup, 1995). Time domain-reflectometry is a specific methodology among the microwave dielectric impulse techniques. A device based on the TDR principle (Nissen and Moldrup, 1995) launches electromagnetic waves and then measures the amplitudes of reflections of the waves together with the time intervals between launching the waves and detecting their reflections. From the time measurements, the velocity of electromagnetic waves propagation in the TDR probe is then determined. On the basis of the basic theory of electromagnetism, the velocity of electromagnetic waves propagation can be expressed in dependence on the complex relative permitivity, which is directly dependent on moisture content. For details of TDR methodology see Malicki and Skierucha (1989).

SEMI-SCALE MEASURING AND SIMULATING SYSTEM: DESCRIPTION

The measuring system for testing the hygrothermal performance of multi-layered building envelope systems described in this work is based on point-wise determination of temperature, water content, capillary pressure, electrical conductivity and relative humidity. We will denote it NONSTAT in what follows, according to the original terminology introduced by Plagge, who was the first to come up with the idea of a semi-scale system of this type. The measuring techniques for the determination of the above mentioned field variables present a logical extension of advanced laboratory methods developed by Plagge *et al.* (1999) to the semi-scale conditions, so that, for instance, field probes instead of laboratory probes are employed.

The designed NONSTAT system consists of two basic parts, namely the part for the simulation of climatic conditions (climatic chamber system), and the part for the measurement of field variables in the tested system (devices for monitoring moisture content, salinity, capillary pressure, relative humidity, temperature and heat flux).

The climatic chamber system consists of two climatic chambers, connected by a specially developed tunnel for testing large specimens. The construction of the particular chambers is based on common commercial solutions for controlling temperature and relative humidity conditions, but the solution of the connections between the chambers and the tunnel, and of the organization of additional access holes for parallel measurements, are quite unique. The organization of the system is given by Pavlik *et al.* (2002).

For monitoring moisture content, temperature, capillary pressure and electrical conductivity ('salinity'), a D-LOG/mpts needle pulse TDR technology based, computer aided instrument designed on the principles given by Malicki and Skierucha (1989) and produced by a Polish company, Easy Test Ltd., and Polish Academy of Science is used. This apparatus was originally designed for periodic recording of instantaneous profiles of soil moisture, matric potential (pressure of capillary water), temperature and bulk electrical conductivity ('salinity') in chosen time intervals. Therefore, the application technology of given devices has to be changed for the application for porous construction materials. The devices used are suitable for long-term laboratory investigations (Malicki *et al.*, 1992), and also for field experiments, when monitoring of water, solute and heat transport is required. Table 1 shows the measuring range and accuracy of parameters measured with the help of the following probes: FP/mts – field probe for monitoring dielectric constant, moisture content, temperature and electrical conductivity, LP/p – laboratory probe for determining capillary pressure (Jiřičková, 2003).

Table 1. The measured range and accuracy of used Easy Test devices

Constant		Measured range	Resolution	Accuracy
Dielectric constant	ε	2-90	0.1	Absolute error ± 1 for $2 \le \varepsilon \le 6$ ± 2 for $\varepsilon \ge 6$
Volumetric moisture	θ	0-100% at $\sigma \le 0.3$ S m^{-1}	0.1%	Absolute error ± 2 %
Electrical conductivity	σ	0.000-1 S m^{-1}	0.001 S m^{-1}	Relative error ± 5 %
Temperature	T	-20÷ +60°C	0.01°C	Absolute error less than ± 2 °C
Capillary pressure	ψ	0-900 mbar	1 mbar	Reading accuracy ± 10 mbar

For monitoring relative humidity, temperature, heat flux and air velocity, the measuring technique from the German company Ahlborn is used. The accuracy of particular sensors is as follows: capacitive relative humidity sensors are applicable in the range of humidities of 5-98% with an accuracy of ± 2%, temperature sensors have the accuracy of ± 0.4°C in the temperature range from -20 to 0°C and ± 0.1°C in the range from 0 to +70°C, the accuracy of heat flux sensors is ± 5% from the measured value and the precision of air velocity sensors is ± 0.01 m s^{-1} in the range of air flow velocities from 0.1 to 2.0 m s^{-1}.

The whole measuring system is operated by a computer, including the climatic data entry into the climatic chambers. In the climatic chambers, real climatic data for reference year for Prague are simulated.

MEASURING TECHNOLOGY

In the NONSTAT system, the sensors for the determination of moisture content, capillary pressure, electrical conductivity, temperature, relative humidity, air flow velocity and heat flux are used. The TDR sensors are individually calibrated to obtain their particular reference travel times t_{ref} and characteristic probe lengths l_p (Plagge *et al.*, 1999). In this calibration, the travel times for water t_w and benzene t_b, experimentally determined for each sensor, are used. Taking into account the basic equation used in time-domain reflectometry measurements (Plagge *et al.*, 1999):

$$\sqrt{\varepsilon_a} = \frac{c\Delta t_m}{2l_p}, \tag{1}$$

we obtain:

$$\sqrt{\varepsilon_w} = \frac{c}{2l_p}(t_w - t_{ref}), \tag{2}$$

$$\sqrt{\varepsilon_b} = \frac{c}{2l_p}(t_b - t_{ref}), \tag{3}$$

where: ε_w is the dielectric constant of water, ε_b the dielectric constant of benzene, ε_a the apparent dielectric constant of the measured material, Δt_m the time interval between reflections points identifying the beginning and the end of the sensors rods, t_w the travel time reading from calibration in water, t_b the travel time reading from calibration in benzene. Using the above equations, the reference time t_{ref} and the characteristic probe length l_p are determined in the following form:

$$t_{ref} = \frac{\sqrt{\varepsilon_w}\, t_b - \sqrt{\varepsilon_b}\, t_w}{\sqrt{\varepsilon_w} - \sqrt{\varepsilon_b}}, \tag{4}$$

$$l_p = \frac{c}{2}\frac{t_w - t_b}{\sqrt{\varepsilon_w} - \sqrt{\varepsilon_b}}. \tag{5}$$

Then, the apparent dielectric constant of the measured material is obtained as:

$$\sqrt{\varepsilon_a} = \frac{c}{2l_p}(t_{probe} - t_{ref}). \tag{6}$$

The volumetric moisture content is then determined using the following Eq. (7):

$$\theta = \frac{\sqrt{\varepsilon_a} - 0.819 + 0.168\rho - 0.159\rho^2}{7.17 + 1.18\rho} \tag{7}$$

where: ρ is the bulk density of the material.

In the tested structure, all the used sensors are placed into holes bored beforehand. The upper part of the bore opening is closed by silicon sealing. The probes for monitoring moisture content measure the properties of wet material, therefore it is necessary to fill up the bored hole back with the powder of the same material to avoid air gaps between the rods of the probe and the material. The sensors for monitoring capillary pressure have to be sealed by kaolin to achieve a good contact with pore space.

For a proper setting of initial conditions in the studied structure, it is necessary to achieve first near-steady-state conditions in the wall between the chambers, where the inside and outside climatic conditions are simulated. The heat flow, which is the most important parameter in this respect, is measured by Ahlborn probes. It is necessary to fix the heat flow probe on the specimen without any air layer, therefore the face of the wall has to be ground down. The heat flux sensors are then spot glued onto the frontal side of the measured construction and the space between the sensor and the wall is filled with conducting gel to prevent air spaces from forming.

After positioning all the sensors, the prepared sample is placed in the connecting tunnel. The sample, placed into the connecting tunnel, has to be thermally and water-proof insulated from the tunnel wall in order to achieve one-dimensional heat and moisture transport in the tested structure.

When the climatic chambers are connected, real climatic conditions in both climatic chambers are simulated. In the chamber, which should simulate interior climatic conditions in common residential houses, the constant temperature and relative humidity is set up. On the exterior side, real climatic data for temperature and relative humidity are used.

CONCLUSIONS

1. The functionality and applicability of the presented semi-scale measuring and simulating system, denoted NONSTAT, was proven in the process of verification of functionality of newly designed interior thermal insulation systems on the basis of hydrophilic mineral wool.

2. On the basis of performed semi-scale tests of hygrothermal function of the designed insulation system, the decision was taken about its application at the reconstruction of a historical building in Prague.

3. The NONSTAT system was also applied in the inverse modeling of heat and moisture transport and presently is used for calibration and validation tests of newly proposed complex model for predicting the service life and durability of concrete structures exposed to the real climate.

4. The application of advanced TDR technology for the investigation of moisture content fields, that was mostly applied in soil science only until now, has shown a great potential for its application for building materials. In future work it will be probably necessary to think in greater detail about the contact of the rods of TDR sensors with the measured material.

5. Generally, the accuracy of moisture measurement by TDR methodology can be affected by the conductivity of the material, the polarization on the interfaces of a heterogeneous systems, the type of water bond to the porous matrix, wave scattering, standing wave formation, granulation of the material, amount of dissolved salts, temperature.

6. On the other hand, in comparison with the standard methods commonly used for monitoring moisture content, *eg* resistance methods and capacitance methods, the disadvantages of the TDR method mentioned above do not seem to be very significant. Therefore, an application of TDR measuring technique looks very promising in the field of investigation of porous building materials.

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