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THE USE OF THE HOT-BALL METHOD FOR OBSERVING THE TRANSPORT OF MOISTURE IN POROUS STONES

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ABSTRACT

The effect of moisture on materials leads to changes in their physical and chemical properties. Materials with different porosities are saturated by various mechanisms. This paper is focused on water transport or diffusion in various porous structures. The Hot-Ball Method is used for determining the water content in certain parts of a specimen. The process of water transport or water diffusion is closely related to a porous structure. Porosity affects the transport properties of a material; therefore, knowledge of the mechanisms distributing the water in materials with different porosities is very important. The measurements were carried out by thermal conductivity sensors (hot-ball sensor) located in different positions along the path of the water's movement. The principle of the hot-ball sensor (thermal conductivity sensor) is based on the Hot-Ball Method for measuring thermal conductivity. The local moisture content and local temperature of a porous stone is inspected using the Hot-Ball Method, where the measured values of the thermal conductivity are correlated with the water content. The experimental set up for the investigation of the water diffusion in stones is described.

KEY WORDS

- Thermal conductivity,
- Moisture,
- Water diffusion,
- Thermal conductivity method,
- Porous materials.

1. INTRODUCTION

The measurement of moisture in building materials has been important to building professionals for many years to aid them in diagnosing the nature and cause of building defects. Likewise, building researchers have developed an extensive selection of measurement approaches to aid them in more detailed studies of the fundamental physical processes that underlie moisture transport [1]. The mechanism of fluid flow inside pores is complicated due to the presence of various phases and their interactions with a solid rock matrix. In order to fully understand the transport mechanisms on this scale, one needs to have a better picture of the actual porous structure of a rock [2]. The experimental and theoretical research on such materials concentrates on the processes of heat and moisture

transport in a porous structure. If a building material is in contact with water, it absorbs moisture by capillary suction. Then it is capillary active; if it does not, it is regarded as hydrophobic. The climatic parameter for moisture accumulation is relative humidity. The transport in pores can be described by mathematical models that include the boundary and initial conditions that describe the experiment. Then the mathematical formulation of a mass transfer at the macroscopic level in porous media is usually based on diffusion equations.

If gravity is ignored, the moisture transport for the one-dimensional isothermal problems that will be considered here can be described by a non-linear diffusion equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left(D_{\theta} \frac{\partial \theta}{\partial x} \right) \quad (1)$$

In this equation θ [m^3m^{-3}] is the volumetric moisture content, and D_θ [m^2s^{-1}] is the effective moisture diffusivity. In this diffusion model all the mechanisms for moisture transport, i.e., liquid flow and vapor diffusion, are combined into single moisture diffusivity, which is dependent on the actual moisture content. The moisture diffusivity D_θ has to be determined experimentally for the porous medium of interest. By measuring the transient moisture profiles during the various transport processes, i.e., drying and absorption, the diffusion coefficient can be determined directly [2].

The experimental studies are focused on determining the moisture content in porous materials in a certain area of the material around the sensors to determine the laws by which the moisture is spreading. The porous structure is represented by a composite material, the one component of which is formed by pores and other one is the main solid matrix. The content of the pores can be filled by air (vapour), water or ice. Then the thermophysical parameters of the pore component vary in a broad range. Thus by measuring the effective values of the mentioned parameters, the moisture of the porous structure can be determined.

The measurement of the thermophysical properties consists of an evaluation of thermal conductivity, thermal diffusivity and specific heat, and it provides insight into the optimal selection of a material.

The determination of the thermophysical parameters of materials has two parts. In the first, a heat equation is solved for the given boundary and initial conditions. Due to that solution we get the temperature function, which describes the temperature distribution in the sample. The temperature function includes such parameters as time and parameters characterizing the thermophysical properties of the material. The temperature function also includes additional parameters, such as thermal contact resistance, the coefficient of the heat transfer, etc. Therefore, it must take into account the possibility of the technical realization of the experiment. In the second part, the experiment is realised, which allows for the determination of the temperature field of the specimen. Then we can calculate the thermophysical parameters from the temperature function and experimental data [3]. The moisture of the material is closely related to its pore structure, which is usually modelled as an interconnected system of capillaries with different radii. For the quantitative determination of the capillary suction forces, it is customary to use a cylinder capillary model, as shown in Figure 1.

2. PRINCIPLE OF THE EXPERIMENTAL METHOD

The optimal functionality of the moisture sensor depends on an appropriate method for measuring the thermal conductivity of a body constructed of porous materials. We use the Hot-Ball Method for measuring thermophysical properties. The method makes use of a small ball that generates a transient temperature field in its vicinity and simultaneously measures the temperature. The ball's temperature is a measure of the thermal conductivity of the surrounding material.

Fig. 1 Schematic view of the water column in a cylinder capillary model.

Fig. 2 The temperature response for the constant production of heat.

A typical measurement is shown in Figure 2 along with the characteristic points used for the calculation of the thermal conductivity. The measuring procedure consists of measuring the temperature of the specimen which represents the base line, switching on the heating and simultaneously scanning the ball's temperature. When the ball's temperature stabilizes, the heating is interrupted, and a period of temperature equilibration follows. When the temperature of the specimen is stabilized to the value prior to the heat generation, the next measurement may be realized. The repeatability rate of the measurements depends on the thermal conductivity, and it takes from 5 up to several hundred minutes. The measurement alone takes from 50 up to 400 seconds, depending on the thermal conductivity of the material investigated. For rocks it ranges from 80 up to 150 seconds.

The sensor is made of two components: a thermometer and a resistance (patented) (Fig. 3, left). These components are glued together with epoxy. After the epoxy is cured, the sensor is ready to be calibrated. The diameter of the finished sensor is in a range of 2 to 2.3 mm (Fig. 3, right).

Fig. 3 A sketch of the glued together components (left); the completed sensor compared with a match (right).

The working equation of the hot-ball sensor is based on an ideal model, which assumes a constant heat flux q per surface unit from the empty sphere of radius r_b into the infinite medium for times $t > 0$. Then the temperature distribution within the medium is characterized by the function [3]:

$$T(t, r_b) = T_0 \{ 1 - \exp(u^2) \Theta^*(u) \} \quad (2)$$

where $T_0 = \frac{q}{4\pi r_b \lambda}$, $u = \frac{\sqrt{at}}{r_b}$

λ is thermal conductivity [$\text{Wm}^{-1}\text{K}^{-1}$], and a is thermal diffusivity [m^2s^{-1}]. $\Theta^*(u)$ is the standard complementary error function.

Function (2) can be derived from the partial differential equation governing heat conduction, considering the initial condition $T(0, r) = 0$ and the boundary condition $-\lambda \frac{\partial T}{\partial r} \bigg|_{r=r_b} = qI(t)$. For time tending to infinity, $t \rightarrow \infty$, equation (2) is reduced to its steady-state form:

$$T_m = \frac{q}{4\pi r_b \lambda} \quad (3)$$

By rearranging the latter equation one obtains the working equation of the hot-ball sensor [3]:

$$\lambda = \frac{q}{4\pi r_b T_m} \quad (4)$$

Two evaluation strategies can be applied for the signal shown in Figure 2, namely, the fitting of function (2) over the temperature response measured in the experiment or the use of working equation (4) for long measuring times. The fitting procedure requires the determination of the time window over the temperature response where on the one hand, enough high sensitivity coefficients should exist, considering the thermophysical parameters calculated. On the other hand, the construction parameters of the sensor should not influence the temperature response. The construction parameters mainly influence the temperature response in the initial time period. Working equation (4) requires a good stabilized temperature response, which sometimes cannot be reached in real time for low thermal conductivity materials.

Both strategies require knowledge of the radius of the sensor r_b , which has a high degree of uncertainty due to its construction. Therefore, calibration has to be used to obtain parameter r_b with the help of a fitting (equation (2)) or the use of a working equation (4). The calibration has to be performed with the help of standard fluids such as distilled water and glycerol to avoid any thermal contact resistance between the sensor and the medium.

3. EXPERIMENT AND RESULTS

Sandstones with total porosities of 16.96%, 9.06% and 5.9% were used for the experiments. Hot-ball sensors (thermal conductivity sensors) in certain positions on the sample (Fig. 4) were fixed along the saturation path. The samples of sandstone were dried under a vacuum and moisturized to a water saturated state in order to calculate their moisture content. The same initial states for all the samples were established. The specimen was fixed in a specimen holder in a vertical position and inserted into a climatic device. A temperature of 25 °C and an ambient humidity of 30% were maintained during the experiment.

Fig. 4 Sample of sandstone with three sensors in certain positions.

A one-dimensional transport process under isothermal climatic conditions was realized from the bottom to the top of the sample. A special mechanism was used to keep a constant water level of about 2 mm on the bottom of the sample. While the bottom specimen's surface is in contact with the water, the upper specimen's surface is influenced by the ambient humidity. Three hot-ball sensors were used to determine the quantitative amount of vapor and liquid water (moisture content) in the immediate vicinity of the sandstone. Three RTM devices (Transient MS) were connected to these sensors to collect data. The results of the data from the RTM devices are local values of the moisture acquired by measuring the amount of thermal conductivity provided by the hot-ball sensors. The total increase in moisture of each sample is measured by weighting (the integral moisture of the whole sample). The integral moisture shows any change in weight, depending on the increase in the water content of the sample during the period of saturation.

The sandstone samples were saturated. First, the vapor was diffused, and then the capillary saturation was observed in the samples. The behaviour of the saturation mechanisms and the redistribution of the moisture content in the samples strongly depend on the structure. The structure of the sample and the conditions of the experiment must be considered when measuring thermophysical parameters in heterogeneous materials. The heat spreads throughout the system, and it is very difficult to isolate the sample from its surroundings. Therefore, we maintain the specimens at a constant temperature and also at a constant humidity.

Thermophysical properties are affected by moisture. The capillary flow and flow on a surface can participate in the transport of water (moisture) into a specimen. The water and vapour transport depend on the total atmospheric pressure gradient and also on the radii of the pores (Fig. 1).

The experimental data obtained from the hot-ball sensors are shown in Fig. 5. The gradual saturation of the specimen, depending on the position of the hot-ball sensors, can be determined. Saturation strongly depends on porosity. The complete picture about the processes of water saturation in a material with a certain porosity can be obtained after saturation. Then the values q/T_m (eq. 4) are converted to the percentage increase of the moisture in the specimen. The calibration was made using q/T_m values for the dry and water-saturated stages using a linear function. Figure 5 shows the local values for the sensor, which is the closest to a container with water. This value is plotted depending on the time. Simultaneously, the value obtained by weighting the whole sample is plotted as a function of time (red dots on the graph). The experiment shows that we are able to describe not only the increase in moisture by weight, but also the local value in certain parts of the sample by using the Hot-Ball Method. The hot-ball sensors were in the same positions in all three specimens (Fig. 4).

The graphs in Figure 5 represent the transport of water from the bottom sensors, which are closest to the additional water. The histograms in Figure 6 describe the distribution of pore sizes in a normalized volume obtained by Hg-porosimetry.

Fig. 5 Start of saturation in sandstone with different porosities.

a)

b)

c)

Fig. 6 Histogram of pore sizes vs. normalized volume for sandstone with:
a) 16.69% effective porosity; b) 9.06% effective porosity; c) 5.9% effective porosity.

For the sample with 16.96 % total porosity, water saturation starts very fast (Fig. 5 left). This is typical of materials which contain larger pores, as can be seen in the graphs in figure 7, left. The sandstone with 16.96% porosity has pores in the 200-500 nm range (Fig. 6a) and then a very broad distribution around 200 μm . Saturation is very fast in such materials.

In the sandstone with 9.06% total porosity (Fig. 5, center), the water saturation runs fast too. This sandstone has a large pore distribution of around 15 nm (Fig. 6b) in which the capillary water saturation runs very rapidly. Capillaries (pores) in such materials are narrow. In agreement with Figure 1, when the radius of capillary r is smaller, the water increase is higher.

The sample with 5.9% total porosity represents either pores of about 200 μm or about 10 nm (Fig. 6c). The water saturation is progressive, because at the beginning the water is filling the bigger pores and then continuing with the smallest pores (Fig. 5, right). This corresponds to very low-porous materials where boundary conditions play no role in the transport of water in the sample.

4. CONCLUSIONS

The theory of the hot-ball sensor and its application has been presented. The sensor is based on a ball that generates a constant heat and simultaneously measures the temperature response for $t > 0$. The ideal model of an empty ball in an infinite specimen gives the working relation of the Hot-Ball Method. The working equation

concerns the steady state regime reached after some period of time. The steady state regime could be reached in tens of seconds up to tens of minutes, depending on the thermal conductivity of the tested material. Then the thermal conductivity of the specimen is determined by the stabilized value of the temperature response. A calibration procedure has been used to analyze the sensor's reliability. The experiment describes the water saturation of sandstone. The sandstones were cut from different geographical locations and therefore have various structures and porosities. The hot-ball sensors were applied to monitor the increase in saturated water in the sandstone samples. The experimental data were validated by Hg-porosimetry and compared with possible mechanisms for water saturation. The experiments have shown that the porosity and structure of materials strongly affects the water saturation process and the behavior of the materials.

The Hot-Ball Method, together with the RTM devices, works independently of the operator. So this method is very advantageous for the continuous monitoring of moisture changes in rock massifs, historical monuments, and other applications (monitoring the setting of concrete, polymerization, structural transformation in pores, the ageing of materials).

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