1. INTRODUCTION

A prevailing type of realized wall building structures is masonry construction from block building materials bonded with mortar. A considerable number of building failures are caused and accompanied by the undesirable effects of moisture. Contemporary trends in the building industry lay high demands on failure-free functioning of buildings, especially on the thermal insulation qualities of their envelopes. Up to now insufficient attention has been paid to the material properties of porous building materials and the specification of their characteristic humidity parameters. A necessary quantity for their expression is the coefficient of moisture capillary conductivity κ.

2. INPUT DATA FOR CALCULATION OF THE COEFFICIENT OF CAPILLARY CONDUCTIVITY

If we know the spatial and temporal distribution of moisture in a given material, we can establish the coefficient of the capillary conductivity κ [1]. At present Matan’s method is used in a case where a boundary condition is not applied at the dry end of a specimen as a method for non-stationary moistening in combination with the gravimetric method. We can use this method provided that we know one wetting curve and the time interval corresponding to the curve (see Fig. 1) in order to verify the possibility of obtaining outputs of experimental measurements by means of microwaves without destruction of the explored specimen. As compared with the gravimetric method, determining moisture distribution using
electromagnetic microwave radiation (hereafter EMWR) provides continuous measurement of necessary data together with the elimination of inaccuracies due to human error and measurement of more wetting curves in one specimen, which allows for the use of other calculation methods as well. Fig. 1 shows a theoretical assumption of the course of wetting curves at time intervals \( t \) following the start of moistening as well as boundary conditions needed for calculation of the coefficient of moisture conductivity \( \kappa \). Lengths as coordinates are marked along the \( x \) axis, at a distance from the contact of the measured specimen with the free water level: A is the coordinate of the start of the profile of the wetting front, and B is the coordinate of the length of the wetting front. C is the coordinate into the dry region \( \rightarrow \infty \). Along the vertical axis the values of the humidity by weight are plotted, \( u_1 \) is the humidity by weight in the measured specimen after its moistening, and \( u_2 \) is the humidity by weight in the measured specimen before its moistening.

The experiment simulates actual masonry deliquescence. A specimen of material is placed in the measuring apparatus, whose arrangement is based on an approximation of the one-dimensional water flow, which is described by Equation (1). The coefficient of capillary conductivity is defined by Lykov’s equation, which expresses the flux density of the capillary water \( q \) driven by capillary mechanisms. Its general (spatial) form is:

\[
q = -\rho_s \cdot \mathbf{x} \cdot \nabla u = -\rho_s \cdot \mathbf{x} \frac{\partial u}{\partial x} \quad \text{[kg.m}^{-2} \cdot \text{s}^{-1}] \quad (1)
\]

By combining Lykov’s equation, which is a phenomenological description of the transport liquid moisture of in porous materials, and the continuity equation, whose general form is:

\[
\rho_s \frac{\partial u}{\partial t} = \mathbf{V} \cdot \mathbf{q} = -\frac{\partial u}{\partial x} q \quad (2)
\]

which expresses the classic conservation of matter principle that liquid moisture in a given elementary volume is decreased during an elementary time interval by the quantity of the liquid, which is drained during this interval through the closed surface enclosing this volume. Thus we obtain a non-linear equation (4) of the diffusion type, which plays a principal role in describing the transport of moisture in capillary porous materials under isothermal conditions:

\[
\frac{\partial u}{\partial t} = \frac{1}{\kappa} \frac{\partial^2 u}{\partial x^2} \quad (3) \quad \text{[2]}
\]

If we arrange the measurements in such a way that the liquid can rise through the specimen only in the direction of the \( x \) axis, and in the directions of the axes \( z \) and \( y \), parallel with the water level, the humidity gradients equal zero, and the last equation can be expressed in a one-dimensional form:

\[
\rho_s \frac{\partial u}{\partial t} = -\mathbf{V} \cdot (\rho_s \cdot \mathbf{x} \cdot \mathbf{V} u) \quad (4) \quad \text{[2]}
\]

(temporal change in the quantity of liquid water in the material equals the negative spatial change in flow density)

In order simplify the calculations, we can use Boltzmann’s transformation. By gradual rearrangements by means of Boltzmann’s transformation and by converting function \( u \) of two variables \( x, t \) to function \( \omega \) of one variable \( \eta \) with boundary conditions \( u(0), \omega(0) = u_1 \) \( a(x,0) = \omega(\eta) = u_2 \), we can obtain a common
differential equation, which cannot be solved analytically for inconstant $\kappa(u)$. However, the numerical solution of the common differential equation is much simpler than the solution of the partial differential equation. If we arrange the measurements so that the liquid can rise through the specimen only in the direction of the $x$ axis, and in the directions $z$ and $y$, parallel with the liquid level, the humidity gradients are equal to zero, and the last equation can be expressed in a one-dimensional form [1]:

$$\frac{d}{d\eta} \left[ \kappa(\omega) \frac{d\omega}{d\eta} \right] + 2 \eta \frac{d\omega}{d\eta} = 0$$

(5)

where $\omega$ is the humidity as a function of the new variable $\eta$ under the condition that $t$ is the given time interval of deliquescence [-]. $u_1$ is the relative humidity attained by the weight of a material in time $t$ [-]. $u_2$ is the humidity by weight of a material in a steady state [-].

The coefficient of capillary conductivity can be calculated either by gradual integration according to the $x$ coordinate ($\xi$) or by introducing $\xi$ to substitute the distance measured along the specimen’s length from the point on the curve representing the wetting front $du$, expressed in the formula up to $x$. In practice, however, it is included in the interval on the measured specimen up to the distance, where moisture occurs in a steady state, i.e., $u_2$, which is the value of the relative humidity in the material measured.

If we know the moisture distribution $u(x)$ in a given time $t$, (i.e. $t$ is a constant and $u(x)$ is a function of a single variable $x$), we can express the moisture conductivity coefficient $\kappa$:

$$\kappa(u(x)) = \frac{1}{2.t.u'(x)} \int_0^x u'(\xi) d\xi$$

(6) [1]

where $\kappa(u(x))$ is the capillary conductivity coefficient as a function of the humidity in the length of a specimen $[m^2.s^{-1}]$. $t$, time interval, in which humidity is measured as a function of curve $u(x)$ [s]. $\zeta$, substitution of the distance measured along the specimen’s length from the point on the curve representing the wetting front $du$, expressed in the formula up to the distance, where moisture occurs in a steady state. $\omega$, new variable, assuming that $t$ is a concrete time interval [-]. $\eta$, transformation denoted as a Boltzmann coordinate $[m.s^{-1/2}]$. $x$, coordinate in the length of the specimen from the bottom of the measured specimen [m]. $u_1$, maximum (attained) value of the humidity by weight [-]. $u_2$, humidity of the material by weight in a state of relative humidity [-].

### 3. EXPERIMENTAL MEASUREMENT USING ELECTROMAGNETIC MICROWAVE RADIATION

At the Department of Building Constructions, University of Technology Brno, a measuring apparatus was experimentally set up.
to detect the transport of moisture in a building material using EMWR based on theoretical assumptions for expressing the input data needed for calculation of the capillary conductivity coefficient. The principle of detecting liquid moisture was based on the knowledge of EMWR behaviour in an interaction with various materials. Fig. 2 represents a detailed construction diagram of the experimentally assembled apparatus for monitoring the transport of moisture in porous materials. It is made up of a tank to contain the liquid, and a positioning mechanism, which serves to vary the level of the liquid. The tested specimen is placed beneath the tank and is fastened to a stirrup hanging on a digital scale. In the space above the tank a waveguide transmitting microwave radiation, which is linked to a radiation source (in this case the Gunn diode) is accommodated. On the other side of the tank, opposite the transmitting waveguide, a receiving waveguide is situated. Both waveguides, as one unit, are height adjustable and are arranged on a supporting frame (not shown in the figure). Both waveguides have built-in shutters, by means of which radiation intensity can be regulated. The specimen is put between the two ends of the waveguides. A microwave receiver is connected to a volt-milliammeter, where the values of the varying radiation intensity can be read at the output. A volt-milliammeter is linked to a computer, where, by means of appropriate software, you can monitor the results. They are shown in the form of the recorded values of the EMWR intensity variations at pre-set time intervals. A communication program serves to transfer the indicated quantities, which read the data on the digital scale display. A synchronized power unit for waveguide motion enables the conversion of the velocity of their shift into units of length to express the x coordinate showing the location of the moisture concentration.

4. APPLICATION OF EMWR

In order detect the location of moisture by weight in a porous structure of an inert material; we use EMWR properties applied to the measurement of the moisture content by microwave methods. They enable non-destructive measurement and have a relatively high sensitivity; the measurement results are not influenced either by the chemical composition or the content of the chemically bound water. Microwaves pass through the materials without affecting their properties. A suitable frequency for measuring moisture content in porous building materials is about 10^{10} Hz. Fig. 3 indicates the transmission of the tested building materials measured by the experimental measuring apparatus.

Fig. 3 shows a graphic representation of the dependence of a drop in detected voltage values, which represents the input EMVZ flux, to which corresponds a voltage of 500 mV, which is decreased following the passage through the specimen. The voltage is generated by the EMWR flux sensor in the experimental apparatus. Measurements were taken for the ceramic burnt body having a bulk density \( \rho_m = 1800 \text{ kg/m}^3 \), where you can see the linear dependence of the difference between voltage \( U_{in} \) represented by the EMWR input flux, and voltage \( U_{out} \) represented by the flux after the passage through the specimen on the value of the voltage determining the input flux.

5. METHODOLOGY OF MEASUREMENT USING THE EXPERIMENTAL APPARATUS

The methodology of measurement using the experimental apparatus was developed on the basis of test measurements on specimens taken from porous materials with various bulk densities. Fig. 4 shows the procedure for acquiring data to calculate the capillary conductivity coefficient both by the Matan method and integral method. Use of this procedure makes it possible to continuously obtain several wetting curves in a non-stationary state at selected intervals for inert porous materials without their destruction and without interrupting the measurement. \( \kappa \) is the coefficient of capillary conductivity; \( u_m \) humidity by weight; \( X \) coordinate of the location of the wetting front profile - see Fig. 1.
6. MEASUREMENTS FOR CALCULATION OF THE CAPILLARY CONDUCTIVITY COEFFICIENT

In order to calculate the capillary conductivity coefficient, it is necessary to obtain wetting curves – i.e., the function expressing the dependence between moisture and distance from the source of the moisture. The procedure for obtaining wetting curves is as follows.

6.1. Dependence between the quantity of radiation passing through a specimen and moisture content in a specimen

The dependence was determined by means of the gravimetric method, which determines moisture in specimens by weight and simultaneously the quantity of radiation passing through the specimen. The dependence of moisture by weight $u$ on the quantity of radiation $z$, passing through the specimen, is determined from the values measured in 6 specimens.

Fig. 5 presents a measurement graph of the functional dependence of a change of intensity of EMWR on moisture by weight for a ceramic burnt body with a bulk density of approx. 1800 kg.m$^{-3}$ (Štíty na Moravě brick factory) in the Maple program.

6.2. Relationship between the quantity of MW radiation passing through a specimen and the distance from the source of the moisture

The values of the coordinates determining the location of the wetting front’s profile are obtained from measurements using a microwave measuring apparatus. The detection quantity of moisture the diffusing in the material is carried out at selected time intervals from the start of the moistening of the specimen material, which is prepared for monitoring of the moisture transport. Fig.6 shows a specimen of a ceramic burnt body during moistening.

The output of radiation intensity, depending on the quantity of the moisture content, is continuously recorded at preset time intervals by moving waveguides at a synchronized velocity along the length of the tested material specimen, which is fixed in the stirrup of the hanger on the scale in order to touch the water level.

The travel velocity of the waveguides is constant, and the position coordinates of the absorbed EMWR, depending on the moisture by weight, is determined by their conversion into units of length using Linregrese Excel - see Fig. 8

Fig. 8 shows a conversion of the temporal data in compliance with the travel velocity of the waveguides to units of length $[1 \text{ graduation line is } 3 \text{ mm}]$ of the X coordinate defining the wetting front profile for foam concrete at time intervals of 10, 20 and 30 minutes in Linregrese Excel. These graphs prove that moisture transport can be...
Fig. 6 Specimen of ceramic burnt body and gas-silicate during moistening while monitoring moisture transport

Fig. 7 Initial measured values for determination of the location of the wetting front’s profile for a ceramic burnt body

Fig. 8 Conversion of temporal data in compliance with the travel velocity of waveguides to units of length of the X coordinate defining the wetting front profile [mm] for a ceramic burnt body at time intervals of 10 minutes using Linregrese Excel

MONITORING OF MOISTURE IN BUILDING MATERIAL BY EMW RADIATION
continuously monitored in the course of moistening of a specimen and that data on moisture distribution can be recorded at selected time intervals.

Provided that the measurement is carried out from the start of the specimen length of the “x” coordinate at the origin, i.e. from the contact of a measured specimen with a free water surface, it is possible to consider the values of the length or height to be decisive for determining the location of the propagating wetting front, see Fig. 5.

6.3 Dependence of EMWR on the location of moisture in the specimen material

By using the least squares method in the Maple program, the equations of dependence were determined from the values measured for the three different time intervals (10, 20, 30 min.) from the start of the moistening. The equations describe the dependence of radiation z from the distance from the source of the moisture expressed by the coordinate, the anticipated moistening curves and the functional dependence of change in the EMWR intensity on the moisture by weight $u_m$ and on the length of the specimen at a selected time interval of its moistening:

$$z_{10} = 351628808 \cdot 1x^4 - 44819350 \cdot 86x^3 - 1664476 \cdot 757x^2 - 8156 \cdot 829195x + 2 \cdot 964486146$$
$$z_{20} = 274311438 \cdot 3x^4 - 40235433 \cdot 35x^3 + 1815352 \cdot 482x^2 - 17809 \cdot 74743x + 29 \cdot 24692066$$
$$z_{30} = 621621193 \cdot 02x^4 - 16736345 \cdot 45x^3 + 1107438 \cdot 297x^2 - 14377 \cdot 52465x + 29 \cdot 45082869$$

Fig. 9 shows the expression of the initial measurement of the outputs presented in Fig. 7 and processed the Linregrese Excel program (see Fig. 8) and then in the Maple program.

6.4 Representation of wetting curves

Wetting curves are determined as graphs of complex functions, which are established by combining the functions from previous calculations. The graph plotting of the functions expressing the dependence of the moisture content on the distance from the moisture source, i.e., complex functions according to the assumptions in part 1 are:

$$u_{m1} = f(z_{10}(x))$$
$$u_{m20} = f(z_{20}(x))$$
$$u_{m30} = f(z_{30}(x))$$

6.5 Time course of moistening of specimen

Fig. 11 represents the time course of moisture propagation through the ceramic burnt body and foam concrete at short time intervals from the start of the moistening under the assumption that the bottom of the specimen is in close contact with the water surface (see Fig. 13).

The data on the total quantity of water absorbed by the contact area of a specimen from the water surface, is found by weighing, because the specimen is freely hanging on the scale during measurements. The findings about the course of moistening are needed for choosing time intervals $t_x$ and for selecting representations of the wetting profiles $u(x)$ in order to calculate the coefficient of capillary conductivity as an assumption shown in Fig. 1.
7. VERIFICATION OF THE WETTING CURVE

Fig. 12 shows a graphic representation of the moisture distribution in a specimen from a ceramic burnt body. The wetting curves are determined by the gravimetric method by breaking the tested specimen into segments of 20 mm each, which are measured from the point of contact with the water level at a selected time interval from the start of the moistening. The graph includes values measured in 6 specimens.

8. CONCLUSION

This method for calculation of the capillary conductivity coefficient as compared with the gravimetric method offers a higher frequency of measurement and accuracy of data on the moisture content in building materials.
detailed cross sections along the length of the tested specimen by converting the shift in the direction of the longitudinal axis of the specimen at a measured time interval to the sections of the measured coordinate. The values received from the continual measurement plotted as curves are suitable for mathematical processing, thanks to the accuracy of the measurement, because the closest possible approximation to the actual state is achieved by modelling the moisture field as well as by calculating the coefficient of capillary conductivity. The detection of EMWR in mV is more accurate in the regions with lower moisture content.

The experimental measuring apparatus and proposed method of measurement make it possible to continue with mathematical processing of the outputs obtained for computing the capillary conductivity coefficient κ.

The advantage is a non-destructive, contactless, continuous and relatively fast measurement. The drawback of this method is the need to determine the “calibrating” curves for individual materials, i.e., to determine the dependence of EMWR absorption on the humidity by weight for different building materials.

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