



# Monitoring of the absolute water content in porous materials based on embedded humidity sensors



Christoph Strangfeld <sup>a,\*</sup>, Sabine Kruschwitz <sup>a,b</sup>

<sup>a</sup> Bundesanstalt für Materialforschung und -prüfung, Unter den Eichen 87, 12205 Berlin, Germany

<sup>b</sup> Technische Universität Berlin, Gustav-Meyer-Allee 25, 13355 Berlin, Germany

## HIGHLIGHTS

- Monitoring of moisture transport in porous building materials.
- Humidity sensors are embedded into screed during concreting.
- Conversion of water vapour pressure into pore saturation.
- Aggregation of the pore saturation to free liquid water in the material.
- Prediction of the sorption isotherm hysteresis based on the pore volume distribution.

## ARTICLE INFO

### Article history:

Received 4 December 2017

Received in revised form 12 April 2018

Accepted 6 May 2018

### Keywords:

Moisture monitoring

Screed

Kelvin equation

Embedded sensors

Material moisture

## ABSTRACT

Moisture transport monitoring may indicate the onset of deterioration in porous building materials prior to damage occurring. Most moisture measurement systems provide only qualitative values, require extensive calibration, or are destructive. Thus, non-destructive and calibration-free monitoring systems are required. Our approach of moisture monitoring is to embed sensors that measure the relative humidity. In our experiment, screed samples are monitored during the hydration and evaporation process. Every test sample is equipped with 10 embedded sensors which measure the relative humidity across the sample thickness. Based on Hillerborg's approach, the relative humidity is converted into the corresponding pore saturation. In our study, the free water is computed without knowledge of the sorption isotherm. The free water in the pore system is predicted and validated. The predicted weight decrease corresponds conclusively to gravimetrically measured weights. The embedded sensors yield the absolute liquid water content and enable an experimental, non-destructive monitoring of liquid water in porous materials.

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## 1. Introduction

Moisture and moisture transport in concrete are important factors affecting the durability of concrete. Temperature gradients, mass transfer, and ion migration are mainly influenced by the free liquid water in the capillary system in porous materials. Thus, several chemical reactions leading to deterioration of our infrastructure are caused or highly accelerated due to moisture. In case of corrosion, free liquid water is a required reactant which further reduces the electrical resistance of concrete [1,2]. The alkali-silica reaction is also promoted by free liquid water [3]. If cracks already exist, freeze-thaw cycles of water may immediately damage the

concrete structure. Modern infrastructure objects like bridges, highways, tunnels, foundations, etc. are mainly built of reinforced concrete. Thus, almost the entire infrastructure is exposed to these deteriorations. For example, in Germany annual costs for repair and replacement are more than 13 billions Euro to maintain the status quo. Thus, a secure, powerful, and cost-efficient infrastructure mainly relies on early and accurate detection of hazardous moisture.

Although the exact knowledge of the amount of free liquid water in concrete is a crucial parameter in structural health monitoring, universal non-destructive methods to quantify moisture are missing so far. Thus, in practice, generally a two-stage approach is conducted. First, non-destructive devices based on resistivity or capacity measurements are used to measure the moisture distribution qualitatively. Then, at distinct spots, destructive moisture measurements like the calcium-carbide method or

\* Corresponding author.

E-mail addresses: [christoph.strangfeld@bam.de](mailto:christoph.strangfeld@bam.de) (C. Strangfeld), [sabine.kruschwitz@bam.de](mailto:sabine.kruschwitz@bam.de) (S. Kruschwitz).

Darr drying are performed. These tests are destructive, time-consuming, and provide only a point information. Furthermore, spatial moisture gradients or temporal varying moisture distributions are not recorded. Thus, experimental moisture monitoring is not feasible although it is crucial for most mass transfer processes. In the laboratory, approaches of moisture monitoring based on embedded electrodes [4] or embedded time domain reflectometry sensors [5] are elaborated. By means of calibrations, the sensor systems measure the moisture quantitatively. However, the calibration is complex, highly time-consuming, and only valid for one distinct material under one distinct environmental condition. Hence, a transfer into the field is impossible or associated with a high measurement uncertainty.

Another approach to quantify the free water is based on the measurement of the humidity [6]. The free liquid water content in porous materials correlates with the equilibrium moisture content. Thus, humidity measurements in boreholes [6], crushed material samples, or via embedded sensors are performed [7–10]. By applying the sorption isotherms isotherm and scanning-isotherm, the humidity values are converted directly into moisture [11]. Nevertheless, experimental determination of the sorption isotherm is costly, only feasible for one distinct material and the process may take months. Several models and simulations exist to approximate sorption isotherms [12]. Nevertheless, most models still require semi-empirical material parameters such as permeability, diffusivity, or conductivity.

Hillerborg [13] extends the well known Brunauer-Emmett-Teller (BET) theory [14]. In contrast to the BET theory, Hillerborg considers non-flat surfaces as well. Therefore, he adapted the Kelvin equation to adsorbed water layers inside cylindrical pores. The two input parameters, pore radius and relative humidity, determine the saturation of a pore. Chaube et al. [15] use Hillerborg's approach to predict the water release of a reference concrete block. The agreement between experiments and theoretical predictions are satisfying. Based on this work, Ishida et al. introduced the so-called inkbottle effect to predict the entire sorption isotherm, including the hysteresis between adsorption and desorption. This approach is extended to non-isothermal conditions [16]. However, the investigated test samples have a size of 4 cm × 4 cm × 16 cm and have to completely reach the equilibrium moisture content to take a measurement [17]. Thus, the measurements take approximately two years and only a total weight loss is determined. Other researchers used Hillerborg's approach to predict other parameters, for example, the shrinkage of concrete in an early age of hydration [18], or to validate simulations of moisture transport models [19].

Although several studies show the high potential of Hillerborg's approach, the analyses so far only result in an averaged moisture content for concrete blocks. However, advanced monitoring systems in civil engineering as well as complex mass transfer models for porous materials require a high spatial and temporal resolution of the moisture distribution. To fill this gap, we used embedded humidity sensor arrays of 10 sensors in 16 different screed samples. During hardening and drying, the humidity inside the samples was monitored. Based on the humidity profiles, the absolute free liquid water content is predicted with a spatial resolution of 0.1 mm for more than 300 days. Hence, the weight loss is calculated and experimentally validated by means of a high precision balance. The agreement between experiment and prediction proves the concept of quantifying the adsorbed liquid water based on the adaption of Hillerborg's theory. Furthermore, this approach of measuring the relative humidity is independent of any calibration for the used materials. The sorption isotherm is no longer required, on the contrary, the sorption isotherm may be predicted based on this approach.

## 2. Free liquid water calculation in porous materials

In cement paste and screed, the moisture transport occurs in the pore system of the material. The mass balance adapted to moisture in porous materials describes the transport process. Thereby, a thermodynamic equilibrium between the free liquid water in the pores and the water vapour partial pressure is assumed. Eq. (1) quantifies the moisture transport.

$$\frac{\partial \Theta}{\partial t} + \text{div}(J) + Q \equiv 0 \quad (1)$$

The mass balance consists of three general terms.  $\Theta$  is the mass of moisture in a unit volume of the considered material in kg/m<sup>3</sup>. The time derivation of  $\Theta$  expresses the total water adsorption or desorption over time. The second term represents the spatial evolution of the moisture flux  $J$  in kg/m<sup>2</sup> s.  $Q$  is a source/sink term of material moisture in kg/m<sup>3</sup> s. With  $\Theta = \rho_l \phi s(r, h)$ ,  $\Theta$  is replaced by the density of water  $\rho_l$  in kg/m<sup>3</sup> and the degree of pore saturation  $s$  and the pore volume distribution  $\phi$ . Under isotherm and isobar conditions, the pore saturation itself depends only on the pore radius  $r$  in nm and the relative humidity  $h$  in rH. The contribution of water vapour to the pore saturation is neglected in the current formulation. Eq. (2) quantifies the pore saturation for cylindrical pores which relates the total volume of a pore to the water volume inside this pore [13].

$$s = 1 - \left( \frac{r - t_a}{r} \right)^2 \quad 0 \leq t_a \leq r \quad (2)$$

The thickness of the adsorbed water layer  $t_a$  in nm begins at the fringe of the pore. If the humidity increases, more water passes into the liquid state due to the increase of the water vapour pressure. The adsorbed water layer increases and the pore fills up which coincides with a higher pore saturation. Based on the theory by Hillerborg, the resulting water layer is calculated by means of Eqs. (3) and (4) [13].

$$t_a = \frac{t_w h C}{\left(1 - \frac{h}{h_m}\right) \left(1 - \frac{h}{h_m} + Ch\right)} \quad (3)$$

$$h_m = \exp\left(-\frac{\gamma M}{\rho_l R T (r - t_a)}\right) \quad (4)$$

$C$  is a material constant related to the moisture diffusivity and adapted to cement based materials.  $t_w$  is the thickness of one monomolecular water layer in nm.  $R$  is the ideal gas constant in J/mol K,  $T$  the temperature in K,  $M$  the molecular mass of water in kg/mol, and  $\gamma$  is the surface tension of liquid water in N/m. During adsorption, the humidity, at which the air volume in the centre of cylindrical pore disappears, is the so called maximum humidity  $h_m$ . Eq. (4) is based on the Kelvin equation and takes into account the variation of the water vapour pressure due to the curved liquid-vapour interface at the inner layer [20]. Hence, every pore radius possesses an individual maximum humidity  $h_m$ .

For every pore radius, the saturation is known based on this approach. The capillary saturation  $S_{cp}$  is the summation of the pore saturation multiplied with the corresponding pore volume and the density of liquid water. Based on Eq. (5), the absolute water content is determined.

$$S_{cp} = \rho_l \int_{r_{\min}}^{r_{\max}} \phi s dr = \rho_l \sum_{r_{\min}}^{r_{\max}} \frac{\Delta V}{\Delta r} s \Delta r = \rho_l \sum_{r_{\min}}^{r_{\max}} s \Delta V(r) \quad (5)$$

In our experiments, the pore volume distribution is measured at discrete radii. Thus, the incremental given pore volume is defined as  $\phi = \frac{\Delta V}{\Delta r}$  and the integral in Eq. (5) is substituted by a summation.

The given theory is able to predict saturation during adsorption. Nevertheless, the saturation depends highly on the moisture

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