Comparison of different methods for determining the moisture diffusivity of porous building materials

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Abstract. This paper compares the X-ray method, the ruler method and the multi-step method to non-destructively determine the moisture diffusivity of calcium silicate and ceramic brick. Results show that the ruler method and multi-step method produce acceptable diffusivities and λ -profiles compared with the common X-ray method, meaning that both methods can determine moisture diffusivity reliably to some extent without the expensive X-ray setup and complicated data processing.

1. Introduction

The moisture diffusivity, as an important hygric property, is relevant to moisture transfer in building materials, and as such influences construction durability, energy consumption of buildings, and even human comfort and health [1, 2]. Therefore, much research is devoted to procedures for measuring or predicting the moisture diffusivity of building materials. Most of the well-established and non-destructive methods rely on expensive laboratory equipment, such as X-ray projection methods, computerized tomography techniques and nuclear magnetic resonance approaches [3, 4]. Although these methods are obviously able to determine the moisture diffusivity reliably, the high equipment price causes that only a few laboratories are capable to conduct moisture diffusivity measurements, which is not conducive to in-depth research developments, and even affects the development process in the entire moisture transfer field.

There are methods available though to derive the moisture diffusivity from plain capillary absorption experiments, without the requirement of moisture profile characterization. Evangelides et al [5] proposed a method with a simple set-up for estimating the moisture front propagation. In this method, the weight of specimens is measured by an analytical balance in a capillary uptake test, while observing the moisture front height visually via a ruler attached along the height of the specimens. The obtained data are used to produce an approximate moisture content profile and then to estimate the moisture diffusivity. In 2018, Bianchi Janetti [6] proposed to approximate the moisture

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diffusivity as a multi-step function of moisture content to estimate the moisture content profile of building material. In this method, a series of capillary uptake tests with specimens at different initial moisture contents are performed to characterize this multi-step diffusivity. Regrettably, the accuracy of this method was only verified by simulation.

In this study, experiments are performed with the above-mentioned two methods to determine the moisture diffusivity of calcium silicate and ceramic brick. The outcomes are furthermore verified by the established X-ray attenuation experiment.

2 Materials and methods

2.1 Materials

Calcium silicate (CS) and ceramic brick (CB) are chosen as target materials. Their basic properties relevant to this study were determined by preliminary tests at the ambient temperature of 20-22 °C and are presented in Table 1. For both the ruler and the multi-step methods, raw materials are cut into 5 duplicate samples of sizes 150 mm × 80 mm × 40 mm and 120 mm × 80 mm × 40 mm for the ruler test and the multi-step test respectively, while their dimensions are 120 mm × 80 mm × 10 mm in the X-ray attenuation experiment.

Table 1. Properties of CS and CB.

Property	CS	CB
bulk density ρ_{dry} (kg/m ³)	268	1753
Capillary moisture content W_{cap} (kg/m ³)	746	215
Capillary absorption coefficients A_{cap} (kg/(m ² s ^{0.5}))	1.057	0.615

2.2 Methods

2.2.1 The X-ray method

As an established method, the X-ray attenuation test was detailedly described in ref. [7], and here we just introduce it briefly. During the test, a normal capillary absorption is carried out, while simultaneously a facility is projecting X-ray on the sample and measuring its strength after passing through the sample. The moisture content at any position of the sample can be derived based on the X-ray's attenuation. As the capillary absorption process goes on, the transient moisture profile throughout the sample is obtained regularly and later converted to a λ -profile by the Boltzmann transformation. The moisture diffusivity is finally calculated by:

$$D(w) = -\frac{1}{2} \frac{\int_{w_0}^w \lambda dw}{\frac{dw}{d\lambda}} \tag{1}$$

where $D(w)$ the diffusivity (m²/s), w the moisture content (kg/kg), λ the Boltzmann transformation variable $\lambda=x/t^{0.5}$ (m/s^{0.5}), x the position of the water front (m), t the time (s).

In this test, two samples each of calcium silicate and ceramic brick were evaluated, and their average results were used in the subsequent analysis.

2.2.2 The ruler method

Our test process is modified from Evangelides’ test [5]. While weighing the sample at time t during the standard capillary uptake test [8], the distance of the moisture front from the sample’s bottom (x , m) was observed at the same time. The boundary value $\lambda_f = x/t^{0.5}$ is calculated as average of multiple measuring values. Note that samples were not wrapped with plastic membranes in order to facilitate the observation of the discoloration caused by the moisture front in this study. Trial measurements proved that this had limited impact on the results. Four samples of calcium silicate and five samples of ceramic brick were tested, and the respective average outcome was used in the subsequent analysis.

According to Evangelides et al. [5], the λ -profile can be approximated with the following function:

$$w(\lambda) = -[w_{cap} + a \tan^{-1}(b \lambda + c)] \tag{2}$$

where a , b and c the fitting parameters. To determine the fitting parameters, Eq. (2) is combined with the following boundary conditions:

$$w = w_{cap}, \lambda = 0 \text{ , } w = 0, \lambda = \lambda_f \tag{3}$$

and then parameters a , b and c are optimized to satisfy the following condition [9]:

$$A_{cap} = \int_0^{w_{cap}} \lambda \, dw \tag{4}$$

After obtaining the fitting parameters a , b and c , the λ -profile becomes known and can be used to calculate the moisture diffusivity D with Eq. (1).

2.2.3 The multi-step method

According to Bianchi Janetti [6], the moisture diffusivity D can be expressed by a multi-step function. The more steps are employed for the function, the more accurate the λ -profile and the resulting moisture diffusivity D is. In this study, a step number $n = 4$ is used, as trials showed that additional step numbers lead to great optimization difficulties without much improvement in the accuracy. A four-step diffusivity corresponds to four saturation degree intervals between 0 and 1, so four capillary uptake tests from different initial saturation degrees need to be performed. For saving time, only a single sample was tested for each initial saturation. Each sample, after having absorbed water to reach the respective initial mass, was sealed with plastic membranes and kept in a desiccator until its internal moisture distribution reached equilibrium. The corresponding initial saturation degrees of the capillary moisture content are included in Table 2.

Table 2. Initial saturation degrees (based on capillary moisture content) of CS and CB.

n=4	1	2	3	4
CS	0%	39.01%	78.86%	87.79%
CB	0%	47.55%	68.21%	87.92%

D_i are then determined from the highest initial saturation degree downward, decreasing step by step to the lowest one. According to Bianchi Janetti [6], the diffusivity D_4 can be first obtained by:

$$D_n = \frac{\pi}{4t} \left[\frac{m_t - m_0}{A w_{cap}(1 - s_{n-1}^*)} \right]^2 \quad (5)$$

Then, D_3, D_2, D_1 can be determined in turn through the optimization technique by:

$$f(\lambda_k, \dots, \lambda_i, \dots, \lambda_{n-1}, D_k) = \left| \frac{m_t - m_0}{A w_{cap}} - \sum_{i=k}^n \left\{ \sqrt{\frac{4tD_i}{\pi}} \frac{(s_{i-1}^* - s_i^*) \left[e^{-\frac{\lambda_{i-1}^{*2}}{(4D_i)}} - e^{-\frac{\lambda_i^{*2}}{(4D_i)}} \right]}{\left[\operatorname{erf}\left(\frac{\lambda_{i-1}^*}{\sqrt{4D_i}}\right) - \operatorname{erf}\left(\frac{\lambda_i^*}{\sqrt{4D_i}}\right) \right]} + \sqrt{t} [\lambda_{i-1}^* (s_{i-1}^* - s_0) - \lambda_i^* (s_i^* - s_0)] \right\} + \sum_{i=k}^{n-1} \left| \frac{D_i (s_{i-1}^* - s_i^*) e^{-\frac{\lambda_i^{*2}}{4D_i}}}{\sqrt{D_i} \pi \left[\operatorname{erf}\left(\frac{\lambda_{i-1}^*}{\sqrt{4D_i}}\right) - \operatorname{erf}\left(\frac{\lambda_i^*}{\sqrt{4D_i}}\right) \right]} - \frac{D_{i+1} (s_i^* - s_{i+1}^*) e^{-\frac{\lambda_{i+1}^{*2}}{4D_{i+1}}}}{\sqrt{D_{i+1}} \pi \left[\operatorname{erf}\left(\frac{\lambda_i^*}{\sqrt{4D_{i+1}}}\right) - \operatorname{erf}\left(\frac{\lambda_{i+1}^*}{\sqrt{4D_{i+1}}}\right) \right]} \right| \right| \quad (6)$$

where s is the saturation degree (based on capillary moisture content) (-), s_i^* the limit saturation degree (-), D_i constant diffusivity in each step, $s_0 = s_{k-1}^*, k=1,2,3$, m_t and m_0 is mass of specimen after time t and at the start (kg), A surface area of specimen (m^2), ρ density of water (kg/m^3). In this study, the excel “GRG” algorithm was used to search for the zero of function f .

Fig. 1. Measurements, from left to right: 1) CS samples in the capillary uptake test with rulers; 2) CB samples in the capillary uptake test with rulers; 3) CS samples in the multi-step test; 4) CB samples in the multi-step test; 5) CS sample in an X-ray attenuation experiment.

3. Results and discussions

After data processing, the results are shown in terms of moisture content in Fig. 2 and Fig. 3. Fig. 2 compares the λ -profiles from different methods. In Fig. 2 left, the λ -profiles for CS from the ruler method, the multi-step method and the X-ray method have very similar trends, and their capillary absorption coefficients (equal to the area under the λ -profiles) are almost equal, indicating that the ruler and multi-step method's approach to the capillary water absorption process is reliable. For ceramic brick (Fig. 2 right), the λ -profile from the ruler method nearly overlaps with the X-ray result for λ 0 to $0.0027 \text{ m/s}^{0.5}$, but it drops sharply at higher λ , causing a deviation on the values of capillary absorption coefficient. The same is likely to happen for the multi-step method. Please note that the λ -profiles calculated from the multi-step method cannot be smooth, due to the limited number of substeps and the concave end shape resulting from its defining equations.

Fig. 2. Transformed profiles from different methods: CS (left) and CB (right).

For calcium silicate (Fig. 3 left), the diffusivity functions of the ruler method show great consistency with that of the X-ray method, except for the highest capillary saturation degrees ($s > 90\%$). The diffusivity function from the multi-step method is somewhat overestimating on the other hand, especially in the lower moisture content range, where the deviation is about half an order of magnitude. For ceramic brick (Fig. 3 right), the diffusivity functions also present similar trends, except for a wider band of scatter, which is not only for the small variation among samples of CB but also attributed to the difference in methods.

Fig. 3. Diffusivity functions $D(w)$ from different methods: CS (left) and CB (right).

4. Conclusions

Two recent methods for estimating the diffusivity of building materials, the ruler method and the multi-step method, are compared to the common X-ray measurement. Results show that the estimated diffusivity functions by all three methods present good agreement for calcium silicate and ceramic brick. On the other hand, while the λ -profiles from these three methods are almost same for CS, the λ -profiles from the ruler method and the multi-step method are somewhat underestimating for CB. However, there is also significant uncertainty on the X-ray results as a common method, especially for the material with a high density and a low water absorption such as CB. In addition, it causes an error to some extent that we have only used one single sample in each step to determine the whole profile. So, we cannot conclude arbitrarily whether the ruler method and the multi-step method are suitable only depending on this experiment's results. In the future, the work of repeatability, the application to other kinds of materials as well as the exploration of the more suitable optimization algorithm shall be done.

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