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In-situ characterization of the relative humidity at the surface of building materials

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Abstract. Standardized laboratory testing is normally used for characterization of building materials and components. In real life, especially when assessing buildings in terms of water-damaged building materials, built-in moisture, rising damp or other problems, information on the hygrothermal state of the constructions may be relevant, but is often sparse. This paper presents a study where application of a newly developed non-destructive experimental method is used to measure the relative humidity (RH) at the surface of four types of building materials. Knowing the RH at the surface, a risk assessment of fungal growth can be made. The materials include concrete, brick, aerated concrete, and gypsum, with and without a surface treatment. The method is based on the idea of establishing a water vapor transport towards equilibrium within a small air volume in contact with the surface of interest. In the laboratory the specimens were conditioned at respectively 65 % RH and 90 % RH in a climate chamber, and then transferred to conditions with 50 % RH. The open side of a Petri dish, equipped with a temperature and relative humidity sensor, was attached to the materials using reusable adhesive. The development of the relative humidity over time within the petri dish was monitored and parameterized mathematically, solving an exponential rate equation. The parameterization and certain sets of assumptions allow among other things a calculation of time to equilibrium which makes it possible to assess the reproducibility and comparison in between materials. As the materials were tested with and without surface treatment, it was possible to estimate the effect of a typical surface treatment on the moisture transport. The measurements compared well to simulations made by a model, though the model predicts slightly faster achievement of equilibrium. Despite the limited number of cases in the current study, the presented results are promising with regards to enable rough estimates of RH at the surface of building materials outside the laboratory with a very simple, inexpensive, and non-destructive method.

1. Introduction

Moist indoor building materials with a surface equilibrium above 75 % relative humidity (RH) may be at risk for fungal growth given enough fungal nutrients available [1]. A measure of the RH in the indoor air may not be adequate to assess this risk since this measure not necessarily represents the conditions close to the surface of the materials as the temperature is likely lower on the surface of external components compared to ambient conditions.

Standard methods for measuring the moisture conditions of porous building materials in the interior, include destructive methods, such as weighing-drying-weighing methods of samples, e.g. [2], where a sample is removed from the wall, weighed, dried and weighed for determination of moisture content. Other methods include built-in moisture measuring dowels [3], or the non-destructive capacitive

moisture sensor [4], however this is primarily for investigation of moisture distribution and gives relative numbers. However, the above-mentioned methods of oven-drying, capacitive measurements and built-in dowels are not optimal for determination of risk of mould growth on the surface for several reasons; the methods may be either lengthy (weigh-dry-weigh takes 1-3 days), and conversion from gathered moisture content to relative humidity is connected to uncertainties as sorption curves rarely exit for a given material. The relative humidity can be measured directly in e.g., concrete, either by placing a sample in a sealed container with a relative humidity sensor, or by placing a relative humidity sensor in a drilled hole of the element in question [5]. These methods are however also destructive, and time consuming as it may take a week to reach equilibrium [4]. Furthermore, the methods do not yield specific results about the surface conditions, which is relevant regarding mould growth.
In some cases, hygrothermal simulations e.g., WUFI [6] or Delphin [7], can help evaluate cases, and predict the surface conditions to be expected. However, such simulations are highly dependent on the input, and some parameters might not be known, e.g., specific material characterization, indoor and outdoor climate conditions, or surface treatments. Therefore, assumptions are often used, which compromises the results.
This motivated the development of a simple non-destructive experimental method enabling a measure of the RH at the surface of building materials. The method relies on the establishment of a water vapour pressure equilibrium within a small air volume in contact with the surface of interest. The open side of a Petri dish, equipped with a temperature and relative humidity sensor, is attached to the material using reusable adhesive and allows a measure of the RH within the small air volume close to the surface. The method is not dependent of knowledge of type and characteristics of material, though relies on an airtight attachment to the surface. The performance of the method has been evaluated in the laboratory by measuring the RH at the surface of four types of damped building materials. The reproducibility of the response time, i.e., the time to reach equilibrium between the material and air within the Petri dish, were analysed for the different materials.

Through the development of a method for determination of the RH of the surface in non-destructive in situ manner, the assessment of risk for fungal growth may become more accessible. The goal of the paper is to present the performance of the method used on damp building materials in the laboratory. Further the materials are characterized according to time to equilibrium and a comparison is made to simulations performed with a model.

2. Materials and methods

2.1 Moisture cap

The method is based on the idea of establishing a water vapour transport towards equilibrium within a small air volume in contact with the surface of interest. The moisture cap consists of a plastic petri dish, 88 mm in diameter and 14 mm high. A Profort data collector connected to a computer logged data every 4 minutes from a wireless sensor, measuring temperature and relative humidity (ClimaSpot version 004860, https://profort.com/wordpress/wp-content/uploads/manual_climaSpot_3.01.pdf). ClimaSpot records temperature in the range -10 °C – +55 °C with an uncertainty of ±0.3 °C between 0 °C and 55 °C. The relative humidity (RH) is recorded in the range 10-90 % with an uncertainty of ±1.8 % RH. The moisture cap is mounted to the material using a removable adhesive, i.e., leaving the surface intact after the measurement (Fig. 1).

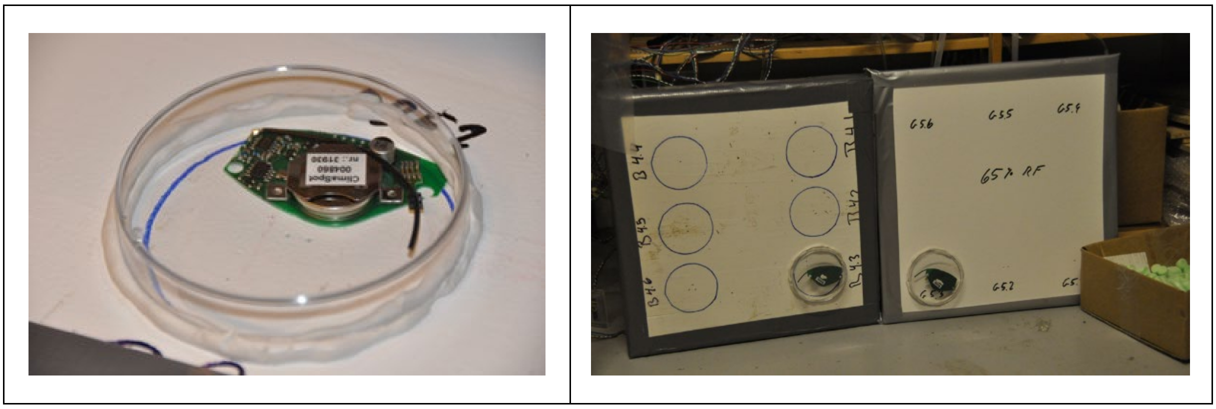

Figure 1. Left: moisture cap mounted on treated surface. Right: concrete tile and gypsum board with surface treatment and sealed edges (and reverse) and moisture cap mounted.

2.2 Experiment and building materials.

The moisture cap was evaluated on four types of building materials in laboratory experiments. The sample items were individually conditioned in climate chamber (1) to respectively 65 % RH or 90 % RH (at 20-23 °C). The conditioned sample was moved to a climate chamber (2) with 50 % RH and a moisture cap was mounted. The data was logged while the concentration of the water vapor in the air inside the moisture cap increased towards an equilibrium with the conditioned sample. The procedure is illustrated in Fig. 2.

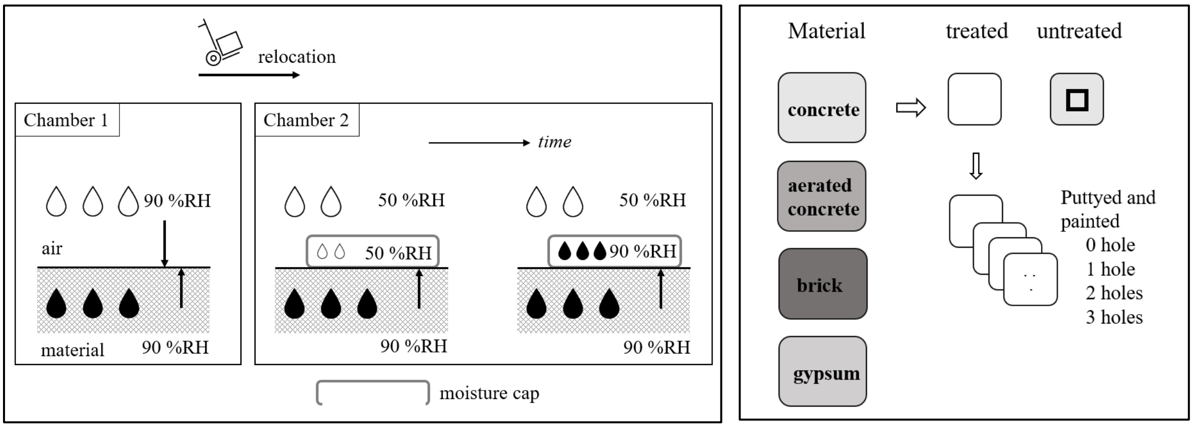

Figure 2. Schematic illustration of the procedure in the laboratory experiment with samples of different building material being conditioned in one chamber (1), moved to another climate chamber (2) with lower RH and the moisture cap mounted. Four types of material with different surface treatments were tested.

The tested materials were samples of concrete, aerated concrete, brick, and gypsum board (Fig. 2 and Table 1). One surface was treated with putty, primer and two layers of acrylic paint, while the reverse and the edges remained untreated. The test items are divided into treated surfaces and untreated surfaces. The treated surfaces were pierced with 0, 1, 2 or 3 small holes within the area covered by the moisture cap when measuring. The untreated surfaces were wrapped in a 0.2 mm PE (polyethylene) foil, tightly attached to the treated surface with duct tape. The samples were conditioned in a climate chamber before they were wrapped in PE foil. After trials with treated surfaces, the untreated surface was tested by making a 4 cm x 4 cm hole in the PE foil, attached to the test piece with duct tape, which also formed the edge of the square. All tests were performed as triple measurements with the moisture cap. Table 1 presents some properties of the materials.

Table 1**.** Dimensions, density, and moisture properties of materials used in the laboratory experiments.

Material	Dimension, mm	Density, kg/m^3 [A]	
Concrete	400 x 400 x 50	2200	
Aerated concrete	600 x 400 x 50	535	
Brick	230 x 110 x 50	1830	
Gypsum	400 x 400 x 12,5	750	
			Water vapor resistance, $(GPa{\cdot}m^2{\cdot}s)$ /kg
Petri dish	88 / 14 [B]		> 500 [D]
Surface treatment			1.6 [C]
Adhesive	2		233 [C]
PE-foil	0.2		500 [D]

[A] Average values determined by weighing and measurement [B] Dimensions is given as diameter / height. [C] The vapor resistance is determined by El-Khattam and Andersen[8]. [D] Water vapor resistance are from SBi guideline 224, Moisture in Buildings [5].

2.3 Curve fitting of measurement

The measurements during the time span from mounting the moisture cap until equilibrium is established, follow a typical pattern as illustrated in Fig. 3a. The figure illustrates the measurements over time from a single sample of surface treated aerated concrete conditioned at 65 % RH, respectively 90 % RH. At the beginning of the experiments, the concentration of water vapor in the air of the moisture cap has insignificant influence on the evaporation from the surface and the flux is close to constant, i.e., the curve is approximately linear. Due to the evaporation, the water vapor content increases in the moisture cap and at a certain point the (net) evaporation at the surface of the material begins to decrease and the curve becomes curvilinear. The progress is like a first order rate reaction. There were varying times to equilibrium for the different building materials tested, though using a value of 700 min (approximately 11 h) after the beginning of the experiment, ensured establishment of equilibrium for all measurements performed. Therefore, the values measured at this point (700 min) are used as values characterizing equilibrium.

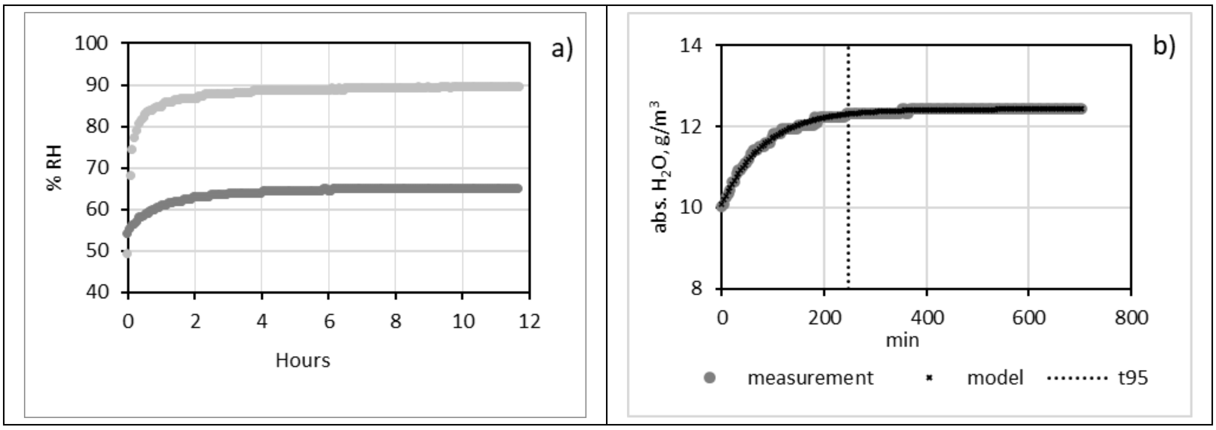

Figure 3. Surface treated aerated concrete a) % RH measurements in moisture caps mounted on samples conditioned at 65 % RH, respectively 90 % RH, b) measurements (sample 65 % RH conditioning) recalculated to absolute water content shown together with the curve fit and calculation of *t95* (see below).

The air in the moisture cap has a RH of about 50 % when it is mounted on the sample in the 50 % RH climate chamber. This value is associated with some uncertainty due to the handling of the samples and sometimes a slight difference in temperature between chambers. Therefore, based on measured temperature and RH, the data is recalculated to absolute water content (*abs.* H_2O). Further, it has been chosen to include this initial value as a parameter in the expression for the curve fitting.

Fig. 3b shows the data from surface treated aerated concrete conditioned at 65 % RH, recalculated to absolute water content. Further, the curve fit is shown, based on the non-linear regression analysis with the least squares method (Excel, version 2016). The fitting was obtained using data from the beginning of the experiment until an equilibrium was established (i.e., the first 700 minutes of measurements is used for all regressions). The non-linear regression was fitted to the equation:

$$abs.\ H_2O(t) = \beta_1 - \beta_1 \cdot \exp(-\beta_2 \cdot t) + \beta_0 \quad (1)$$

where β_1 is the increase in concentration until equilibrium, β_2 characterize the steepness of the curve and β_0 is the initial concentration (at time $t = 0$), when the moisture cap is mounted. Curve fitting according to eq. 1 has been done for all datasets. The coefficient of determination, R^2 was 0.9 or more in 54 of 60 experiments at the 65 % RH conditioning and 54 of 58 experiments at 90 % conditioning [9]. The time to 95% of the equilibrium concentration, *t95*, can be calculated (see also [10]) as:

$$t95 = \ln(0.05)/\beta_2 \quad (2)$$

t95 is illustrated in Fig. 3b. This term is, among other things, suitable for comparing time to equilibrium for the different materials.

2.4 Simulations with WUFI

A WUFI 2D ® (version 4.4) simulation model was developed for each of the materials (see Table 2) to compare the measured data with hygrothermal simulations. All materials are modelled with a dimension of 400 mm x 50 mm, see Fig. 4, and the moisture cap is modelled as 88 mm x 20 mm. On the surface towards the moisture cap, a surface treatment (s_d value of 0,3 m) was added, and all surfaces of the 'material and air volume' was covered with a vapor barrier with a s_d value of 100 m. The air volume was modelled as the WUFI material 'Air layer 20 mm – without additional moisture capacity'. The materials used in the simulations were taken from the WUFI database, and only gypsum board had a vapor diffusion resistance factor that decreased with an increasing relative humidity. The other materials had a constant vapor diffusion resistance factor.

Table 2. Material properties applied in WUFI.

	Density, kg/m^3	Heat capacity, J/kg K	Thermal conductivity, W/m K	Vapor diffusion resistance factor, -
Concrete	2200	850	1.6	92
Aerated concrete	600	850	0.14	8.3
Brick	1744	889	0.54	15
Gypsum board	625	850	0.2	8.3
Air layer, 20 mm	1.3	1000	0.13	0.56

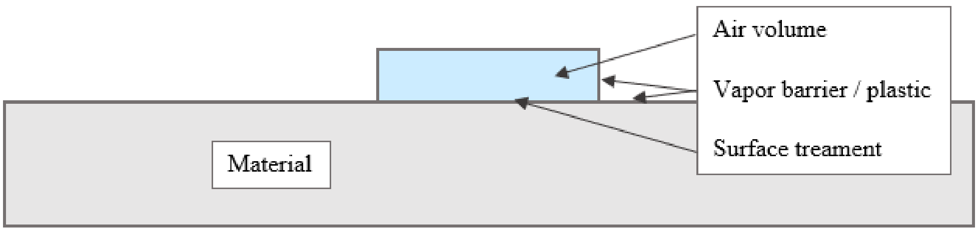

Figure 4. WUFI model.

The initial conditions for the samples were set to either 65 % RH or 90 % RH and a constant temperature at 22 °C. The air volume in the moisture cap and the boundary conditions were set to 50 % RH and a constant temperature of 22 °C. This setup allows the moisture from the material to move into the moisture cap and the RH is an average of the entire air volume. The grid was set to fine, and automatic adjusted by WUFI. The simulation was run with a time step of 5 min for 6 h. The simulations are compared to measurements.

3. Results and discussion

3.1 Comparison of estimated t95 and measurements

In Fig. 5 the measured values of % RH at time of equilibrium (700 min) are compared to estimated values of *t95* based on eq. 2 for the different building materials and samples conditioned at 65 % RH and 90 % RH, respectively. A good agreement is seen between *t95* and measurements.

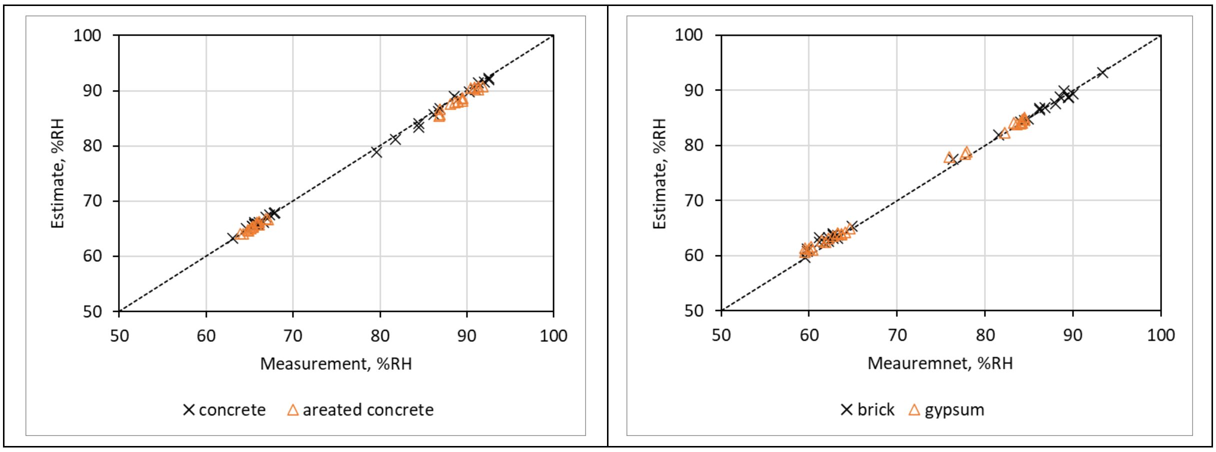

Figure 5. Estimated % RH at equilibrium against measured values (after 700 min) for all test items, i.e., untreated and treated (with/without holes) materials, conditioned at respectively 65 % RH and 90 % RH. The 1:1 line is shown.

3.2 t95 in between materials

Based on estimates of *t95*, the samples and materials were compared. Within the uncertainties seen for the samples (triple measurements), no difference were seen between treated samples with and without pierced holes and the samples were pooled [9]. Fig. 5 shows the mean values ± standard deviation (SD) for the treated and untreated surfaces and the conditioning at respectively 65 % RH and 90 % RH for the different materials.

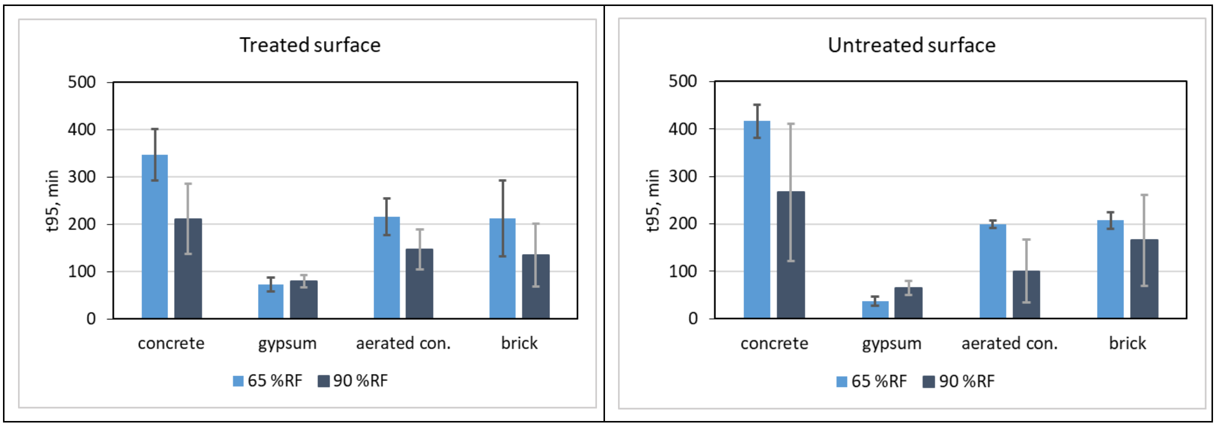

Figure 6. Mean value (± SD) for time to equilibrium (*t95*, min) for the four material types, treated (all types) and untreated, respectively, and conditioned at 65 % RH and 90 % RH.

It is seen from Fig. 6, that the *t95* estimated from all experiments conditioned at 65 % RH in general have a small variation, while for 90 % RH the variation increases, especially for untreated samples. For the surface treated samples conditioned at 65 % RH, concrete has the highest *t95*, gypsum the lowest and aerated concrete and brick are in between at comparable levels. The same pattern and to some extent comparable values are seen for the untreated samples, though here the evaporating area are barely a quarter of the area evaporating in the treated samples. The water vapor resistance factors listed in Table 2 are highest for concrete and about equal for aerated concrete and gypsum, while brick is slightly higher. The *t95* values are about equal for aerated concrete and brick and lowest for gypsum. We have no explanation for this deviation in patterns in between the materials. For treated samples, concrete averaged between 200 and 350 min (3 to 6 h) to reach near equilibrium at the two conditionings. For the other materials, the time is less than 3 h. For the untreated samples, concrete takes 6 to 7 h to reach close to equilibrium, with the other materials reaching equilibrium on average within 3 h. The untreated samples are based on an evaporation area of 4 cm x 4 cm, while a user situation is expected to use the entire area under the moisture cap. This means that the time to equilibrium will be shorter, as more surface area can give off water vapor.

3.3 Comparison of simulations and measurements
The simulations were very alike for the different materials at the respective conditionings (Fig.7 left). The simulations were compared to some of the datasets (Fig. 7 right). Differences in temperatures between simulations and measurements are ignored. Further, a simulation for gypsum with end point 85 % RH is added to compare to the measurements. A good agreement is seen between simulations and measurements, though most of the measurements have a less steep increase towards equilibrium, i.e., the equilibrium is obtained later than predicted by the simulation.

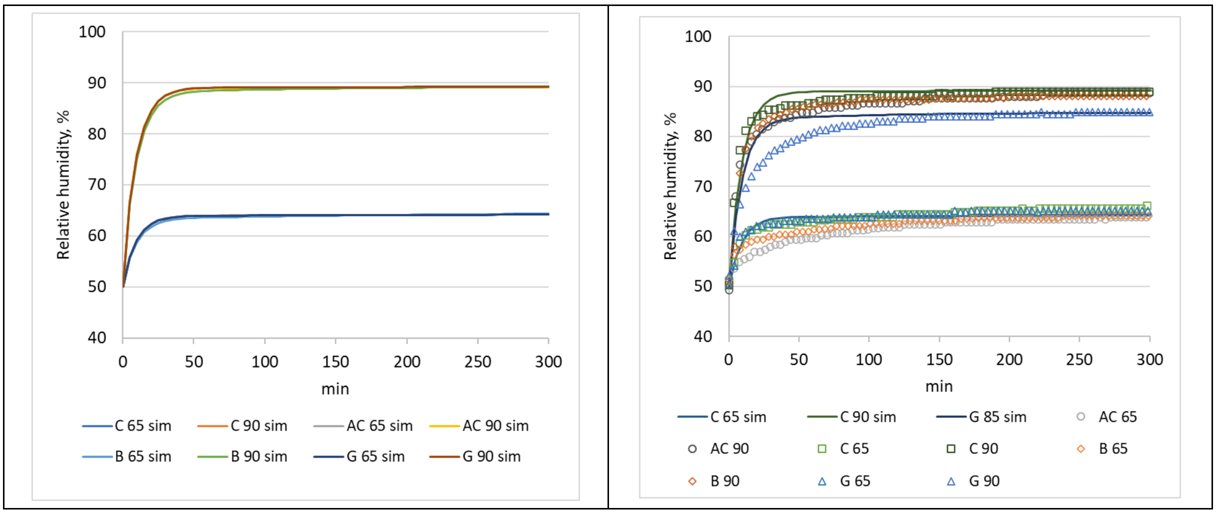

Figure 7. Simulated ("sim") values of the RH versus time for materials conditioned at 65 % RH, respectively 90 % RH (left) and simulations and measurements at conditioning at respectively 65 % RH and 90 % RH (right). C: concrete, AC: aerated concrete; B: brick; G: gypsum. Simulation of gypsum with material conditioned at 85 % RH is also shown.

4. Conclusions
It is concluded that the moisture cap is suitable to measure the RH in equilibrium with the surface of a material where the moisture cap is mounted, thereby enabling a risk assessment for fungal growth. The mathematical curve fit worked well and enabled a comparison of reproducibility of the measurements and comparison between different types of material. The attachment to the surface and the adhesion of a potential surface treatment the substrate is crucial for a correct measurement. The distribution of *t95* for the different materials did not strictly follow the pattern of the permeabilities. Future work should focus on comparison with the permeabilities determined on the specific materials used and further explore whether the method can be used for estimation of the moisture transport properties, too. Actual information about these would help an optimization of drying conditions e.g., when drying out building's concrete floors after water damage.

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