



**SBE21**

# Sustainable Built Heritage

14-16 April 2021,  
Online conference

**DRAFT PAPER**

This version is intended for personal use during the conference and may not be divulged to others

The SBE21 Heritage Conference is co-financed by:



International co-promoters:



Under the patronage of:



In collaboration with:



# Experimental measurement of material's drying coefficient for internal insulation: new approaches for laboratory testing

Alexander Rieser<sup>1,3</sup>, Daniel Herrera-Avellanosa<sup>2</sup>, Eleonora Leonardi<sup>2</sup>, Marco Larcher<sup>2</sup> and Rainer Pfluger<sup>1</sup>

<sup>1</sup> Department of Energy-Efficient Buildings, University of Innsbruck, 6020 Innsbruck, Austria;

<sup>2</sup> Institute for Renewable Energy, Eurac Research, 39100 Bolzano, Italy;

<sup>3</sup> Corresponding author, alexander.rieser@uibk.ac.at

**Abstract.** Materials' drying behaviour plays an important role in the renovation of historic buildings since internal insulation is frequently used to avoid intervening on the outer finish. However, the use of internal insulation in many cases requires the verification of the insulated wall system by means of hygrothermal dynamic simulations. As simulation models are a mathematical simplification of the physical reality, there is no guarantee that the model describes the hygrothermal performance accurately. A qualitative comparison of simulations with a drying coefficient that is based purely on experimental data provides additional security and clarity in the adoption of capillary active insulation materials. New approaches for the laboratory tests developed in parallel in two different research projects, Interreg AS ATLAS and HyLAB, are presented in this paper. An analysis of the drying apparatus designed by Scheffler revealed a series of limitations that could be further improved. The results of the material calcium silicate of two different experimental set ups, with considerations to the usability and accuracy of the apparatus, are presented, compared and discussed in the following paper. Further simulations resulted in comparable drying coefficients for the two experimental set-ups and were able to identify possible discrepancies in the results of the measurements.

**Keywords** – internal insulation; drying coefficient; historic buildings; capillary activity; moisture storage

## 1. Introduction

### *1.1. Justification of a drying coefficient*

The refurbishment of historic buildings is a complex process. In addition to technical compatibility and energy efficiency, requirements are also placed on the visual appearance of the building. Especially in the case of historical walls, the façade is in many cases an expression of historical building culture and decisive for the character of the building. Thus, in most cases, the only option left to improve energy efficiency and living comfort is internal insulation. The choice of a suitable internal insulation system depends on the condition of the existing wall. Rising damp in the walls, lack of protection against driving rain and poor air-tightness of the building are the main challenges that can arise in the course of a refurbishment [1, 2]. Since diffusion-open systems have certain advantages in relation to these challenges, under consideration of certain framework conditions, it is not surprising that this system is used in many cases. Even when capillary-active materials are used, the problems of driving rain, rising damp and insufficient air tightness must be solved, but there is a certain tolerance compared to diffusion-tight and diffusion-retarding systems in the application [3–5].

The main issue with capillary active materials is the correct evaluation of the material functions. The vapour diffusion is described by the vapour diffusion resistance factor. EN ISO 12572 [6] describes a standardised procedure to measure it. The liquid conductivity function in the capillary moisture range is

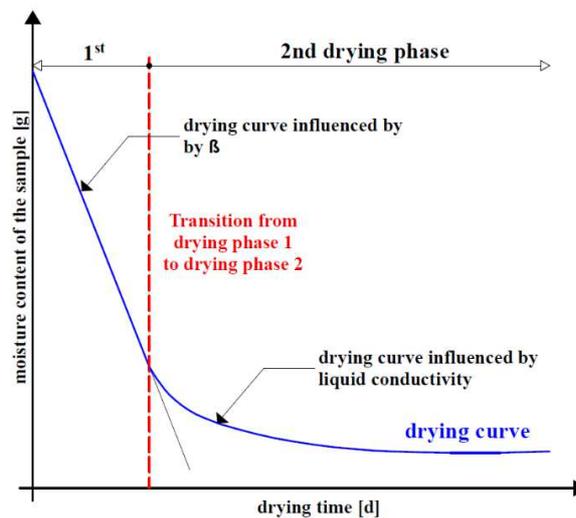
derived from the water uptake experiment, whose behavior is summarized by the capillary absorption coefficient, which is a measure of the absorption rate of liquid water. In the case of capillary-active materials, however, the most relevant moisture range is the lower overhygroscopic moisture range which is covered by the drying experiment [7]. Scheffler and Plagge [8, 9] introduced a drying coefficient to describe the material behavior in this moisture range. The drying behaviour of porous materials was also treated on a normative level and, similarly to Scheffler and Plagge, evaluates the second drying phase presented in chapter 1.2. In the EN 16332 [10], a drying index is introduced as a result, which serves as a reference point for materials that have no, or weakly defined, first drying phase.

The drying behaviour of building materials has been analysed in numerous studies. According to Zhao et al. [11], there are three different approaches in literature that can describe the drying behavior: (1) the above mentioned drying coefficient / index, (2) numerical modelling with differential equations and (3) analytic modelling with approximation of drying course.

### 1.2. The drying characteristics of porous building materials

In a dry sample, vapour diffusion is the dominant moisture transport mechanism. With increasing moisture content, capillary condensation occurs in the pore of the porous building material and mechanisms such as surface diffusion and capillary conduction are added as transport mechanisms. When the pore is saturated, liquid transport in the form of capillary conduction predominates.

These transport mechanisms vary depending on the material and are strongly dependent on the moisture storage of the respective material. In addition to the material properties, the transport mechanisms are also influenced by the driving gradients (temperature and humidity) as well as the transition conditions at the drying surface (air velocity, surface roughness) [8, 12]. The driving force of vapour diffusion, for example, is the gradient of the water vapour partial pressures. In the case of surface diffusion and capillary conduction, the gradient of relative humidity is decisive for the transport process [13]. These different mechanisms are evident in the drying curve of a porous material and the drying process can be divided into two phases. The first drying phase is characterized by a linear decrease in moisture content as shown in Figure 1.



**Figure 1:** drying phases of a porous material according Scheffler and Plagge [9]

In this phase, the moisture is transported to the material surface faster than it is removed by the surrounding air. Therefore, it can be concluded that the first drying phase is entirely dependent on the moisture transfer coefficient  $\beta$  and the surrounding temperature and relative humidity. Simply put, the greater the removal due to increased air speed and low relative humidity, the steeper the curve of the first drying section.

As the moisture content decreases, the second drying phase begins. Smaller moisture content leads to a reduced gradient of the driving potential and to smaller liquid conductivity values and therefore not as much moisture is transported to the surface as can be removed by the surrounding air. Here, the

driving moisture mechanisms are diffusion due to the partial vapour pressure gradient, surface diffusion and capillary conduction due to the relative humidity gradient. In this phase, the drying behaviour strongly depends on the material properties. Due to the progressive decrease in these gradients as a result of drying and to the decrease of the liquid conductivity with the moisture content, the curve flattens out until the transport mechanisms come to a complete end.

### 1.3. Previous research

Plagge and Scheffler [8, 9] showed that the square root of the duration of the second drying phase,  $\sqrt{t_{d,2nd}}$ , has a linear relationship to the sample height of the tested material,  $h$ . Therefore, they proposed the following definition of a drying coefficient:

$$D = \frac{\sqrt{t_{d,2nd}}}{h} \quad (1)$$

Plagge and Scheffler [8, 9], also used simulations to investigate the influence of various parameters and their impact on the drying curve of the sample. It was shown that the surface temperature of the sample can be used to determine the transition from the first to the second drying phase. Generally, the surface temperature decreases at the beginning of the drying phase until it reaches the so-called wet bulb temperature. After some time, however, it begins to rise again and thus marks the transition to the second drying phase [15].

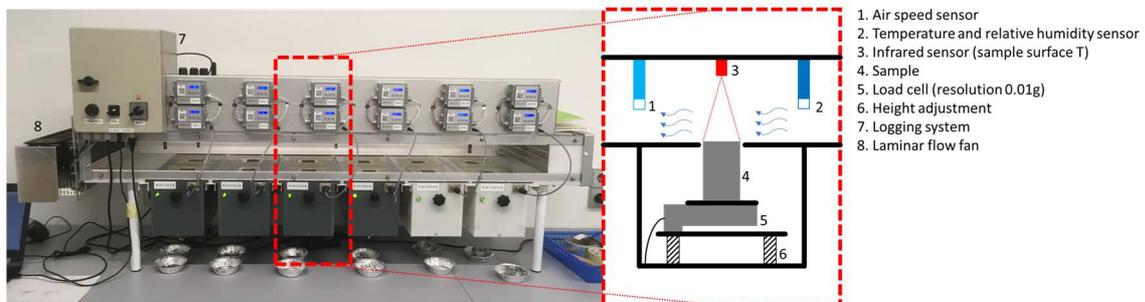
In order to obtain a reliable drying coefficient from the measurement data, a consistent mathematically applicable procedure must be followed for evaluating the duration of the second drying phase. Although Plagge and Scheffler [8, 9] state that the drying phase two  $t_{d,2nd}$  begins at the transition from the linear drying process and ends at the completion of the drying process, these two points are significantly affected by the interpretation.

This paper presents the experimental set-up and procedure developed by Eurac Research and University of Innsbruck and the experience in carrying out measurements, and the calculation of a drying coefficient will be discussed. The effects of different ambient temperatures and relative humidity's are investigated with the different set ups and by means of simulation.

## 2. Methods

In the following, the two different test setups of Eurac Research and University of Innsbruck are presented. Furthermore, the proposed method for the calculation of the second drying stage duration is explained. The method is applied and discussed on the basis of measured and simulated data for the material calcium silicate. The aim is to confirm the independence of the drying coefficient from the different measurement set-ups and to identify, if any, weak points in the new set-up by means of simulations.

### 2.1. Apparatus of Eurac Research



**Figure 2:** Eurac Research drying apparatus

Based on the methodology proposed by Scheffler [7], the “Hygrothermal Testing Laboratory” of Eurac Research has developed a new apparatus that overcomes some of the limitations of the original set-up, namely:

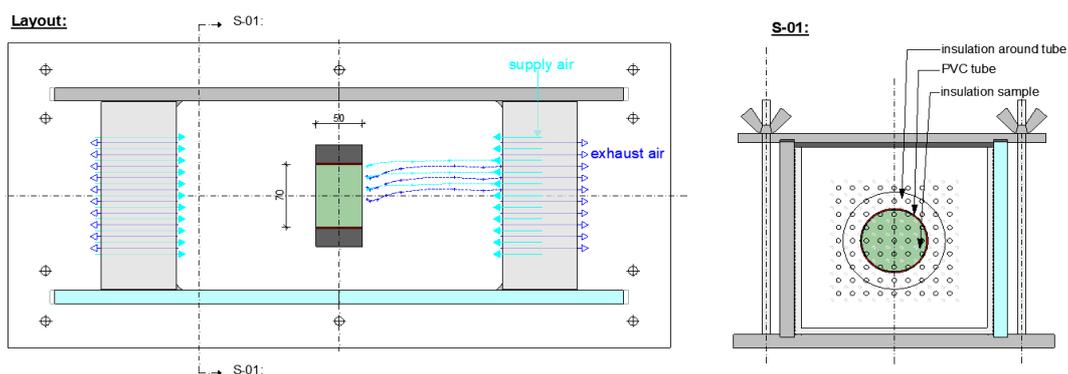
- the original set up with horizontal axis fans created a turbulent flow that resulted in a heterogenous distribution of air. Fans have been substituted to create a laminar flow and a more homogenous distribution of the air in the chamber
- Scheffler's set-up was very labor intensive with manual weighing of the samples at regular intervals. In addition to that, the lack of measured data out of working hours jeopardized the representativeness of the results. With the new configuration, sample's mass is retrieved automatically with load cells under each sample and logged every minute by a dedicated monitoring system.
- use of contact sensors for the monitoring of the surface temperature became incompatible with the use of load cells. Instead, the new set-up proposed here uses infrared sensors for the acquisition of samples' surface temperature.
- the proposed setup is placed in a conditioned room with controlled temperature and relative humidity. The setpoints are fixed at a temperature of 23 °C and a relative humidity of 40%.

## 2.2. Apparatus of University of Innsbruck, Unit Energy Efficient Buildings (EEB)

The experimental set-up at the University of Innsbruck included some basic changes compared to the set-up at Dresden [7] and Eurac Research. The following points were considered critical in the previous experimental set-ups and were improved in the new set-up of EEB.

- The airflow on the surface of the sample is horizontal. This can result in a moisture profile on the surface (the rear area dries slower than the front area). Little irregularities on the sample surface can lead to heterogenous air velocities on the evaporation surface by the lateral air flow.
- Due to the one-sided aeration of the sample, a changed moisture profile is created towards the bottom of the sample. Edge effects could thus change the one-dimensional moisture transport.
- The air temperature and humidity depend on the room climate where the device is set up.
- Due to the relative room air humidity of 40% the drying of the first drying phase, takes a relatively long time.

To improve the above-mentioned aspects, the sample was suspended vertically and ventilated on both sides. This way, a symmetrical moisture profile over the sample should be achieved. By ventilating on both sides, the signal to noise ratio of the measurement (weight of evaporated water divided by sample weight) is enhanced by a factor of two.



**Figure 3:** Schematic drawing of the experimental set-up. The floor plan and section of the apparatus are shown. The light blue arrows represent the supply air (dry compressed air) which is introduced into the sample chamber via a distribution network in the ventilation box. The air is introduced through small openings and blows vertically onto the sample. The air is removed through the bigger openings in the box.

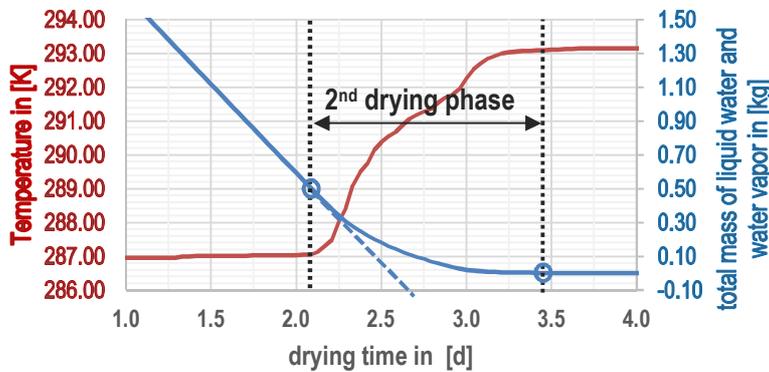
Furthermore, the supply air is brought into the distribution boxes by means of a compressed air line which brings extremely dry air (20 °C, 0.2 % RH) into the distribution boxes. Thus, this type of

ventilation ensures constant boundary conditions and dries the sample faster but also to a lower moisture content level.

With the current test set-up, only a single sample can be tested at a time. This has an enormous disadvantage in terms of time compared to the previous set-up when several samples are tested at the same time. The vertical storage of the sample can also have an effect on the result of some materials due to gravity. It could be shown by simulation that no noteworthy effects can be observed in the case of calcium silicate.

### 2.3. Method for the calculation of a drying coefficient from measurement and simulation data

In order to calculate the drying coefficient, the beginning and the end of the second drying phase must be defined analytically. As already mentioned in chapter 1.3, the surface temperature of the sample can be used for the transition from the first to the second phase. Due to the evaporation enthalpy at the surface of the sample, the surface temperature decreases significantly. At the end of phase 1, however, sufficient liquid can no longer be transported to the surfaces and a temperature increase occurs due to the lower evaporation. This drop can be seen clearly in Figure 4. Exactly at the time of the abrupt rise in temperature, the linear drying function deviates.



**Figure 4:** Typical behaviour of the moisture content of the sample and of the surface temperature during a drying experiment. The beginning and the end of the second drying phase are indicated by vertical dashed lines.

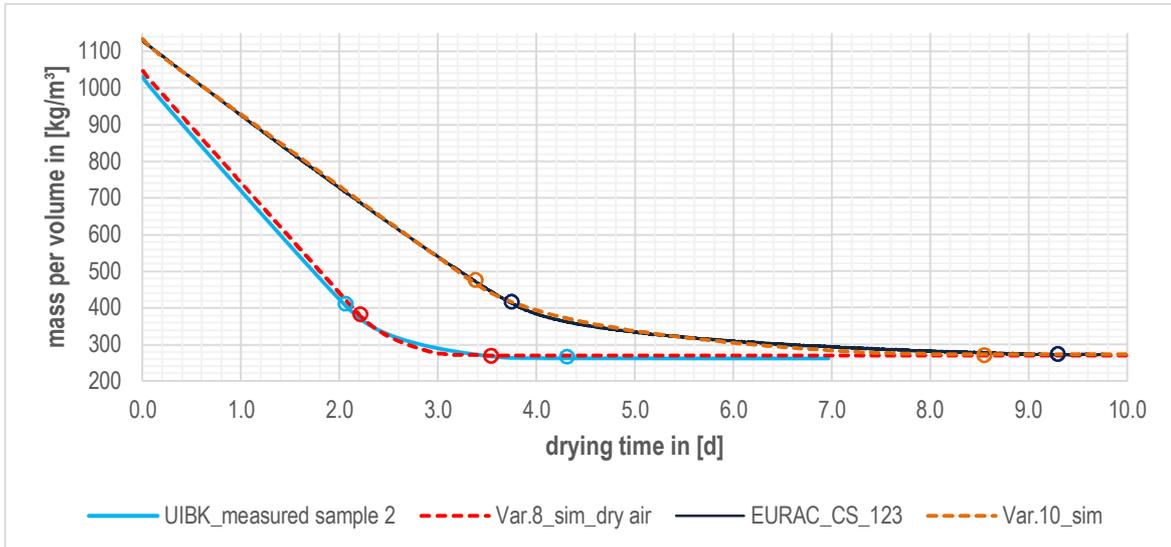
In order to determine this point analytically, it is necessary to smooth the measured temperature because measurement inaccuracies can influence the result. For this purpose, temperature results are presented as 12 hours running average,  $\bar{T}_i = \frac{1}{n} \sum_{j=i}^{i+12h} T_j$ . Subsequently, the temperature gradient is calculated for each time step,  $\Delta\bar{T}_i = \bar{T}_{i+1} - \bar{T}_i$ , and finally the maximum is defined as the beginning of the second drying phase  $t_{d,2nd,start} = \max(\Delta\bar{T}_i)$ . This guarantees to find the time of the abrupt rise and to exclude local maximums.

The second important point is defined as point when the sample is dry. According to a definition commonly found in standards dealing with hygrothermal characteristics of building materials, a sample is considered dry when the 24 hours mass change is less than 0.1 %. The following procedure is used for the calculation: first a running average is performed to smooth measurement fluctuations  $\bar{m}_i = \frac{1}{n} \sum_{j=i-1h}^{i+1h} m_j$ . Then, the relative mass change in 24 hours is calculated for each time step as follows  $\Delta\bar{m}_i = \frac{\bar{m}_{i-24h} - \bar{m}_i}{\bar{m}_i}$ . Finally, the end of the second drying phase,  $t_{d,2nd,end}$  is defined as the time when  $\Delta\bar{m}_i$  becomes smaller than 0.1% minus 24 hours.

The drying coefficient is determined according to (1). In the case of the experimental set-up of the University of Innsbruck, the effective drying height must be used instead of the total sample height since the sample is dried on both sides. Thus, a total sample height of 50 mm results in an effective sample height of 25 mm.

### 3. Results

#### 3.1. Agreement between simulation and experimentally determined results



**Figure 4:** Measured and simulated drying curve of Calcium Silicate in mass per volume [ $\text{kg}/\text{m}^3$ ] as a function of time [d]. Circles of the same colour mark the beginning and end of the second drying phase.

In order to check the plausibility of the measured data and a correctness of the set-up, it was chosen to make a comparison with simulation. For the material calcium silicate, a hygrothermal simulation was therefore carried out with the software Delphin 6.1, developed by Dresden University of Technology, using the experimental conditions of the two different test setups. It is worth pointing out that the material used for the experimental work in this paper is the same used by Dresden Technical University in the characterization of calcium silicate in Delphin.

In order to compare the results despite their different volumes, the drying curve in mass per volume is plotted against the drying time in days. The saturation reached by the respective samples was given as the starting moisture. The moisture transfer coefficient  $\beta$  was adjusted in the simulation until a parallel slope of the first drying phase of measured data and simulation was reached. Figure 5 shows the drying curves resulted from measurements and simulations. There is a high degree of agreement between both sets of data. In the case of the Eurac Research test setup, there is a small discrepancy between both curves in the period of 3.5 - 5.0 days. The start and end points of phase 2 are slightly delayed compared to simulation, but the duration of the second drying phase is comparable. In the case of the test set-up at the University of Innsbruck, a slightly larger deviation can be seen in the phase 2 of the curve but the total duration of the second phase differs more than in the test set up of Eurac Research.

#### 3.2. Drying coefficient results: calcium silicate

The results obtained for calcium silicate with the new set-ups developed at Eurac Research and University of Innsbruck are summarized in Table 1.

**Table 1.** Comparison of the drying coefficients of the different set ups and simulations.

	UIBK set-up	UIBK simul.	EURAC set-up	EURAC simul.
Duration 2 <sup>nd</sup> drying phase [d]	2,25	1,33	5,36	5,13
Drying coefficient [ $\text{d}^{0.5}/\text{m}$ ]	57,80	46,19	47,06	45,28

Due to the different set-ups, it is primarily interesting to see whether comparable values for the drying coefficient can be determined under different conditions and whether the values determined by measurement correlate with the simulated values. Table 1 shows the calculated durations of the second

drying phase and the resulting drying coefficients, based on the evaluation methods presented in chapter 2.4. The drying coefficient determined from the simulation and measurement of the Eurac Research test setup deviate from each other by approx. 4%. The results of the University of Innsbruck, however, by approx. 20 %. The simulated deviation of the two test setups in relation to the external environmental conditions show a deviation of approx. 2%.

#### 4. Discussion

The deviation between experiment and simulation can either lie in the experimental method, the evaluation method, or in the practical execution of the test (including the preparation of the sample). The two test methods present differences in the relative humidity and in the thickness of the sample. Scheffler and Plagge [8, 9] already published a detailed study on the impact of different parameters on the drying coefficient, narrowing down possible sources of error. According to their results, the relative humidity and temperature have hardly any effect on the duration of the second drying phase. The simulations also confirm this thesis due to a minor deviation in the calculated drying coefficient of approx. 2%.

Looking at the moisture distribution in the sample in the course of drying, it quickly becomes obvious that the point at which the surface is dry enough to start the second drying phase, is reached much faster when drying with a lower relative humidity compared to a similar sample that is dried with a higher relative humidity. The  $kg$  of water per  $m^3$  of calcium silicate of the sample when reaching this point is much lower in the case of the test setup of the University of Innsbruck (RH 0.2 %) than in the case of the test setup of Eurac Research (RH 40.0 %). The core can dry out faster due to the increased relative humidity gradient. However, for the remaining duration of the second drying phase, a lower humidity level must be reached for the test setup with dry air, but the gradient of the water vapour partial pressure as well as the gradient of the relative humidity is also bigger. These effects balance each other out to such an extent that this aspect can be assessed as minor. The simulation results also support this conclusion, at least in the case of calcium silicate.

The surface temperature was measured in Eurac Research's experimental set-up using infrared sensors. This measurement provides accurate results circa twice per minute. In the case of the University of Innsbruck, the temperature was measured every two minutes with the help of a temperature probe placed close to the sample's surface in order to avoid contact and thus an influence on the weighing. Due to the less accurate measuring technique, the evaluation of the point of abrupt temperature rise is less accurate and might lead to a slightly error in the result.

The last source of deviation between experiment and simulation is therefore the installation and preparation of the sample. To avoid a lateral diffusion flow, samples were sealed with aluminium tape. In the case of the test setup at Eurac Research, the bottom was also sealed with aluminium tape to guarantee a unilateral diffusion flow. In the case of the University of Innsbruck, the sample holder (PVC pipe) was additionally insulated from the side to avoid a lateral heat flow. To ensure flushing between the sample and the PVC holder, the gap was additionally filled with silicone. However, small edge areas of the calcium silicate surface were also sealed by the silicone, which could possibly lead to a smaller evaporation surface. With a diameter of 72 mm, an all-round seal of 1 mm already results in a surface area reduction of 4.5 %. With 2 mm of sealing even 11 %.

#### 5. Conclusion

With the help of these investigations, the justification of a drying coefficient as an important material parameter can be confirmed. Comparable drying curves of calcium silicate could be measured in two different test setups and fundamental assumptions of previous research results could be confirmed.

In addition to the definition of the calculation of the coefficient, it was precisely the determination of the duration of the second drying phase that resulted critical. A clear analytical method for determining the start and end time of the second drying phase needs to be defined. For the determination of the starting point, the abrupt increase of the surface temperature during drying was included as a decisive factor in the calculation and a 0.1% mass loss in 24 h was defined as the end point. However, the stability and consistency of this definition should be validated by means of more simulation and measurements data.

While the results obtained with the apparatus proposed by Eurac Research showed good agreement with the simulation data, the alternative set-up proposed by University of Innsbruck showed larger discrepancy. However, simulation results have excluded the differences between both apparatus as the source of disagreement. In order to obtain meaningful and, above all, comparable results, the newly developed test set-up of the University of Innsbruck must be improved, especially with regard to the surface temperature measurement and the sample installations. At the moment, new round robin test with other materials such as wood fibre and perlite are being tested in order to further investigate the differences between the two apparatus.

In conclusion, the introduction of a robust method for the measurement and calculation of the drying coefficient is essential for the appraisal of capillary active materials and should be further investigated in the future. A further simulation study by varying parameters and simulating entire wall constructions should investigate the practical application of the drying coefficient. A correlation between the coefficient and the actual hygric behaviour in the critical transition layer of an internal insulation would confirm the practical application of a drying coefficient.

## 6. References

- [1] Posani M, Veiga M D R and Freitas V P de 2019 Towards Resilience and Sustainability for Historic Buildings: A Review of Envelope Retrofit Possibilities and a Discussion on Hygric Compatibility of Thermal Insulations *International Journal of Architectural Heritage* 1–17
- [2] D'Agostino D 2013 Moisture dynamics in an historical masonry structure: The Cathedral of Lecce (South Italy) *Building and Environment* **63** 122–33
- [3] Vereecken E and Roels S 2016 Capillary Active Interior Insulation Systems for Wall Retrofitting: A More Nuanced Story *International Journal of Architectural Heritage* **10** 558–69
- [4] Jensen N F, Odgaard T R, Bjarløv S P, Andersen B, Rode C and Møller E B 2020 Hygrothermal assessment of diffusion open insulation systems for interior retrofitting of solid masonry walls *Building and Environment* **182** 107011
- [5] Vereecken E and Roels S 2015 Capillary active interior insulation: do the advantages really offset potential disadvantages? *Mater Struct* **48** 3009–21
- [6] 2016 Hygrothermal performance of building materials and products – Determination of water vapour transmission properties – Cup method (EN ISO 12572)
- [7] Scheffler Gregor A. 2008 Validation of hygrothermal material modelling under consideration of the hysteresis of moisture storage. *Phd Thesis* Dresden University of Technology
- [8] Scheffler Gregor A. and Plagge Rudolf 2009 Ein Trocknungskoeffizient für Baustoffe. *Bauphysik* **31** 125–38
- [9] Scheffler Gregor A. and Plagge Rudolf 2010 *Thermal performance of the exterior envelopes of whole buildings XI: Introduction of a drying coefficient for building materials, in: Proceedings, Buildings XI Conference*, (Atlanta, Ga.: American Soc. of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE))
- [10] 2013 Conservation of Cultural Heritage – Test Methods – Determination of Drying Properties (EN 16322)
- [11] Zhao J, Meissener F, Grunewald J and Feng S 2020 Experimental investigation of the drying behaviour of the building materials *E3S Web Conf.* **172** 17002
- [12] Karagiannis N, Karoglou M, Bakolas A, Krokida M and Moropoulou A 2017 Drying kinetics of building materials capillary moisture *Construction and Building Materials* **137** 441–9
- [13] Künzle H M 1995 *Simultaneous Heat and Moisture Transport in Building Components: One- and two-dimensional calculation using simple parameters* (Stuttgart: Fraunhofer IRB Verlag)
- [14] Bianchi Janetti M, Colombo L P, Ochs F and Feist W 2018 Effect of evaporation cooling on drying capillary active building materials *Energy and Buildings* **166** 550–60

## Acknowledgments

The authors are grateful to the European Regional Development Fund for the financial support of the Project ATLAS (ID: ASP644) under the Interreg Alpine Space programme and to the Provincia Autonoma di Bolzano – Alto Adige for the financial support of the project HyLAB.