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# Robustness of internal insulation systems in practice – Role of installation, physical impact, paint types, and surface covering

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ABSTRACT

To investigate the robustness of internal insulation throughout the service-life, this paper describes several practical issues connected to the installation and the performance of different systems in the operation phase. The study was conducted through laboratory and field tests, calibrated numerical simulations, and practical knowledge acquired on-site and from the users. Five issues were studied: 1) Practical problems in the installation were recorded through observations and interviews with craftsmen. This showed that the installation process was relatively easy for most systems and, therefore, robust towards installation. 2) A physical robustness experiment evaluated the robustness of the insulation systems against unintentional hitting. The results of standardized laboratory tests revealed that hemp with lime, and phenolic foam were the most robust systems, and aerogel was the weakest and needed the most repairs. However, no damage was observed on any systems after 5–8 years of daily use. 3) A wet cup test was conducted to test the vapor diffusion resistance of typical wall paint types that may be applied during the system's lifetime. The results were used in simulations to determine the paint's influence on the wall's diffusivity. Wet cup tests showed that both the silicate and acrylic paint are diffusion-open, with the acrylic ones being less open, and it is unlikely that a surface can be made too diffusion-tight by conventional silicate or acrylic paint. 4) Experiments were done regarding the microclimate between the external wall and furniture and paintings. The results indicate that it is a good idea to keep some distance to furniture and decorations from a wall insulated with capillary active insulation system to eliminate increased risk of mold growth. 5) Through inspections and questionnaires, residents were asked about the pros and cons of living with interior insulation. The walls showed no extraordinary signs of wear, and in general, the residents appreciated the better comfort and accepted the downside of having a more fragile wall. The process was made through observations and questionnaires to the craftsmen and the residents, and the results revealed that the installation process was relatively easy for most systems.

## 1. Introduction

### 1.1. Background

The current study is driven by a combination of the European and Danish authorities' climate action plans and growing awareness of the need to reduce space heating consumption while maintaining the traditional masonry's architectural features and creating a more comfortable and healthy interior environment [1]. The housing stock that was constructed as traditional brick buildings until 1960s, offers much potential for energy saving; internal insulation could be a possible way to obtain this, but the insulation method has to be robust and suitable to become more widely used [2–4].

Internal insulation is often considered risky due to the numerous problem cases that have made people reluctant to use it. The conventional approach of a diffusion open insulation behind a vapor barrier and gypsum board has frequently increased the moisture

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levels at the interface between the newly installed internal insulation and the existing wall structure, increasing the possibility of moisture-induced damage, including fungal growth, wood rot, and frost damage [4–6]. Research into building materials and techniques appropriate for internally retrofitting historic buildings with solid masonry façade walls has increased recently due to the desire to reduce energy consumption and $CO_2$ emissions. This has led to the development and introduction of other insulation systems [2–4]. These systems are diffusion-open and may or may not also be capillary active. The systems work in a different way compared to the standard diffusion-tight systems.

The present study investigates all three types of internal insulation systems. Contrary to many other studies, such as [7–10], that often concentrate on the hygrothermal conditions, e.g. at the interface between wall and interior insulation, this study focuses on practical problems that hinder the use of internal insulation; the physical robustness of these materials against everyday use problems, such as accidently hitting or leaning on the wall (experiment 1), painting the wall with the wrong type of paint (experiment 2), and placing furniture or paintings close or against the wall (experiment 3). Additionally, the practical aspect during the application process is in focus as well; whether the insulation system is easy to apply in practice and if the application of the insulation system is of high importance for the final performance of the wall.

### 1.2. State of the art

In many cases, the approach to evaluate the hygrothermal performance of building envelopes is based on either field data or lab tests [11]. The field measurements on a building site enable monitoring of the hygrothermal performance of a specific envelope [11]. However, the in-situ measurements may not always attain the precision of laboratory measurements, which may result in difficult calibration of numerical simulations with in-situ measurements. This is especially true when measuring long-term moisture conditions. An in-between solution between real-life in-situ measurements and laboratory measurements is provided by semi-scale experiments for evaluating the hygrothermal performance of building envelopes [11,12]. Semi-scale experimental systems measure temperature and moisture and simulate conditions that are not feasible to monitor on the construction site [11]. The present study applied a combination of on-site measurements, lab experiments, and simulation models to determine the robustness of internal insulation systems.

#### 1.2.1. Insulation systems

In the present study, different insulation systems have been examined; diffusion-tight, diffusion-open and capillary active, and diffusion-open and non-capillary active. The diffusion-tight insulation systems, which are the traditional insulation systems using vapor barrier, are impermeable to both vapor and liquid moisture transfer [2–4]. Grunewald et al. [13–16] investigated the hygrothermal performance of both cellular glass (vapor tight) and calcium silicate (vapor open and capillary active) using numerical simulations. The findings revealed that cellular glass hindered inward drying, resulting in significantly higher moisture levels than calcium silicate. However, the risk of mold growth was lower in the cellular glass system compared to the calcium silicate system.

The diffusion-open and capillary active insulation systems – if hygroscopic – may buffer moisture, and eventually, capillary actions will lead the material to begin redistributing moisture inwards, where it will evaporate if the right indoor air conditions are met [4,5,16–19]. Over the last years, many studies [11,13,14,17,18,20–32] have examined the hygrothermal performance of such systems, having good performance results. However, there are studies, such as [33], where it is found that these systems might also be problematic, and the high moisture storage might have an adverse impact on the hygrothermal performance [13–16]. Diffusion-open and capillary active systems require high attention to application and operation phases [34]. The insulation boards must be fully adhered to the interior surface of the existing masonry wall during application [13–16]. Failure to do so would limit the capillary transport potential of the insulation systems.

Certain insulation systems may not be capillary active but still be diffusion-open [2–4]. Water vapor can diffuse through the applied system, but it lacks the capillary properties that would allow moisture to be redistributed back into the interior environment except through the slow transport mechanism of diffusion [15–19]. When using diffusion-open insulation materials, there is a risk that moisture will accumulate in the case of thicker insulation and that the masonry/insulation interface will have high relative humidity levels [2–4]. The hygrothermal performance of several diffusion-open, organic, insulating materials was examined in Ref. [35], reporting the relative humidity levels at the masonry/insulation interface to be non-critical.

#### 1.2.2. Robustness

In most homes, the walls serve as frames for a room and as a possibility to lean on or place things against [36]. Sometimes, a chair or other object can accidently hit the wall, and the wall should withstand when that happens. Ball tests will examine how well the internal insulation boards can tolerate normal wear and strain [36]. According to the literature review, the study made by Jacobsen and Dabelsteen [36] was the only available relevant research regarding mechanical robustness testing on internal insulation systems. Their findings showed that autoclaved aerated concrete (AAC) and Polyurethane foam with calcium silicate channels (PUR-CS) had medium performance in terms of physical robustness but better compared to calcium silicate (CS).

However, robustness also applies to defects in installation, maintenance etc. [7–10]. However, the real-life buildings' physical performance also seems to be dependent on craftsmanship, including the preparation of the wall prior to the insulation and the robustness of the solution for the user's interaction during future service life. For instance, if insulation systems are easy to install and come with easily applicable and adjustable solutions for details like windows, partition walls, and electrical installations etc., the resulting performance of the insulation is expected to be closer to the theoretical performance than if the opposite is the case. Especially in studies where a significant deviation was found between the simulated and monitored performance, failures in the craftsmanship and the installation process are often given as a reason why the real-life performance is not the same as the expected one

[37,38]. However, whether the missing quality in installation plays a significant role in the performance of the internal insulation in real life has been investigated in Ref. [39], but has not been widely studied. The aim is, therefore, to also study the role of the installation process and craftsmanship in the robustness and hygrothermal performance of internal insulation.

#### 1.2.3. Interior paint

In recent years, we have seen an increase in the use of capillary active insulation materials open for diffusion in internal insulation of historic building facades. When using capillary active internal insulation, it is generally stated that the systems should be constructed without the use of a vapor barrier and should only be painted internally using suitable diffusion-open paints [40–42]. This potential sensitivity regarding applied paint types has raised concerns from housing associations and professional rental companies, as it is impossible to fully control what tenants are doing in their apartments. This partly keeps building owners from energy retrofitting their buildings.

Vereecken & Roles [43] simulated a 0.1 mm latex interior finishing coat (Sd-value up to 4) on a solid masonry wall insulated with 75 mm CS exposed to wind driven rain (WDR). A considerable increase in relative humidity in the masonry/insulation interface was found, as inwards drying potential was reduced, and had a negative effect on the moisture buffering potential of the wall structure. Dysted & Sandholdt [44] carried out hot-box cold-box experiments and hygrothermal simulations for three capillary active insulation systems (PUR-CS and two AAC products) with 2 and 4 layers or diffusion-open and acrylic paints, which showed little to no effect on the hygrothermal performance. Furthermore, they conducted a wet cup experiment for acrylic paint on gypsum (1–4 layers), which resulted in an equation for the vapor diffusion resistance, Z $[(s \bullet m^2 \bullet GPa)/kg]$, based on a number of layers of acrylic paint: $Z = 0.59n + 0.55$. They also compared findings for acrylic paint with recommendations for an AAC product and concluded that acrylic paint would not reach the recommended limit unless an excessive number of layers was applied. However [44], was only a small study, and the issue needs to be further explored.

#### 1.2.4. Microclimate

As mentioned above, due to the nature of the capillary active insulation materials, moisture transport to the interior surface must not be obstructed, which also includes placing heavy furniture, such as a couch, directly up against the interior surface. This could result in a local microclimate with increased relative humidity and a potentially risk of mold growth in the interface between insulation and furniture or wall-hanging decorations [45,46]. The current study's systemic literature review found no studies investigating the effect of placing heavy furniture against capillary active internal insulation on hygrothermal performance. The search was done in Scopus, Web of Science, and the Aalborg University library search engine. The only available study is by Jacobsen & Dabelsteen [36], who conducted a preliminary assessment for the present project (initial 2-month data from 2016). Their findings showed mixed results, with some insulation systems showing lower temperatures and increased relative humidity behind the mounted acrylic plates and leather patches. In contrast, other systems showed reduced relative humidity levels.

### 1.3. Aim

As state-of-the-art research has revealed, there are many studies of the hygrothermal performance of internal insulation, especially under perfect and controlled conditions. However, there is a lack of investigation into how different insulation systems perform in practice, both during installation and in everyday life, as seen from the perspective of the residents and building owners. The service

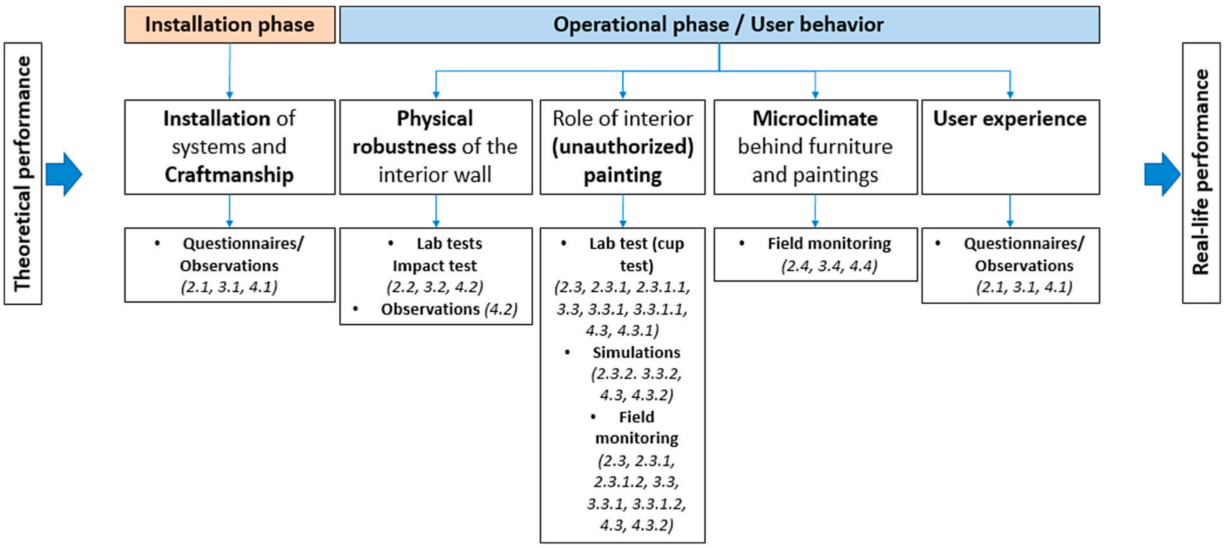



**Fig. 1.** Research framework flow diagram including section numbers.

life of an older, refurbished building includes, amongst other phases, the installation phase of the internal insulation system (craftsmanship) and the operation phase (users-tenants). The robustness of the building envelope in the installation phase is connected to the knowledge and skills of the craftsmen during the application and maintenance process. At the same time, the robustness regarding the operation phase is tightly connected to the user behavior: accidently hitting the wall, painting the wall with the wrong type of paint, and placing furniture or paintings against the wall. The building owners are interested in the service-life of their buildings and the possible internal insulation before deciding to refurbish them; if they decide to insulate, it is important to know the practical pros and

**Table 1**
Properties of examined materials and material layers. $\lambda_{dry}$ = Thermal conductivity in dry state, $\mu_{dry}$ = water vapor resistance factor in dry state, $A_w$ = water uptake coefficient, d = thickness, Z = vapor diffusion resistance. Red: diffusion-tight (or semi-diffusion-tight), Green: Diffusion-open and capillary active, Blue: Diffusion-open. This distinguish was done based on the Aw of the materials. A material is considered as capillary active if Aw>0.25 kg/(m$^2$·s½) (similar to typical historic bricks or higher).

| ID | Material layers (from exterior to interior side) | Density [kg/m³] | $\lambda_{dry}$ [W/(m·K)] | $\mu_{dry}$ [-] | $A_w$ [kg/(m²·s½)] | d [mm] | Z [m²·s·GPa/kg] |
|---|---|---|---|---|---|---|---|
| **Wall** | Brick masonry | 1900 | 0.6 | 10 | 0.11 | 348 | 18.43 |
| | Lime plaster | 1600 | 0.7 | 7 | 0.05 | 10 | 0.37 |
| **GF** | Bitumen glue mortar | 1100 | 0.17 | 100000 | 0 | 8 | >500 |
| | **Glass foam** | 120 | 0.036 | ∞ | 0 | 100 | >500 |
| | Interior plaster | 466 | 0.106 | 8.4 | 0.0135 | 8 | 0.44 |
| **PF** | Glue mortar | 833 | 0.155 | 15 | 0.003 | 8 | 0.64 |
| | **Phenolic foam** | 60 | 0.02 | 10 | 0.08 | 100 | 57.6 |
| **CS** | Glue mortar | 833 | 0.155 | 15 | 0.003 | 8 | 0.64 |
| | **Calcium silicate** | 270 | 0.062 | 4 | 1.12 | 100 | 2.12 |
| | Glue mortar | 833 | 0.155 | 15 | 0.003 | 8 | 0.64 |
| **AAC** | Glue mortar | 833 | 0.155 | 15 | 0.003 | 8 | 0.64 |
| | **Autoclaved aerated concrete** | 115 | 0.04 | 4 | 0.013 | 100 | 2.12 |
| | Glue mortar | 833 | 0.155 | 15 | 0.003 | 8 | 0.64 |
| **PUR-CS** | Glue mortar | 1313 | 0.497 | 18.7 | 0.0052 | 10 | 0.99 |
| | **Polyurethane foam with calcium silicate channels** | 45 | 0.031 | 69 | 0.0027 | 80 | 29.23 |
| | Interior plaster | 466 | 0.106 | 8.4 | 0.0135 | 10 | 0.44 |
| **AG** | Glue mortar | 833 | 0.155 | 15 | 0.003 | 8 | 0.64 |
| | **Aerogel** | 146 | 0.014 | 4.7 | 0.0004 | 10 | 0.25 |
| | Interior lime plaster | 1600 | 0.7 | 7 | 0.05 | 10 | 0.37 |
| **HL** | **Hemp with lime** | 280 | 0.0812 | 4.1 | 0.317 | 120+30 | 3.26 |
| | Interior clay plaster | 1568 | 0.4837 | 11 | 0.183 | 20 | 1.17 |
| **LC** | **Cork-lime plaster** | 252 | 0.037 | 3 | 0.048 | 40 | 0.64 |
| | Interior plaster | 1600 | 0.7 | 12 | 0.17 | 8 | 0.51 |

cons of different systems. Therefore, it is crucial to investigate these four aspects. Additionally, it is important to know how satisfied the residents are with having an internally insulated wall. The current study will add knowledge and quantify the influence of practical conditions on the insulation systems' performance and robustness compared to the theoretical performance. Fig. 1 presents the research framework flow illustrating the research idea.

## 2. Method and materials

Several internal insulation systems have been tested in this study. The selection of systems was made based on a combination of the most common systems and the wish to test diffusion-open and diffusion-tight systems as well as capillary active systems. The properties and details of the different tested materials and wall systems are depicted in Table 1. Some material properties vary a little between the experiments because the experiments were conducted at different times and with different material brands. However, since the differences are small, it is believed that the results from the various tests can be compared.

### 2.1. *Method for evaluation of craftmanship and user behavior*

The role of the installation process of the insulation systems is studied by following and documenting a real case, where four different types of internal insulation systems were installed, and afterward monitored for their hygrothermal performance. Each one of the four insulation systems was installed in two rooms, one facing South-East (SE) and the other facing North-West (NW) (see Fig. 2). This case, together with the monitored and the expected performance based on dynamic hygrothermal simulations, is described in Refs. [47,48]. The building is from 1837 and is representative of a large amount of Danish residential buildings. The studied 3rd floor has a 360 mm façade of solid masonry.

The installation process of 4 different systems (see Table 2) was documented with photographs, observations and interviews. Furthermore, these systems' available product guidelines and technical information were studied to assess if the installation was in line with the product guidelines or if any deviations were observed that might be critical for the correct installation. Users were asked about their habits and their experience with the insulated wall. In addition, visual inspections were conducted in other dwellings insulated 5–8 years earlier. Also here, the users were asked about their experience with the insulated wall. These cases and their hygrothermal performance are presented in Refs. [49,50].

### 2.2. *Physical robustness of the interior wall - method*

The experimental set-up for the physical robustness was designed to imitate scenarios likely to arise in daily use, such as impacts from hard objects, like furniture or body parts, that could damage the walls [51]. The results of the experiments will indicate how the systems would perform in everyday use. The European standard ETAG 004 [52] and the ISO 7892:1988 [53] was utilized as a starting point for these tests, with the 'hard body impact test' being used in 'Vertical building elements - Impact resistance tests - Impact bodies and general test methods' to determine if walls can sustain impacts without the interior insulation breaking [51]. According to the standards, a 0.5 kg, 1 kg and 3 kg steel ball with a force of 3, 10 and 30 J, respectively, should strike the wall. It was decided that steel balls weighing 1 kg and 3 kg would be used for the experiments. Although the standard recommended a soft cell ball for the 3 kg testing, a hard cell ball was used since that was the only one that the electromagnet could hold. But, since there is no threshold value to compare with and all the tests were implemented with the same ball, the results are believed to be trustworthy. Furthermore, the metal

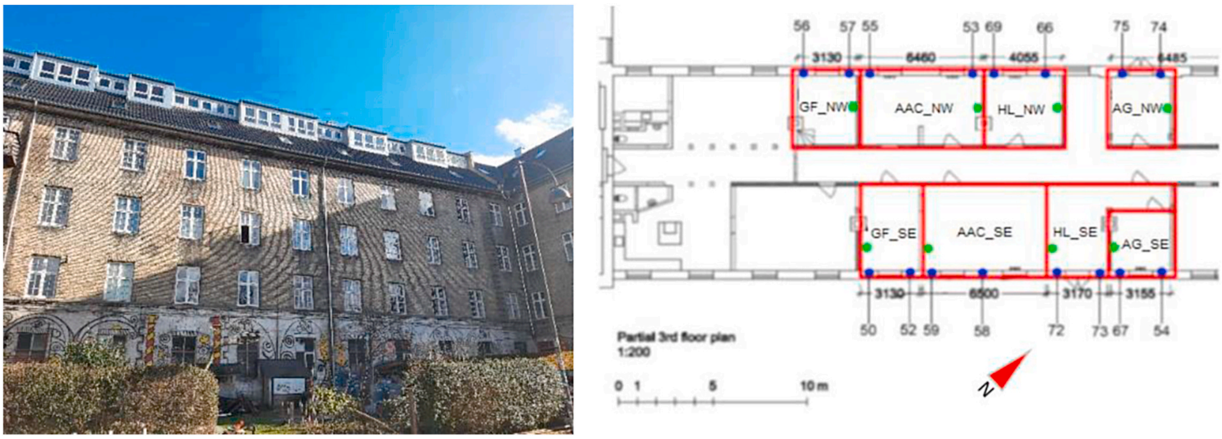



**Fig. 2.** Case building from outside (left) and the floor plan of the section with rooms with internal insulation (right). Each insulation system was installed on both sides of the corridor to test two orientations (SE and NW). The insulated rooms are highlighted in red. The blue dots indicate the interface temperature and relative humidity sensor placement. The green dots are the indoor climate sensors. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 2**
Insulated area of the installed insulation systems in the case building.

| Materials | Insulated area ($m^2$) |
|---|---|
| **GF** | NW: 5,0<br>SE: 7,5 |
| **AAC** | NW: 15,7<br>SE: 15,8 |
| **HL** | NW: 10,4<br>SE: 6,9 |
| **AG** | NW: 16,6<br>SE: 7,6 |

ball has to hit the same spot on the wall three times based on the ETAG 004 requirements. The diameter of the impacts was measured to determine the extent of the damage. Five different insulation systems were investigated, with all their layers (resembling the real-life systems); Autoclaved Aerated Concrete (AAC), Aerogel (AG), Hemp with lime (HL), Glass foam (GF) and Phenolic Foam (PF). Instead of hitting a vertical surface, the balls were dropped from two different heights on a horizontal surface.

The experimental set-up shown in Fig. 3 was used for the experiment. To determine the proper distance for a 10 J and a 30 J hit, the distance was calculated based on whether a 1 kg or 3 kg ball was used. As seen in the figure, a set-up was created and the correct heights (distances) from where the ball should be released were fixed. The set-up included a metal structure with an electromagnet that held the metal ball at the same fixed point for every hit. When the power was turned off, the metal ball was released and landed on the exact same spot every time. In this way, high accuracy was obtained in terms of height and point of impact. The same electromagnet was used for the two types of balls; the distance from the floor was the only modification. A caliper recorded the diameter and the depth of the crater from each impact, and every initial fall was captured on camera - in many cases all three falls were recorded for comparison purposes. Each test with 3 hits was performed 3 times.

### 2.3. *Role of interior (unauthorized) painting*

#### 2.3.1. *Experimental method*

*2.3.1.1. Laboratory test of diffusion tightness – wet cup method.* This experiment aimed to investigate the diffusion resistance of traditional acrylic wall paint and highly diffusion-open silicate paint typically used for interior surfaces of capillary active internal insulation systems where transport of the moisture to the interior surfaces and drying from the surface to interior is critical for the performance of the system.

The experiment was conducted as wet cup according to DS/EN ISO 12572 [54], with test conditions set to 23 °C ± 1 and 50/93 % RH ±5 %. The relative humidity inside the cup was maintained using Ammonium dihydrogen phosphate ($NH_4H_2PO_4$, CAS). The test was carried out in a climate chamber, and the ambient chamber temperature and relative humidity conditions were measured every 15 min. The test cups were weighted periodically. Specimens comprised gypsum board disks with a diameter of 180 mm, of which 160 mm was free for diffusion during the experiment (test area 0.02 $m^2$). The specimens were painted either with a widely used acrylic paint [55–57] or a diffusion-open silicate paint [58], each disk had approximately 5 g of paint to ensure the correct paint thickness of

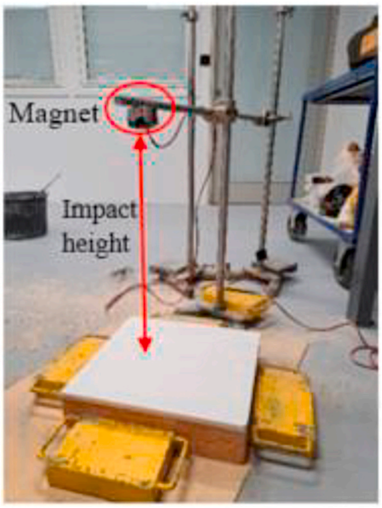



**Fig. 3.** Experimental set-up for the impact test.

one paint layer. Gypsum disks were weighed after each paint treatment and again before applying the next layer. The study investigated several paint variations, and 5 specimens were produced for each variation.

- Acrylic paint: 2-layers (A-2), 5-layers (A-5), 10-layers (A-10)
- Silicate paint: 2-layers (S-2), 5-layers (S-5), 10-layers (S-10), 10-layers + 2-layers acrylic paint (S/A - 10 + 2)
- Unpainted reference specimens

Gypsum disks were sealed inside the test cup using a mixture of 60 % beeswax and 40 % paraffin wax, as recommended in DS/EN ISO 12572. Prior to the paint treatments, the edge and outermost part of specimens were treated with epoxy paint [59]. This was done to prevent unintentional penetration of the wax mixture into the gypsum disks. In Fig. 4, the stages of the preparation of the samples are presented.

*2.3.1.2. Field experiment with different paints - method.* A large field experiment was constructed at the Technical University of Denmark (DTU) on the test site in Kongens Lyngby, Denmark. It involved containers with 1 × 2 m cutouts in the façade, filled with a 348 mm (1½-stone) masonry wall with 12 mm render. More information regarding the field experiment may be found in Refs. [7,60,61].

For this study, two southwest facing test walls insulated with 100 mm AAC boards were examined, one with the diffusion-open paint recommended for system (Z = 0.11 $m^2$ s GPa/kg) and one with a wide used acrylic paint (Z = 1.85 $m^2$ s GPa/kg). Indoor set points were 20 °C and 60 % RH, and the measured values are available in Ref. [60]. Temperature and relative humidity were measured between May 2015 and May 2020, and measured every 10 min using digital HYT221 sensors [62] with an accuracy of 0.2 K between 0 and 60 °C, and 1.8 % RH at 23 °C between 0 and 90 % RH. The focus was on measurements from sensor locations 3 and 4 (shown with red dots in Fig. 5).

The risk of mold growth was evaluated using the VTT mold growth model [63,64]. The VTT model allows the evaluation of the hygrothermal performance over time, and the model output is the mold index (M), ranging from 0 to 6, where 0 corresponds no growth and 6 to heavy growth (100 % coverage). Values 3–6 are within the visual range. The critical limit for interfaces not in contact with the indoor air is M > 3 [65]. The following model parameters were used: sensitivity class 3 (medium resistant, e.g., cement-based materials, plastic-based materials, mineral wools) and decline factor of 0.25 (e.g., concrete, PUR foam, glass wool).

*2.3.2. Simulation method*

In addition to the field experiment, several simulations were carried out to investigate the effect of interior paint treatment on the hygrothermal performance of diffusion-open interior insulation systems. Simulations were done in WUFI® Pro, version 6.6, and the models were simulated with 9 years (2011–2019) of measured outdoor climate data for Sjælsmark, 20 km north of Copenhagen, Denmark, and indoor humidity class 2 according to EN-ISO 13788 [66]. The outdoor climate data were accumulated from DMI (Danish Meteorological Institute) [67]. The simulation models are not validated since the measurements and the simulation are not correlated.


**Fig. 4.** Cup experiment: (a) Paint treatment of gypsum board disks, (b) Sealing test cups with mixture of beeswax and paraffin, (c) Placement of test cups inside climate chamber.

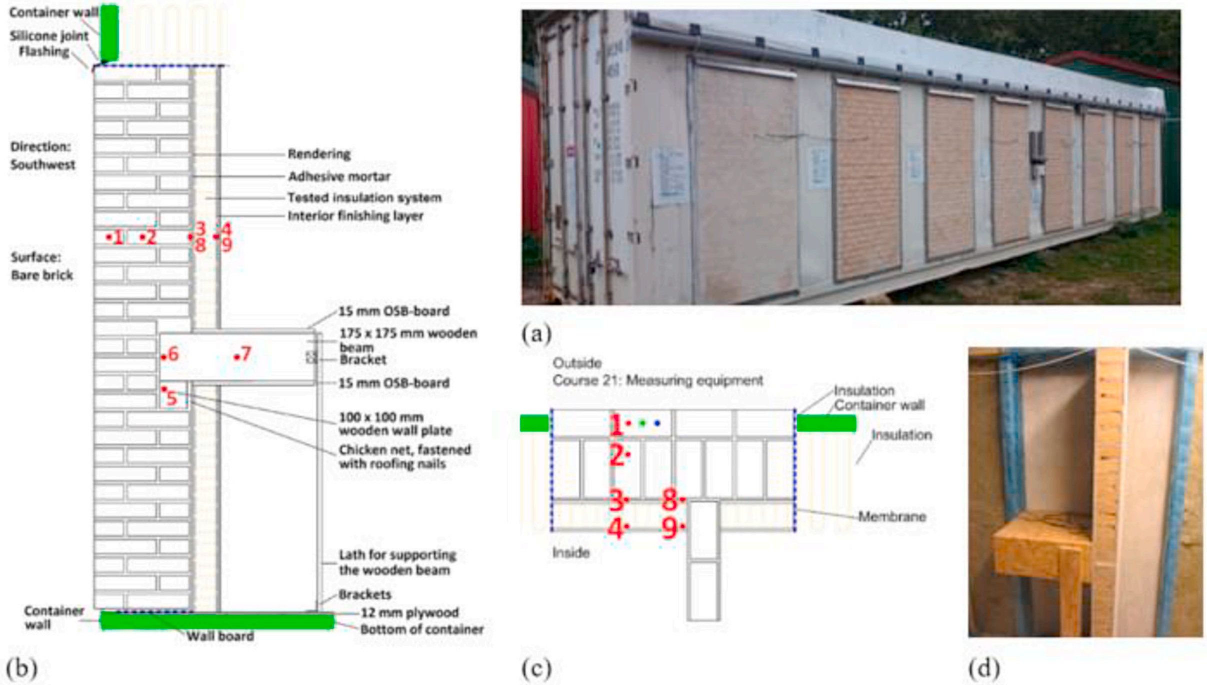



**Fig. 5.** Field experiment configuration: (a) External view of test container, (b) Vertical section of a test wall, (c) Horizontal section of a test wall, (d) Internal view of test wall.

The simulations are used as a parametric study, investigating only the effect of internal conditions. The type of brick that was used was chosen from the WUFI material library ("Solid brick masonry", $\lambda = 0.6$ W/mK).

The wall comprised 348 mm solid masonry with 10 mm interior plaster and was simulated with and without hydrophobization of the exterior surface. The hygrothermal performance was evaluated for 6 insulation systems: Calcium Silicate (CS), Polyurethane foam with calcium silicate channels (PUR-CS), Autoclaved Aerated Concrete (AAC), Aerogel (AG), Hemp with lime (HL), and Lime-cork plaster (LC). The simulation of hydrophobization was implemented according to Refs. [68,69]. To simulate the effect of different interior paint treatments, several variations of the interior Z-value were simulated: 0.05, 0.5, 2.6, 5.3, 10.6, 21, 32, 42, 53, 79, 106, 159, 212, 265, and 530 $m^2$ s GPa/kg. Moreover, the performance of walls without insulation was also simulated.

### *2.4. Method for creating and measuring microclimate behind furniture and paintings*

An experiment was conducted to investigate the hygrothermal conditions between internally insulated solid masonry walls and furniture placed up against the interior surfaces. As aforementioned, keeping the interior surfaces free is important to allow diffusion-open capillary active insulation systems to transport moisture to the surface from where it can evaporate to the indoor air.

This study examined eight test walls of the earlier-mentioned container, all facing southwest (see Fig. 5). The test walls with the installed insulation systems and exterior surface treatments are shown in Table 3. Each test wall was fitted with a 250 × 200 mm acrylic plate simulating a picture frame mounted on the interior surface (15 mm from the wall), while two AAC walls were also fitted with a 250 × 200 mm leather patch simulating a leather sofa placed directly up against the interior surface (see Fig. 6).

Indoor set points were 20 °C and 60 % RH, and the measured values are available in Ref. [60]. Digital HYT221 sensors [62] were placed between the insulation systems' interior surface and the acrylic plates and leather patches to measure the hygrothermal

**Table 3**
Combinations of examined insulation systems, exterior surface treatments and interior obstructions, i.e., acrylic plate or leather patch.

| Insulation systems | Exterior surface treatment | Acrylic plate | Leather patch |
|---|---|---|---|
| **PUR-CS** | No treatment | X | |
| **PUR-CS** | Hydrophobization | X | |
| **CS** | No treatment | X | |
| **AAC** | No treatment | X | X |
| **AAC** | Hydrophobization | X | X |
| **AAC** | Plaster | X | |
| **Reference (uninsulated)** | No treatment | X | |
| **Reference (uninsulated)** | Hydrophobization | X | |

conditions. Temperature and relative humidity were measured every 10 min between May 2016 and May 2020. The risk of mold growth was evaluated using the VTT model (see section 3.4). However, here the focus was the interior surface, and the critical limit was M > 2.

## 3. Results

### 3.1. Installation of systems and user behavior

A team of two semi-professionals installed the four insulation systems and aimed to follow the respective product guidelines. The installation process was followed by the research team and was documented, as seen in some illustrative photos in Fig. 7.

The studied case included installation of every insulation system in 2 different rooms (Fig. 2). The wall area in every room to be insulated varied from 5 $m^2$ to 17 $m^2$. Every wall had either a window or a terrace door, which increased the complexity of the installation. The original wall and window reveals were carefully cleaned in every room by removing all existing finishes and plaster (Fig. 7a). Afterward, the wall surface (except for system HL) was built again with mortar plaster to enable the mounting of the insulation boards on an even surface. The fastening of the insulation boards to the mortar plaster took place with a glue mortar using a notched trowel (systems AAC and AG) or with a bitumen-based glue, also using a notched trowel (system GF, see Fig. 7d). Installation of HL system included no glue, but the boards were installed with an approx. 30–40 mm gap to the masonry, which was then filled with wet HL granulate to create a contact with the original wall (see Fig. 7e).

According to the craftsmen, the installation process was easy, especially for the HL system and AAC and AG. On the contrary, installing the GF system was very challenging due to the messy bitumen glue and the short working time window. Also, the GF insulation blocks were delivered with surprisingly uneven edges, which made the mounting difficult and time-consuming. However, installing any of the studied systems involved numerous adjustments and customized solutions to fit the insulation to the old building without standard measures. Earlier studies [49,50] showed that installing the PUR-CS system was challenging as it required certified craftsmen.

When asked about their experience with the insulated wall after at least one heating season, all the tenants were satisfied with the increased comfort; it was easier to keep the desired temperature in the room, and the wall was experienced as warmer than before. Also, nobody complained about the lost square meters. Most tenants knew that they should treat the wall with some care, as the insulated wall would be more fragile than the old masonry. Consequently, almost no tenant had tried to hang up paintings or like, and no attempts were made to hang up heavy things. The fragility of the wall was accepted, but it was also seen as a downside to the insulation. Also, some tenants had experienced difficulty in cleaning the surface painted with silicate paint, as it was too easily washed away.

Visual inspections in eight flats insulated for 5–8 years earlier, described in Refs. [49,50], showed no extraordinary sign of living: i.e. no holes or bumps or worn surfaces were found on the surface of the insulated wall. In some apartments, the tenants had painted the wall several times with unauthorized – but probably acrylic – paint, while the wall in other flats still had the original and authorized diffusion-open paint even after 5 years.

### 3.2. Physical robustness of the interior wall - results

The purpose of this experiment was to test the robustness of the insulated wall systems against impacts from hard objects. The results from the impressions of the impacts on each insulation system are presented in Table 4. The two different kinds of impacts are depicted in the table, for 1 and 3 kg ball, respectively. The impressions illustrated are from the 3rd hit on the same spot.

Table 5 illustrates the measured results from all three hits, with both types of balls (1 and 3 kg). The results include the impression's diameter and the impact's depth. The diameter was calculated as an average of two perpendicular directions.

In Fig. 8, the results regarding the size of the diameter and the depth for each hit are depicted graphically. In all materials, the last

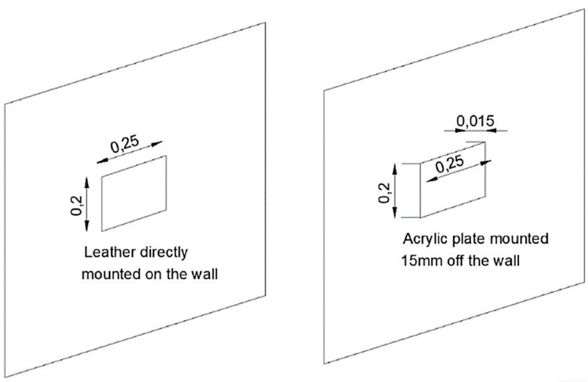



**Fig. 6.** Simplified drawing (distorted dimensions) of how different materials were placed against the internal insulation.


**Fig. 7.** Photos from the installation of the studied insulation systems. a) Existing wall was cleaned for all old plaster, wall paper and dust, b) New mortar plaster was used to make an even underlay for the insulation (except for system HL), c) Cutting and installation of system AAC, d) Bitumen based glue on system GF was difficult to work with, e) System HL was installed without new mortar plaster as the uneven void between boards and the wall was filled in with HL as a wet granulate, f) System HL under construction also showing the partition wall.

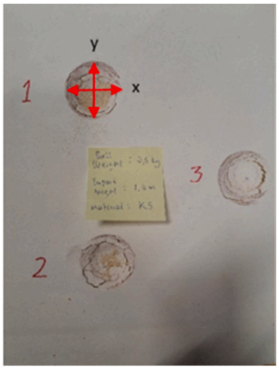
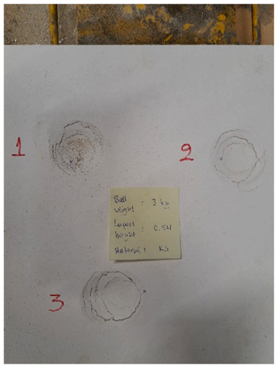
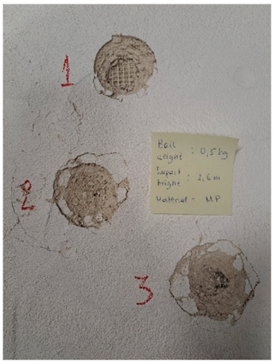
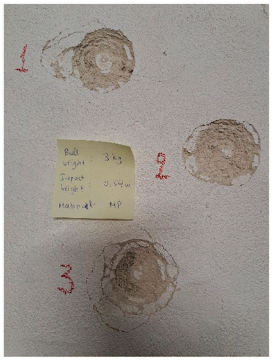
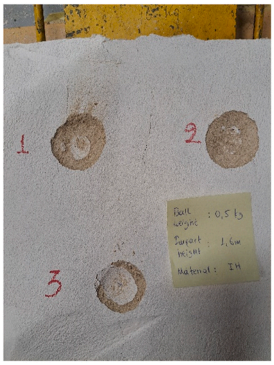
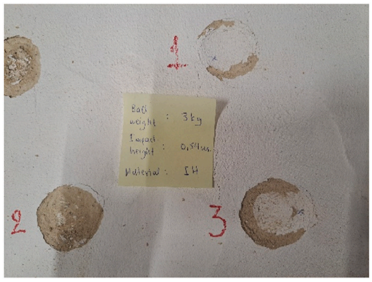
(3rd hit) was compared to highlight the biggest damage. In terms of diameter, the biggest one is found for AG for the 1 kg hit (~7.5 cm) and for GF for the 3 kg hit (~8 cm). The lowest ones are found for HL for both the 1 kg (~4.8 cm) and 3 kg (~5.7 cm) hits. Moreover, the depth of each hit can vary from few mm (~3 mm) and reach up until ~2 cm. The maximum impact depth was found for PF which was ~2.1 cm for the 1 kg hit and ~1.8 cm for GF for the 3 kg hit (when comparing the 3rd hit in all cases). The minimum impact appeared to be found on HL for both weights; ~0.8 and ~0.7 cm for 1 and 3 kg, respectively. Since the impact depth was more than 1 cm in many cases (which is approximately equivalent to the paint and mortar layer thickness), these final layers were completely destroyed and the mesh was visible. In many cases, the damage appeared to be deeper than the mesh.

### *3.3. Role of interior (unauthorized) painting*

#### *3.3.1. Experimental results*

*3.3.1.1. Laboratory experiment – wet cup results.* The results from the wet cup test are presented in Fig. 9. The results include the determination of the water vapor resistance (Z-value) for the different amounts and types of paint layers on the samples. Because the samples were highly wetted at the underside, facing the high relative humidity, and the solution inside the cups had dried out faster than expected, the cup test was repeated, but this time with the painted layer towards the higher humidity. However, since some measurements were taken during the first time, it was decided that they should be presented as well. Thus, two rounds of measurements are available for some samples (1 and 2). The silicate paint samples (S), as it was expected, appear to have Z-values below 0.15 ($m^2$ s GPa/kg). Even the samples with the 10 layers of silicate paint (S-10) were found to be Z < 1 ($m^2$ s GPa/kg). On the other hand, the

**Table 4**
Impressions of the different impacts on each insulation system.

| Materials | 1 kg | 3 kg |
|---|---|---|
| **PF** |  |  |
| **AAC** |  |  |
| **HL** |  |  |
| **GF** |  |  |

(continued on next page)

**Table 4** (*continued*)

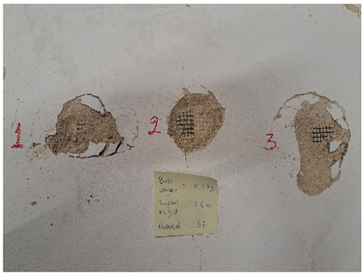
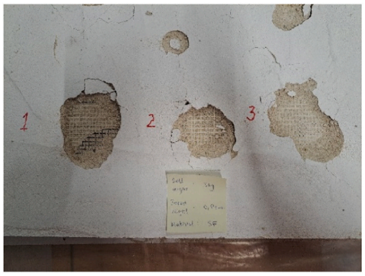
| Materials | 1 kg | 3 kg |
|---|---|---|
| **AG** |  |  |

**Table 5**
Measured results from the impact test. The total max values are marked with red.

| Materials | Average Measurements (mm) | 1st hit | | 2nd hit | | 3rd hit | |
|---|---|---|---|---|---|---|---|
| | | 1kg | 3kg | 1kg | 3kg | 1kg | 3kg |
| **PF** | Diameter | 49.80 | 40.57 | 46.99 | 53.10 | 46.83 | 61.57 |
| | Impact depth | 8.12 | 3.53 | 12.69 | 5.02 | 21.42 | 7.16 |
| **AAC** | Diameter | 44.47 | 48.71 | 64.66 | 62.07 | 71.45 | 73.10 |
| | Impact depth | 5.18 | 4.36 | 7.19 | 4.93 | 17.90 | 6.89 |
| **HL** | Diameter | 34.49 | 40.01 | 42.90 | 51.45 | 48.79 | 57.90 |
| | Impact depth | 4.89 | 4.10 | 6.81 | 5.73 | 8.11 | 6.95 |
| **GF** | Diameter | 47.18 | 57.16 | 55.87 | 67.96 | 61.63 | 79.47 |
| | Impact depth | 5.69 | 6.05 | 11.85 | 13.64 | 16.86 | 18.30 |
| **AG** | Diameter | 40.69 | 60.44 | 57.37 | 72.55 | 75.00 | 77.42 |
| | Impact depth | 3.18 | 4.07 | 9.56 | 9.21 | 11.73 | 10.26 |

acrylic paint samples (A) showed Z-values ranging from 0.45 to 10.65 ($m^2$ s GPa/kg). Among the acrylic samples, the specimen with the 10 layers of paint (A-10) were found to have the highest Z-values. Furthermore, the A-2 samples seem to have significant differences between the two rounds of measurements. The samples with 10 layers of silicate paint and 2 layers of acrylic paint (S/A-10 + 2) have Z-values around 0.6 ($m^2$ s GPa/kg). In general, the values for acrylic paint had much higher variations than those for silicate paint.

*3.3.1.2. Field experiment – results with different paints.* The measurements from the large experimental set-up are presented in Fig. 10. The results did not show considerable differences between the diffusion-open and acrylic paint treatments in the masonry/insulation interface (P3). Temperatures were almost identical between the walls painted with diffusion-open and acrylic paints for both sensor locations. The largest differences were seen for the relative humidity levels behind the interior plaster (P4). Lower relative humidity levels were found in the wall painted with acrylic paint during winter periods, while during summer periods the wall with acrylic paint had the highest relative humidity levels. Only exception was during the summer of 2017 where both walls had similar relative humidity levels.

### 3.3.2. Simulation results

The results from the WUFI simulations with the variation of interior Z-value are presented in Fig. 11. Although 6–8 materials were tested, only AAC is depicted in the graphs as a representative. The models that were created to simulate the effect of increasing tightness from multiple paint treatments showed higher relative humidity levels in the masonry/insulation interface for walls without hydrophobization with increased interior Z-value. Meanwhile, lower relative humidity levels were seen with increased interior Z-value for walls with hydrophobization. These tendencies were seen for all 6 investigated internal insulation systems and the uninsulated reference walls. Differences in the effect of the Z-value variations on the relative humidity levels in the masonry/insulation interface between the different insulation systems were observed, where the smallest relative humidity differences were observed for the PUR-CS system.

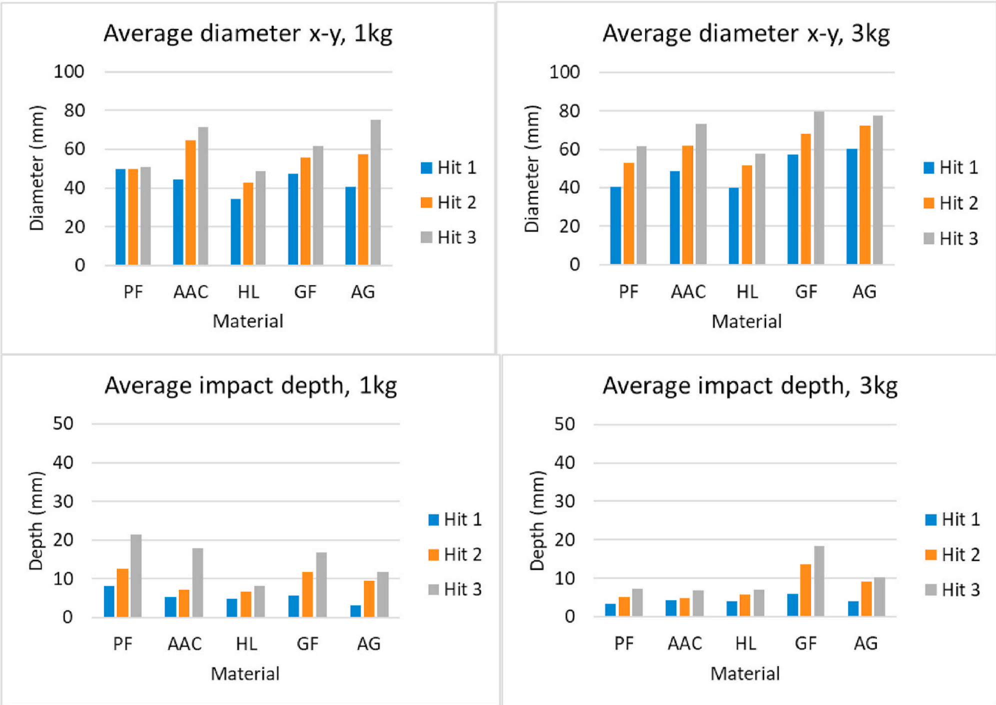



**Fig. 8.** Average diameter of the hits and depth of the impact, with both types of balls (1 and 3 kg).

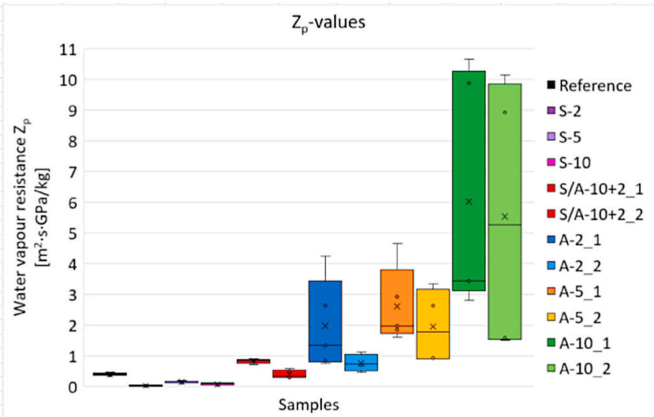



**Fig. 9.** Water vapor resistance $Z_p$ of the different paint layers. The depicted values are measured values minus the reference value.

### 3.4. Results of microclimate behind furniture and paintings

Measurements for the relative humidity at the interior surface, between insulation systems and acrylic plates or leather patches, are shown in Fig. 12. For walls insulated with the semi diffusion-tight PUR-CS system (Fig. 12a–b), relative humidity was slightly higher behind the acrylic plate than the uncovered walls (up to 10 %-points difference). Meanwhile, for the walls insulated with CS or AAC or the reference walls, the results appear more unclear, as in some periods, higher relative humidity was seen behind the acrylic plates and leather patches, and in other periods, lower relative humidity was seen behind the acrylic plates and leather patches.

For walls insulated with AAC, both with and without hydrophobization (Fig. 12d–e), relative humidity was seen to be higher behind the acrylic plates and leather patches during the warm periods in 2016, 2017 and 2018 where relative humidity behind the leather patch is highest, with up to 20 %-points higher relative humidity than the uncovered AAC surface.

Evaluating the potential mold risk over time with the VTT model (Fig. 13) showed low to no risk for any of the examined walls, with the highest risk seen for the wall insulated with AAC and covered by leather patches. The non-hydrophobized and hydrophobized walls with AAC had a Mold Index of 0.36 and 0.44, respectively, while all uncovered surfaces and acrylic plate surfaces had a Mold Index of $M < 0.20$. The acceptable limit for surfaces in contact with air is $M > 2$.

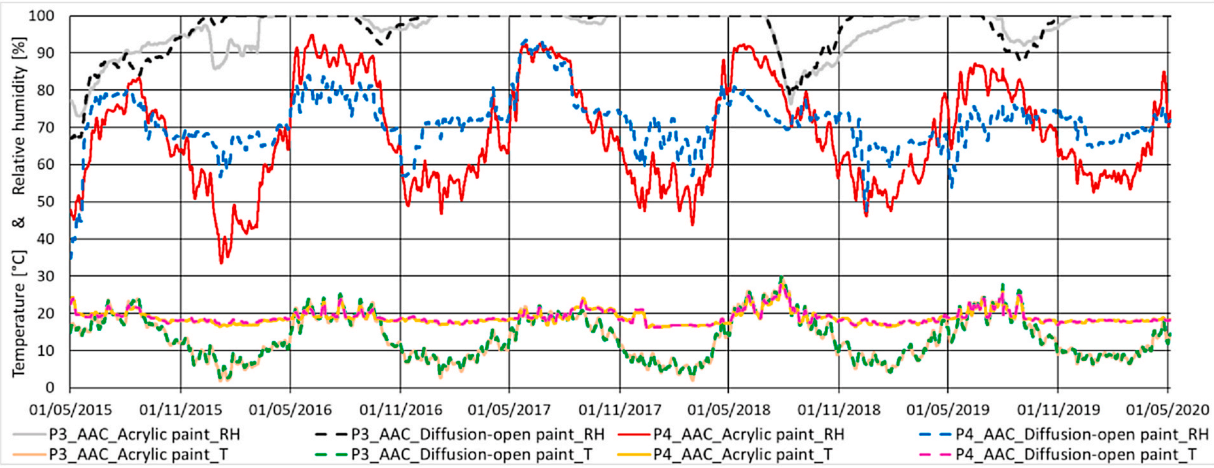



**Fig. 10.** Effect of interior paint treatments on relative humidity levels and temperatures in solid masonry walls insulated internally with AAC insulation. P3: Masonry/insulation interface and P4: Behind interior plaster.

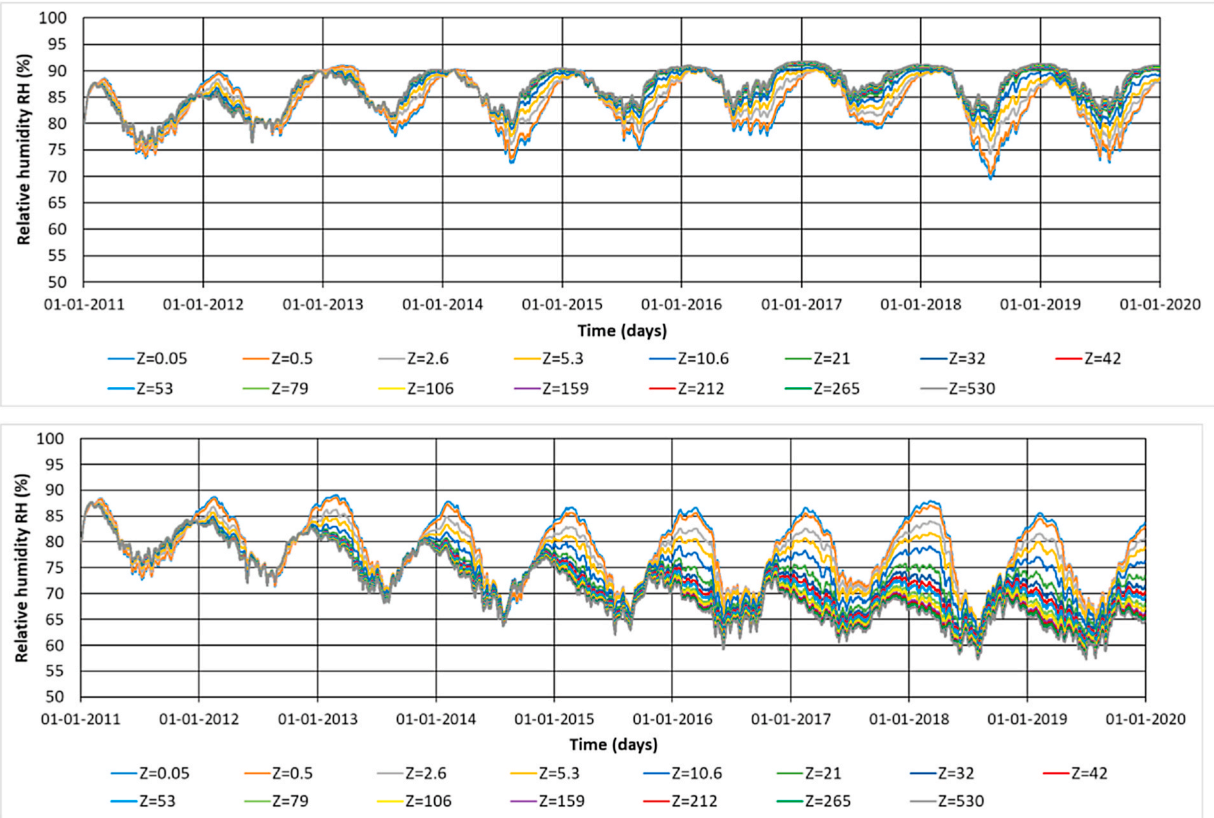



**Fig. 11.** Effect of interior paint treatments by variation of Z-value [$m^2 \cdot s \cdot GPa/kg$], here shown for a solid masonry wall with AAC insulation. Upper graph: Wall without hydrophobization. Lower graph: Wall with hydrophobization.

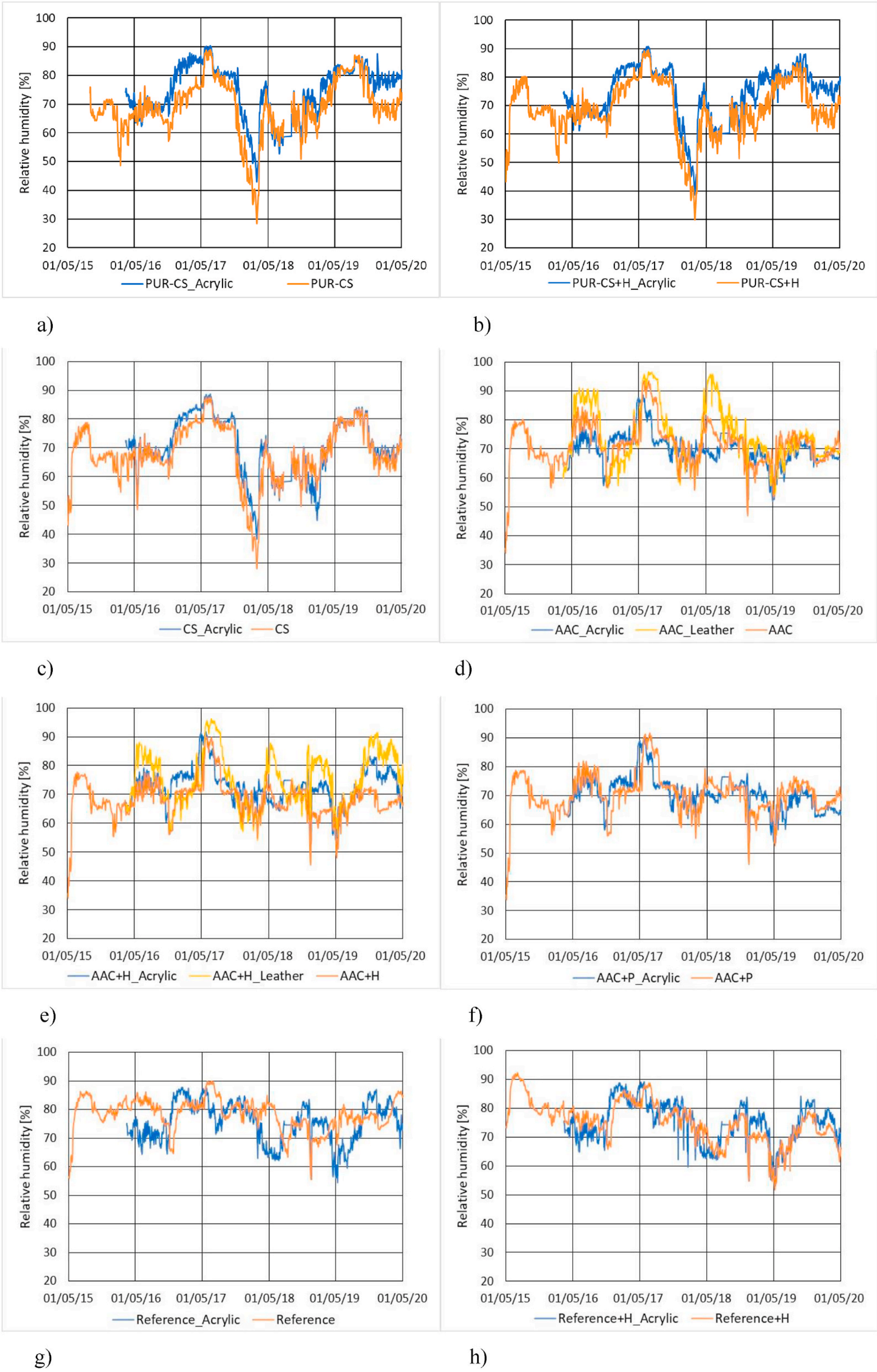



**Fig. 12.** Relative humidity levels at the interior surface, between insulation systems and acrylic plates or leather patches: (a) PUR-CS wall, (b) Hydrophobized PUR-CS wall, (c) CS wall, (d) AAC wall, (e) Hydrophobized AAC wall, (f) AAC wall with exterior plaster, (g) Reference wall, (h) Hydrophobized reference wall. +H: hydrophobization, +P: exterior plaster. Results are presented as 48-h running averages.

## 4. Discussion

### 4.1. Installation of systems

All available guidelines on the installation of internal insulation, including the product guidelines, recommend that the existing wall should be carefully cleaned for any loose matter, old plaster, dust and existing paint, before installing the new insulation system [45]. The main reason for this is to reduce the risk of future mold growth behind the internal insulation as this interface will have a lower temperature and, therefore, a higher relative humidity as a result of the thermal resistance of the insulation. By removing any remaining old mold growth, mold spores, and organic matter, the risk of new growth is assumed to be so low that the system is expected to perform well. In addition, the high alkalinity of most glue mortar systems is expected to "protect" from new mold growth as long as no new spores nor $CO_2$ to neutralize the high pH have access to behind the insulation [7,10].

According to Ref. [10], physical removal of all this existing matter from the interior surface is the only way to ensure that all potential mold spores are removed, and no nutrition is available for any new spores. Also, especially when applying rigid board materials, the wall surface should be firm and plane to enable strong fastening of the boards. Therefore, the existing wall is normally finished with a new plaster layer.

In this current case study, all the original masonry surfaces were carefully cleaned (Fig. 7 a), which is expected to contribute positively to the hygrothermal performance of the insulation systems. However, it was also observed in several cases that no attention was paid to cleaning and removing existing plaster or wallpaper from the adjacent walls, ceiling and floor (Fig. 7 f). This lack of focus on these details, even around thermal bridges, may increase the future risk of mold growth in these areas, and in this way the performance of the system is compromised.

New plaster was applied to all cases except the HL system. However, no special attention was paid to the moisture content of the new plaster before continuing the installation of the insulation. The product guidelines state typical drying times of 1–3 days after each layer of mortar plaster or glue. In addition, most glue mortars add on the excess built-in moisture behind the insulation, which can be seen as very high relative humidity in the first months after the installation, as reported in many monitoring studies [9,48,49,60]. If the system is able to dry out during the first spring and summer season, the high pH of the system glue mortar is normally assumed to protect the system against mold growth during that period [7,9,10,48,49,60].

In addition, according to all guidelines, the construction materials should be stored covered and in a dry place before installation. However, GF insulation blocks were observed to have been stored uncovered for more than a month outside the construction site before installation. This incident may increase the risk of unwanted biological growth even in this moisture-wise relatively robust material.

Especially for the diffusion-open and capillary-active systems, but also for most other systems with rigid insulation boards, it is essential to create good contact with the wall. A potential failure is created the way glue mortar is - however correctly - applied with a notched trowel on both the insulation board and the wall (see Fig. 14), resulting in a "net" of glue mortar with contact down to 25 % instead of 100 % contact [50]. Also, for all the systems (except GF) primer was not used before applying glue mortar, which may have reduced the ideal contact between plaster and glue mortar. Finally, the post-insulation of older buildings is challenging; it involves cutting and customizing the materials and solving insulation of the uneven surfaces and details on-site, which calls for solutions like digital scanning and cutting.

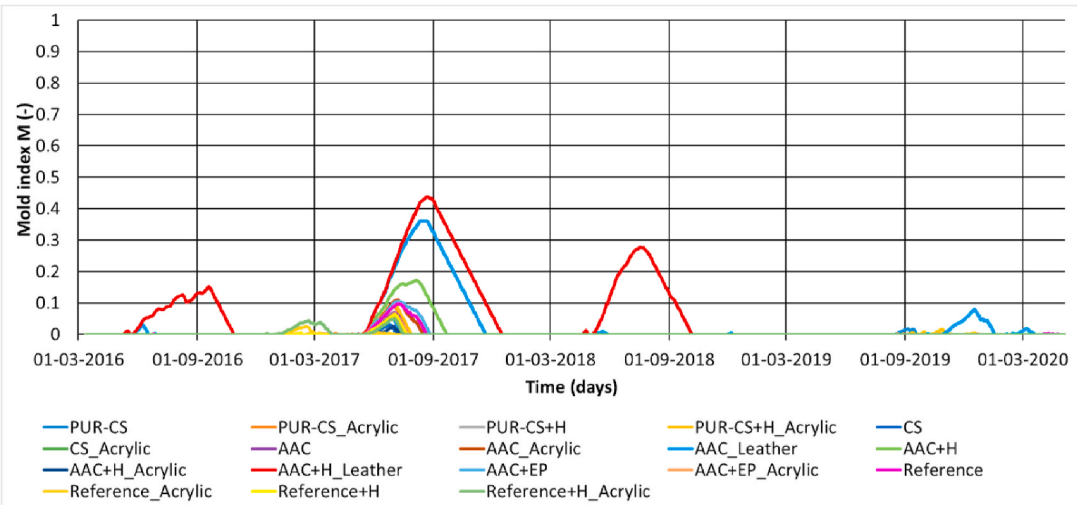



**Fig. 13.** Mold Index at the interior surface, between insulation systems and acrylic plates or leather patches. +H: walls with hydrophobization; +EP: walls with external lime plaster.

### 4.2. Discussion of the physical robustness of the interior wall

According to the results, when the ball with the highest mass hits the wall, in most cases it breaks down the finishing layer. However, looking at the maximum measurements for the two balls (1 and 3 kg), the achieved max diameter was very close (~7, 8, 8.5 cm). It should be noted that the diameter of the 1 kg ball is 6.5 cm and that of the 3 kg ball is 10 cm. Surprisingly, the damage in most cases is more significant for the smaller ball, but the release height should also be considered; the small ball is released from a bigger height (1.67 m) compared to the bigger ball (0.54 m). Thus, although the energy that the surface of the material is hit with is different in the two cases (10 and 30 J, respectively), all materials are vulnerable even to the low energy hit. As a rule of thumb, the 1 kg ball knocked off bigger parts of the finishing layer (paint and mortar) than the 3 kg ball, creating deeper holes. However, there is no threshold value for the impacts, therefore, a comparison between the different systems can be made, but it cannot be determined whether they are acceptable. Thus, the only evaluation parameter would be the repair size that will be needed.

The best performance was noticed in HL, which seems to have the lowest impact diameter and depth for both ball weights (1 and 3 kg). Although the mesh was visible in both cases, the hole created was clean in the perimeter, so easier to repair. At the same time, PF seems to have the smallest damage around the impact after the hits compared to the rest of the materials, because unlike the other systems, which had internal plaster finishing layers, the PF system had a regular gypsum board - which seems to make it more robust and the easiest to fix. Right after, AAC had a medium performance, which agrees with [36], since the damage after the impacts had more unclear impact limits and the influenced part of the impact area is larger than the obstacle size (in that case the size of the metal ball), therefore, major repair is required. GF and AG show similar results, and they use the same mortar. Nevertheless, GF had the worst performance among the examined systems since the impression of the impact was not only the biggest, but the impact depth was also the biggest. Additionally, in GF a large hole was created in the outer mortar. Thus, the repair will also be demanding as the mortar almost crumbles, and it is difficult to patch it up. However, AG was the only material consisting of a soft mat, which led to broader distraction around the relatively small impact spot. Impacts on the wall, from e.g. a chair that needs to be moved, or some other object hitting the wall, can easily cause a big damage to the wall. This means that the repair will be more difficult. Generally, the mortar layer underneath the final paint layer seems very brittle and powdery. In all cases, the difference in diameter between hit 2 and hit 3 seems to be similar, except PF 1 kg, where hit 2 and 3 did not make a noticeable difference.

Although the experiment was carried out successfully, there were some potential sources of error. The first one was the challenge of the ball hitting the exact same spot 3 times. Despite using an electromagnet to ensure that the ball was released from the same spot and therefore hits the same spot every time, it cannot be ruled out that some hits might miss the spot by few mm without being detected, resulting in a bigger impact in one direction. However, since the final measurements were similar for all impacts, the results are accepted as correct. The second source of error was that there was a bouncing effect in specific cases (especially in AG due to the thin soft insulation material). A horizontal position of the specimen was chosen for practical reasons, instead of the vertical position described in the standard, not expecting a bouncing effect, causing the ball to hit the underlay more than once. In some cases, the ball bounced away from the crater; in others, it bounced back to the crater. However, the energy in these extra hits was small. Finally, there is a bigger percentage error for the larger sphere (3 kg) than for the small one (1 kg). However, there were minimal differences in the results when these two were compared; thus, they are believed to give accurate results. Although the standardized test of the physical robustness of these insulation systems showed that all the systems were more or less damaged, the real-life observations of 5–8 year old internal insulation systems showed that internal insulation systems have no problems in withstanding daily life usage. These real-life observations only concern system AAC, but could indicate that the test should be adjusted to resemble real-life observations. However, a test with a 0.5 kg ball (3 J) may have given more useful results.

### 4.3. Role of interior (unauthorized) painting

#### 4.3.1. Laboratory experiment – discussion of wet cup experiment

The paint samples were used in the wet cup test to determine the water vapor diffusion resistance (Z-value) of the different coats of paint. It is generally believed that the amounts of coats of paint behave linearly in terms of Z-values. Thus, the Z-values would increase as the total paint layer thickness increases. The results show an increase in step with adding paint layers, but the trend does not follow a 100 % linear function. It is, however, difficult to conclude whether this tendency is true since there are multiple inaccuracies during the experimental stage.

Generally, all samples examined in this experiment are diffusion-open since materials with $Z > 50$ ($m^2$ s GPa/kg) are considered diffusion-tight [41]. However, some cases are more diffusion-open than others. The most noticeable difference is that the Z-values of the acrylic samples are much higher than those of the silicate samples. The maximum Z-value of the silicate paint samples (S) were just below 1 ($m^2$ s GPa/kg), which shows that these samples were highly diffusion open. On the other hand, the acrylic paint samples (A) demonstrated a max Z-value of 10.65 ($m^2$ s GPa/kg). In both cases, the max Z-value was found in the samples with the most paint layers (10 layers). The samples with 10 layers of silicate paint and 2 layers of acrylic paint (S/A-10 + 2), which demonstrated Z-values around 0.6 ($m^2$ s GPa/kg), seem to have almost doubled their diffusion resistance, as the 2 layers of acrylic paint appear to influence the outcome. Primarily, the silicate samples have a more specific and small range of Z-values, whereas acrylic samples have a bigger range. These results agree with the findings in Ref. [44], where the hygrothermal performance was not influenced by the paint layers, independently of its type (silicate or acrylic).

When external moisture enters the wall from the external side and transports inwards, it is better to meet layers with smaller Z-values than the Z-value of the brick so that it can dry inwards uninhibited. If the opposite occurs, there is a risk of condensation, even though this interface (insulation and interior paint) is on the warm side. Furthermore, in Ref. [51], it was found that more than 1800

**Fig. 14.** a) Many insulation products are installed with glue mortar on both insulation and the wall as illustrated. b) The resulting contact can be down to 25 % instead of 100 % contact as given by guidelines [50].

layers of diffusion-tight paint are required to create a layer as close as a vapor barrier [51]. On the other hand [44], found that 42 layers of acrylic paint are needed to be applied before exceeding the maximum tightness recommended by the manufacturer. In all cases, it is almost impossible to create a vapor barrier with paint, even if the paint layers are unauthorized and vary in type and thickness.

During the wet cup test, there were the following uncertainties.

- The sealing of the cups was difficult and, at the same time, crucial to the test; small leaks would influence the results, proposing a more diffusion-open sample than in reality. This could explain why there is a bigger spread in the results of the tighter samples than the others, as consequences of leaks will increase with an increase of the Z-value.
- During the preparation of the samples, the wax and paraffin mix tended to leak out onto the area of measuring, reducing the actual area where vapor could diffuse through the material. Consequently, some of the samples might have had areas smaller than assumed. However, an effort was made to limit the leakages and remove any excess wax mixture on the diffusion surfaces.
- Some of the samples failed to be within the 5 % deviation in flux that the standard proposes. However, the results were considered acceptable since the $R^2$ value was calculated for all samples and found to be approximately 1.
- The amount of added paint for each layer, even though it was weighted before every round of paint, may not have been the same for every layer. Also, variations in the surface of the samples, such as small cracks or small depressions where the paint can run, might be a factor that affects the final result.

#### *4.3.2. Discussion of field experiment and simulation*

Results from the field experiment did generally not show considerable differences between walls insulated internally using capillary active materials, with interior surface painted with diffusion-open paint or traditional acrylic paint, except behind the interior plaster, where the wall with acrylic paint had slightly higher relative humidity levels during summer but slightly lower during winter. This also agreed with the previous wet cup test results, which showed that the acrylic paint is not diffusion-tight but less diffusion-open than the silicate paint.

The literature on the effect of interior paint on the hygrothermal performance of walls insulated internally using capillary active materials is rather limited. However, the performance of the wall with acrylic paint resembles that of the previously examined wall fitted with mineral wool and vapor barrier in Refs. [4,7,60], however, with less seasonal variations. The wall with mineral wool and vapor barrier experienced the lowest relative humidity levels during winter periods (together with another system containing a vapor barrier) but critically high relative humidity levels (>90 %) during summer periods. The wet cup test demonstrated that there is a significant difference between a vapor barrier and an acrylic paint layer. The acrylic paint is rather diffusion-open compared to a vapor barrier, which is almost 100 % diffusion-tight.

Similar to the earlier studies of a wall with mineral wool and vapor barrier, the high relative humidity levels measured behind the plaster in the wall with acrylic paint is likely the result of inward solar-driven vapor flow (summer condensation) from alternating WDR and solar exposure on the exterior surface. This results in increased moisture accumulation on the exterior side of the acrylic paint due to its higher diffusion resistance compared to the diffusion-open silicate paint. However, in Refs. [4,7,60] it was also concluded that the vapor barrier (or a tight insulation material) was not an issue, when the exterior surface was hydrophobized and thus had considerably reduced intrusion of WDR.

Simulation results showed a worsened hygrothermal performance in the masonry/insulation interface with increased Z-value on the interior surface when the wall was without protection against rain penetration, i.e., hydrophobization. Similarly, improved hygrothermal performance in the interface with increased Z-value were found when the wall was hydropbobized. In addition, the best performance was seen for walls with hydrophobization and high interior Z-value. This indicates that the 6 examined internal insulation systems would likely perform better if the moisture entering the wall construction from both sides was reduced, i.e., reduce both diffusion of the warm moist air outwards by high interior Z-value (similar to a vapor barrier) and rain intrusion from the outside. However, in cases where the exterior surfaces cannot be hydrophobized, it is better to have a highly diffusion-open insulation system on the inside, including the interior paint treatment.

In summary, whether the interior paint treatment will be problematic seems to depend on the capillary properties of the exterior surface, and the results indicate that the best solution will be obtained using a diffusion-tight system in combination with hydrophobization of the exterior surfaces. Hence, interior treatment with conventional acrylic paint should not be a problem if the exterior surface is hydrophobized.

Results support earlier experiment findings in Refs. [4,37,70] and simulations in Refs. [33,34,71], which suggest that the best performance is obtained through a combination of a diffusion-tight solution and hydrophobization. On the other hand, several studies suggest that diffusion-open solutions are preferred over diffusion-tight solutions [9,72–76]. However, the detailed literature review by Jensen [4], showed that these studies were based on simulations and that there seems to be a lack of field and case studies showing superior performance of diffusion-open systems. Vereecken & Roels [43] have similarly concluded that a tight interior surface (paint or vapor barrier) may be problematic if the exterior surface is not protected against WDR intrusion, and in such cases, it would be more suitable to use diffusion-open capillary active insulation systems. In addition, personal correspondence with manufacturers of capillary active insulation systems (including several CS and AAC products, loose-fill cellulose, AG, HL, and LC) do similarly show contradicting findings regarding the use of diffusion-open and acrylic paint treatments on interior surfaces [42].

### *4.4. Discussion on microclimate behind furniture and paintings*

The measurements and theoretical mold risk prediction models indicate that covering the interior surfaces of capillary active insulation systems would slightly increase the relative humidity levels and the mold risk, and that this increase would be higher for the mounted leather patches than the acrylic plates. However, the observed increase in relative humidity was small, and the potential mold risk was very limited; it occurred only in short periods with favorable conditions.

The different results between the mounted leather patches and the acrylic, was likely due to the leather patches being mounted directly up against the interior surface of the capillary active insulation systems (no cavity), while the acrylic plates were mounted on small wooden blocks 15 mm from the interior surface. This allowed a small air circulation to occur behind the acrylic plate and ventilate away some of the moisture building up behind the acrylic plate. On the other hand, very limited or no air circulation occurred behind the leather patches. This suggests that when using capillary active insulation systems for internal insulation, placing heavy furniture such as a couch or similar some distance away from the interior surface should be preferred. Meanwhile, mounting wall-hanging decorations such as picture frames should not be problematic as long as some degree of air circulation can occur behind the item. If this is not fulfilled, it might lead to increased relative humidity levels and a risk of mold growth.

Regarding literature dealing with this topic, the systematic search on Scopus, Web of Science, Google Scholar and the Aalborg University library search engine did not provide any studies regarding the mold risk between capillary active insulation systems and furniture or wall-hanging decorations. Brief mentionings in reports were found, stating that mold could occur behind heavy furniture with high thermal resistance or wall-hanging decorations [45,46], but these reports did not conduct any study on the effect on the hygrothermal performance by altering the microclimate near the interior surface of the insulation systems. This suggests a need for further research on this topic to prove or disprove the suitability of capillary active insulation systems for internal insulation of historic buildings.

## 5. Conclusion

In the present study, the way the user behavior affects the physical robustness of internal insulation materials against everyday use is examined through several experimental tests, simulations and observations. That includes accidently hitting the wall, painting the wall with the wrong type of paint, and placing furniture or paintings against the wall. Additionally, the practical aspect of the application process of the internal post-insulation is explored.

The observations from the installation process of four different internal insulation systems highlighted the importance of following the guidelines, including carefully cleaning and preparing the original wall before mounting the insulation system. This is essential for the expected future performance of the insulation, as when removing any loose organic matter and rest of old mold growth, the risk of new mold growth is assumed low. Most of the systems were relatively easy to apply, while one of the materials (Glass Foam) was difficult to install and handle.

Regarding the mechanical robustness test, the best performance was noticed in Hemp with Lime, which has the smallest damage, with max impact diameter of ~5.7 cm and max depth of ~0.8 cm, and, thus smallest need for repair. At the same time, Phenolic Foam had the smallest damage around the impact area (max diameter ~6 cm), which makes it the easiest to fix. Autoclaved Aerated Concrete had a medium performance with major repair required. Glass Foam has the worst performance among the examined systems since the impression of the impact (~8 cm) and the impact depth (~1.8 cm) were the biggest, thus, the repair will be demanding. However, Phenolic Foam led to wider distractions around the impact spot, which led to the most challenging repair. The medium performance of the Autoclaved Aerated Concrete system must be compared to the real-life observations in inhabited dwellings, in which this system showed no damage after 5–8 years. Therefore, the used standardized test may be too tough to determine if a system is robust toward impacts.

The wet cup test of different painting types and multiple layers of paints showed that no samples were diffusion-tight. However, as expected, multiple layers of acrylic paint resulted in significantly higher diffusion resistance (0.45–10.65 $m^2$ s GPa/kg) than samples with silicate paint samples (<0.15 $m^2$ s GPa/kg). Nevertheless, it was found that it is almost impossible to create a vapor barrier with paint layers, even if the paint layers are unauthorized and vary in type and thickness. The field experiment on the role of the diffusion resistance of the internal paint did not show significant differences between insulated walls with interior surfaces painted either with diffusion-open paint or traditional acrylic paint, which also agrees with the wet cup test results. The simulations indicate that the examined internal insulation systems would perform better if the moisture entering the wall from both sides was reduced. However, in cases where the exterior surfaces cannot be hydrophobized, it is better to have a highly diffusion-open internal insulation system inside, including the interior paint treatment.

The experiment imitating heavy furniture and wall-hanging decorations close up to the interior surface indicated that the relative humidity and mold risk would be slightly higher for the mounted leather patches directly on the interior surface than the acrylic plates 15 mm from the surface, with max Mold Indexes of 0.42 and 0.15 respectively. This suggested that placing heavy furniture and wall-hanging decorations just a small distance away from the interior surface when using capillary active insulation systems will eliminate the increased risk of mold growth.

## CRediT authorship contribution statement

**Panagiota Pagoni:** Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Eva Birgit Møller:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Ruut Hannele Peuhkuri:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Nickolaj Feldt Jensen:** Writing – review & editing, Writing – original draft, Software, Formal analysis, Data curation.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ruut Hannele Peuhkuri reports financial support was provided by Realdania. Ruut Hannele Peuhkuri reports financial support was provided by Grundejernes Investerings Fond. Ruut Hannele Peuhkuri reports financial support was provided by Landsbyggefonden. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

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