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Laboratory based investigation of the materials' water activity and pH relative to fungal growth in internally insulated solid masonry walls

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Abstract

This project investigated fungal growth conditions in artificially contaminated interfaces between solid masonry and adhesive mortar for internal insulation. The project comprised several laboratory experiments: test of three fungal decontamination methods; investigation of development of fungal growth in solid masonry walls fitted with five internal insulation systems; and investigation of Volatile Organic Compounds (VOC) diffusion through materials and whole insulation systems. One aim was to examine whether the alkaline environment (pH> 9) in the adhesive mortars could prevent fungal growth despite the water activity (a_w) in the interface exceeds the level (a_w> 0.75) commonly considered critical for fungal growth. The

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findings indicate that do-it-yourself decontamination solutions were inadequate for removal of fungal growth, while professional solutions were successful. However, the choice of decontamination method was of minor importance in the case of application of internal insulation with high pH adhesive mortar, as the high pH adhesive mortars were found to inactivate existing growth and prevented spore germination during the experimental period. The three tested VOCs were capable of diffusing through most of the examined products and could potentially affect the indoor air quality.

Keywords: internal insulation, solid masonry walls, laboratory study, mould growth, mould decontamination methods, material alkalinity

Practical Implications:

- The risk of fungal growth in the interface between the masonry wall and added internal insulation is reduced considerably if high pH (12+) adhesive mortar is used during the application of the system.
- For fungal decontamination purposes the two professional methods are preferred, however, if followed by application of internal insulation with high pH adhesive mortar, the choice of decontamination method is of minor importance. The impact of not removing organic matter and fungal growth before application of insulation systems with high pH adhesive mortar is yet to be determined.
- Fungal mycelium is inactivated by the high pH in the adhesive mortar, but the fungal spores remain dormant and can germinate if pH in the construction drops to more favourable levels which could lead to new fungal growth.
- Typical VOCs produced by fungal growth can be transported to the indoor climate by diffusion through interior insulation. The permeability towards VOCs correlates with the water vapour permeability, i.e. diffusion of VOCs to the indoor environment is reduced with increased water vapour diffusion resistance of the insulation system.

1 Introduction

One effective measure of energy conservation in the European building stock is retrofitting the external walls[1]. 41% of all existing multi-story residential buildings in Denmark (3+ floors) were constructed during the period 1850-1930, with solid masonry external walls[2] having an average-weighted U-value of 0.62 $W/m^2 \cdot K$ for the external walls[1], which indicate a large potential for energy conservation. External insulation is considered the more feasible solution for retrofitting solid masonry walls compared to internal insulation as it is safer in terms of moisture related issues, more efficient for reduction of heat losses through the envelope, and protects the existing wall structure against the outdoor climate [3–6]. However, external retrofitting is not always possible for historic buildings if their external appearance is worthy of preservation.

There exists a great deal of scepticism regarding the use of internal insulation, as it in the past have resulted in many cases with mould growth (fungal growth) occurring between the existing wall structure and the insulation system [4]. One of the main problems is that internal insulation causes the existing masonry wall to become colder [6], which in turn increases the risk of interstitial condensation [3,7]. The added insulation system will also increase the diffusion resistance between the existing wall and the room, which reduces the inward moisture diffusion that contributes to drying of the wall [7,8]. In addition, there is risk of summer condensation in periods with alternating rainfalls and solar exposure [3,4]. Insulation systems introduced on the market over the past two decades have tried to overcome these issues through the use of diffusion-open insulation materials with capillary active properties [5,9,10]. These systems allow capillary moisture redistribution in an attempt to avoid unacceptably high moisture levels in critical locations. Previous research does not fully agree on the performance of the diffusion-open capillary active systems. Good performance was observed in a number of studies [5,8,11–13],

69 while other studies [14,15] found potentially critical Relative Humidity (RH) levels in critical
70 locations such as in the masonry/insulation interface or in embedded wooden elements.

71 Several systems for internal retrofitting solid masonry walls comprise an insulation material
72 and an adhesive mortar, and according to the manufacturers these systems prevent fungal
73 growth from occurring by combining inorganic insulation with a highly alkaline adhesive
74 mortar (pH>12) to create an unfavourable environment where fungi cannot survive even if RH
75 is higher than what is normally considered to be acceptable at the given temperature. The
76 optimum environment for most fungal species is between pH 4 and 9, and prevention of fungal
77 growth could potentially be achieved by creating a less favourable pH environment [16].
78 Investigations by Morelli & Møller [13] and Jensen et al. [17] found no fungal growth behind internal
79 insulation with adhesive mortar of high pH after several years despite of high water activities.

80 Several studies have shown difficulties maintaining non-critical RH levels in the interface and
81 in embedded wooden elements of internally insulated solid masonry walls, so the structures
82 must be secured against fungal growth in other ways. This could be done by ensuring that all
83 organic residues (e.g. from glue and wallpaper) are removed prior to installation of the
84 insulation system, since fungi need very little nourishment and can grow even on dirt and dust.
85 Another option is to apply fungicides before installation, but this might create problems for the
86 indoor climate. Exposure to pesticides, including fungicides, may result in short-term skin and
87 eye irritation, dizziness, headaches, and nausea, while long-term effects may include increased
88 risk of cancer, asthma[18] and damage to central nervous system and kidney [19].

89 The purpose of this project was to study the effect of alkaline (pH>9) adhesive mortar joint
90 between existing wall and installed insulation would be sufficient to prevent fungal growth,
91 when the moisture level (water activity (a_w)) in the interface exceeds 0.75, which is considered
92 critical for fungal growth at room temperature [3]. The study also tested the effectiveness of
93 different fungal decontamination methods. Diffusion of Volatile Organic Compounds (VOCs)

through the insulation systems was also tested to determine if VOCs, known to be produced during fungal growth, could enter the indoor environment if fungal growth should occur behind the internal insulation.

2 Methods and materials

The present study was performed in four main steps:

1) Preparation of the experimental setup, Section 2.2
2) Experiment 1: Test of decontamination methods, Section 2.4
3) Experiment 2: Development of fungal growth in interface, Section 2.5
4) Experiment 3: VOC diffusion, Section 2.6.

The following sections will describe the activities under each step in more detail, and Figure 1 shows the activities carried out in relation to the two consecutive experiments with the masonry masonry specimens (experiment 1 and 2), and in the VOC diffusion experiment.

2.1 Investigated insulation systems and preliminary material tests

Five different insulation systems were tested for fungal growth on masonry specimens: 1) Calcium silicate (Casi), 2) Autoclaved aerated concrete (AAC), 3) Composite material of polyurethane foam with calcium silicate channels (PUR-CM), 4) Phenolic resin foam with an aluminium foil (Phenolic), and 5) insulating plaster composed of cork granulate, silica filler, natural volcanic materials and Natural Hydraulic Lime (NHL) (Cork plaster). Except for the cork plaster all systems included an adhesive mortar. The build-up of the masonry specimens and the five insulation systems are shown in Table 1, which also includes material properties, these were determined in the preliminary study or provided by the manufacturers.

A preliminary study was performed to determine the water vapour diffusion resistance, water absorption by capillary action, density, and pH-value for the used adhesive mortars and the

Cork plaster. Density was determined according to the LBM test method 2 [20]. The water vapour diffusion resistance factor, μ was determined through wet cup test (Set C) according to DS/EN ISO 12572 [21]. Three Ø80 mm samples of each product were tested, with a thickness of 10 mm for the adhesive mortars, and 30 mm for the Cork plaster. The water absorption by capillary action was determined through partial immersion according to DS/EN ISO 15148:2003 [22]. Three samples of each product were tested, with a total contact surface of approximately 300 cm^2. The pH-value was determined for the adhesive mortars, 7.7% lime adjusted mortar, and Cork plaster. Samples were crushed into powder, and 5 g was mixed with 12.5 ml demineralized water. Samples were shaken for 60 minutes at 260-270 rpm, followed by a 10 minutes settling period before testing. The pH measurements were performed using a HACH Sension+ MM 374 GLP 2 channel Laboratory Meter for pH (accuracy: ≤0.002 pH).

2.2 Description of the experimental setup used in experiments 1 and 2

The experimental setup comprised 17 small masonry masonry specimens with dimensions (L×W×H): 350 mm × 350 mm × 180 mm (including 10 mm internal render). The masonry specimens were constructed in 2015 (four years before this study began) from yellow soft-moulded bricks and 7.7% lime adjusted mortar resembling the materials used in Danish historic buildings from 1850-1930. The lime adjusted mortar was also used as internal render. The mortar joints were assumed fully carbonated prior to the present study.

The masonry specimens were inserted over a water vessel (small box of 600 mm × 400 mm × 100 mm) within a larger box (780 mm × 560 mm × 440 mm) (Figure 2). The small box contained a plastic grate to keep the masonry specimen above the demineralized water inside the box and a hole was made in the box lid to fit the masonry specimen, while the large box was used to emulate an indoor climate however without conditioning. Prior to the experiments, each masonry specimen was sealed on the vertical sides using a primer and wet room membrane (red lines in Figure 2). The joints between the vertical sides of the masonry specimen and box

lid were sealed using silicone sealant, while the joints between box and lid were sealed using vapour barrier tape. An Ø100 mm hole was made in the lid to refill water into the small box, and the opening was sealed using a rubber plug. The joints between the large box and its lid were sealed using rubber sealing strips and secured using tightening clamps. The indoor climate of the test facility (outside the large outer box) was kept at 20 °C, with RH between 30 and 60%. The desired RH in the masonry/insulation interface was >96%, which should ensure favourable moisture levels for fungal growth. The experiments were carried out as isothermal.

With this experimental setup two experiments were carried out consecutively: 1) Test of decontamination methods; and 2) Development of fungal growth in interface (see Figure 1).

Temperature and RH were measured manually every two weeks throughout both experimental periods using digital HYT221 sensors by Innovative Sensor Technology IST AG, calibrated prior to installation. Sensors were installed inside the large box during the fungal decontamination experiment, and later also in the interface between the masonry specimen and insulation system for the fungal growth experiment. Two sensors were installed for the indoor climate of test facility. The accuracy of the sensors was 0.2 K at 0 to 60 °C for temperature, and 1.8% at 23 °C at 0 to 90% for RH and 2-4% above 90% RH. The sensor range was -40 to 125 °C for temperature, and 1 to 100% for RH.

2.3 Test procedures to determine the presence of fungal growth in experiments 1 and 2

The presence of fungal growth in experiments 1 and 2 was investigated with: 1) The Mycometer method; and 2) Agar imprint test. The sampling method and the test procedures are described below.

Sampling method: Fungal surface sampling in experiment 1 was carried out through swabbing using sterile cotton buds, as described for the Mycometer Surface test below. Fungal sampling of the masonry specimens in experiment 2 was carried out by drilling two core samples of the

166 interior insulation system (including adhesive mortar and internal lime render) from each
167 masonry specimen using an Ø80 mm hole-saw without the pilot bit (Figure 3a). The samples
168 were placed in sealed containers immediately after fungal- and material specimens were taken
169 in the masonry/insulation interface and the hole-saw was disinfected with ethanol 96% between
170 drillings to avoid contamination.

171 **The Mycometer method:** The amount of fungal biomass (living and dead) was assessed
172 quantitatively using the Mycometer method [23]. The method determined the amount of fungal
173 growth by measuring the fluorescent product released from the enzyme-substrate complex
174 relating to the N-acetylhexosaminidase activity found in the mycelium and spores, expressed
175 by a Mycometer value. Two types of Mycometer tests were carried out: 1) The Mycometer
176 Surface test [24]; and 2) The Mycometer Bulk-material test [25].

177 The Mycometer Surface test was used to assess the effectiveness of the fungal decontamination
178 work in experiment 1 and later to determine the extent of the fungal growth in the
179 masonry/insulation interface in experiment 2. The surface sampling was done through
180 swabbing, using sterile cotton buds, within a measurement area of 9 cm^2 (see Figure 3b).

181 The Mycometer Bulk-material test was used to evaluate growth in the adhesive mortars and
182 determine growth in different layers of the insulation system. In the laboratory the Ø80 mm
183 drilling cores were disassembled and prepared for the bulk material test (see Figure 3d). The
184 outer parts (excess insulation and internal finishing layer) were cut away, and the central part
185 of the drilling core was divided into three sections (the outermost 10 mm of insulation i.e.
186 closest to the masonry wall, and the remaining insulation thickness was divided in two equal
187 sized sections). The three sections were crushed into powder so was a section of the adhesive
188 mortar, 100 mg of each was used for the bulk material test. The bulk material tests were
189 performed for the middle and innermost sections of the drilling core only if growth was detected
190 in the outermost section, as previous experience [17] with the bulk material test have shown that

191 if no fungal growth is found in the interface or in the outermost section of the material sample
192 then growth are improbable in the middle and innermost sections. In each of the two sampling
193 rounds (after 6 and 12 months) in experiment 2, two samples were tested for the
194 masonry/insulation interface, and two for each of the insulation layers tested in the bulk material
195 test.

196 The Mycometer values obtained were evaluated as; Category A (green), normal background
197 level: MV ≤ 25 (surface) or MV ≤ 150 (bulk material), Category B (yellow), above normal
198 background level: 25 < MV < 450 (surface) or 150 < MV < 450 (bulk material), and Category
199 C (red), high level of fungi: MV > 450.

200 The accuracy of the Mycometer method was evaluated by the US EPA [26] who found that the
201 relative standard deviation was around 5-10% for tests performed with fungal spores from
202 *Aspergillus flavus* and *Cladosporium herbarum*.

203 **Agar imprint test:** A qualitative assessment of the fungal growth was performed through
204 cultivation on agar media (Dichloran 18% Glycerol agar (DG18) and Original V8 Vegetable
205 Juice agar (V8) [27], allowing for identification of fungal species. The agar imprint test was
206 carried out only in experiment 2. Following the Mycometer Surface swab tests for the
207 masonry/insulation interface, the interface side of the drilling core was pressed down onto V8
208 and DG18 media (see Figure 3c). The media was incubated at 25 °C in darkness for 7 days and
209 fungal colonies were identified under stereo- and light microscope [27].

210 **2.4 Experiment 1: Decontamination methods**

211 **2.4.1 Artificial inoculation of masonry specimens**

212 For experiments 1 and 2 the masonry specimens were artificially inoculated with a mixture of
213 spores from four common indoor climate fungal species from the Fungal Culture Collection at
214 DTU Bioengineering: *Acremonium murorum* (IBT 42592), *Aspergillus versicolor* (IBT 33558),

Penicillium chrysogenum (IBT 34061) and *Wallemia sebi* (IBT 32220) with different a_w requirements for growth.

For this experiment 12 of the 17 masonry masonry specimens were used, four specimens for each of the three decontamination methods, while the remaining 5 masonry specimens were left out of experiment 1 and were to be used only in experiment 2 as "un-inoculated" reference walls. The 12 "decontaminated" masonry specimens would be re-used in experiment 2 to investigate if the choice of decontamination method had any effect on fungal growth in the masonry/insulation interface after application of the internal insulation systems. Woodchip wallpaper was applied to all 12 masonry specimens using wallpaper glue based on potato starch mixed with the fungal spore mixture stated above. The spore concentration in the finished glue mix was approximately 10^5 spores per mL for each fungal species. The small boxes containing the masonry specimens were placed inside the large boxes (Figure 2a) and demineralised water was added to the small boxes. The inoculated masonry specimens were then left for seven weeks.

2.4.2 Decontamination of masonry specimens

The masonry specimens were cleaned for organic residues and fungal growth using following methods: 1) Hand-power: manual removal of wallpaper with a paint scraper (Figure 4a), 2) Mechanical: manual removal of wallpaper and internal render with hammer and chisel (Figure 4b), and application of new render layer, and 3) MicroClean: removal of wallpaper with a paint scraper, and decontaminated using the MicroClean method [28] according to manual and performed by professionals (Figure 4c-d). The MicroClean decontamination was performed in four steps: 1) Vacuum the infected surface; 2) Dry-steam cleaning at 150-160 °C, using plate mouth piece with a steam pressure of 8 atm; 3) Dry-steam cleaning with fibred cotton cloth mouth piece, with simultaneous vacuuming of denatured dissolved biomass. The cotton cloths were changed continually as they became saturated with moisture and biomass; and 4) Vacuum

240 the surface. All boxes were disinfected using fungal disinfection agents. After decontamination
241 of masonry specimens and boxes, the setup was reassembled as shown in Figure 2a.

242 **2.4.3 Surface analysis for fungal growth**

243 After 14 days the effectiveness of the decontamination methods was assessed with Mycometer
244 Surface tests, with two samples for each masonry specimen. For the mechanical method the
245 Mycometer Surface tests were taken on top of the new internal render layer.

246 **2.5 Experiment 2: Development of fungal growth in interface**

247 **2.5.1 Artificial inoculation of masonry specimens**

248 One mL of spore suspension containing the fungal species described in Section 2.4.1,
249 (approximately 10^6 spores per mL of each species) was placed in the centre of the interface
250 surface area of each of the 12 decontaminated masonry specimens and the 5 masonry
251 specimens, which were un-inoculated in experiment 1.

252 **2.5.2 Application of the insulation systems**

253 After application of the spore suspension on all 17 masonry specimens, the CaSi, AAC, PUR-
254 CM, and Phenolic systems were installed according to the manufactures instructions, starting
255 with adhesive mortar. The four systems were installed on 16 of the masonry specimens so that
256 each system would be installed for each of the three decontamination methods and on the un-
257 inoculated masonry specimens (see Figure 5). On the 17th masonry specimen, the Cork plaster
258 was installed.

259 After installation, the small boxes containing the insulated wall specimens were placed back in
260 the large boxes, and water was again added to the small boxes representing the wet climate
261 (Figure 2b). Due to issues reaching the desired RH levels in the interface of the masonry
262 specimens fitted with Phenolic insulation, a 25 W aquarium heater was installed in the small

box two months after experiment start in order to increase the water vapour pressure by raising the water temperature to 24 °C.

2.5.3 Surface and material analyses for fungal growth, pH and moisture content

After 6 and 12 months drilling cores were taken out at the centre of the walls and 15 cm to the side of the centre, respectively, and fungal growth and material samples were taken for analysis according to the procedures in Sections 2.1 and 2.3. The moisture content was determined for the interface materials and in the outermost 10 mm of the insulation through weighing and drying.

2.6 Experiment 3: VOC diffusion

In the experiments described in this section only the insulation materials and corresponding adhesive mortars, finishing layers and membranes were used. Possible diffusion of Volatile Organic Compounds (VOCs) through the materials making up the examined insulation systems were investigated using acetone (CAS-number: 67-64-1 (Matas A/S, Denmark)), ethanol (CAS-number: 64-17-5 (VWR International)), and 2-heptanone (CAS-number: 110-43-0 (Merck Life Science A/S, Denmark)), to mimic the VOCs produced by common indoor fungi [29]. The experiment was carried out similar to the cup method for determination of the water vapour diffusion resistance factor according to DS/EN ISO 12572 [21]. Three Ø80 mm samples of each insulation systems were tested, which were the adhesives, insulation materials, renders, and membranes. Insulation material samples had a thickness of 30 mm, render and adhesives samples 10 mm, and gypsum board with aluminium foil samples 13 mm. Each sample was sealed on the sides using epoxy, which was cast around the sample while placed inside a PVC ring [30]. In contrast to the water vapour diffusion experiment, the cups were filled with one of the aforementioned solvents which diffused through the product samples due to a difference in the vapour pressure. The cups were weighted periodically, and the results were evaluated

through linear correlation between time and weight loss. The experiment was ended after obtaining a R^2 value of minimum 0.97 in relation to the linear weight changes. The results were corrected for variations in the barometric pressure during the tests.

The temperature and RH conditions inside the fume hood during the each of test rounds for the VOC diffusion experiment ranged from 20 to 22 °C and the RH levels from 30 to 45%. The vapour pressure differences over the material samples were calculated using the measured temperatures during each of the test rounds and assuming vapour saturation inside the test cups and no VOC present in the ambient air. The resulting pressure differences were around 26000, 6300, and 155 Pa respectively for acetone, ethanol and 2-heptanone. The saturation vapour pressures were determined using the Antoine equation [31].

Based on the VOC diffusion experiment, the project adopted the similarity approach for modelling the transport of moisture VOCs in materials presented by Rode et al. in [32], where the diffusion similarity factor, $\kappa_{diff,voc}$ [-] were determined according to equations 1-3. A $\kappa_{diff,voc}$ of 1 means that the material has equal diffusion resistance factors for diffusion of VOC as for water vapour, where the diffusion resistance factor is defined as the diffusion coefficient of the gas in still air divided by the diffusion coefficient of the same gas through the porous material.

$$\kappa_{diff,voc} = \frac{\mu_{voc}}{\mu_v} \quad (1)$$

$$\mu_{voc} = \frac{D_{voc,air}}{D_e} \quad (2)$$

$$D_e = D_p \cdot R_{gas} \cdot T \quad (3)$$

Where,

- μ_{voc} and μ_v are the diffusion resistance factors for VOC and water vapour [-]
- $D_{voc,air}$ is the diffusion coefficient of a VOC in air [m^2/s]: acetone 1.24E-05, ethanol 1.15E-05, 2-heptanone 6.24E-06, and water vapour 2.64E-05 m^2/s.

- D_e is the diffusion coefficient [m^2/s] of the material based on vapour content by volume in unit kg/m^3.
- D_p is the diffusion coefficient [kg/(m·s·Pa)] of the material based on vapour pressure, derived from the VOC diffusion measurements.
- R_{gas} is the specific gas constant [J/(kg·K)]: acetone 143.2, ethanol 180.5, 2-heptanone 72.8, and water vapour 461.4 J/kg·K.
- T is the temperature in the VOC diffusion experiment, of 294.5 K.

$\kappa_{diff,voc}$ was determined for the four adhesive mortars, the cork plaster and gypsum board.

2.7 Theoretical VOC mass balance for a room scenario

A VOC mass balance was established for a hypothetical 27 m^3 room scenario with an Air Change per Hour (ACH) of 0.5 h^{-1} (in accordance with local regulations) to calculate the VOC content in the room air in the case of 1 m^2 of fungal growth behind the examined insulation systems. The VOC saturation pressures stated in Section 2.6 were assumed, and the diffusion resistance of the systems were obtained from the VOC diffusion experiment. The VOC content in the room air was calculated with equations 4-10:

The VOC mass balance for the room:

$$G_{voc,entering} + G_{voc,p} = G_{voc,leaving} \Leftrightarrow x_{voc,e} \cdot G_a + G_{voc,p} = x_{voc,i} \cdot G_a \quad (4)$$

$$G_a = \frac{q \cdot \rho_{a,i}}{3600} \quad (5)$$

Adding the mass flow of air, G_a [kg/s] to the equation and solving for $X_{voc,i}$:

$$x_{voc,e} \cdot \frac{q \cdot \rho_{a,i}}{3600} + G_{voc,p} = x_{voc,i} \cdot \frac{q \cdot \rho_{a,i}}{3600} \Leftrightarrow x_{voc,i} = \frac{\left(\frac{q \cdot \rho_{a,i}}{3600}\right) \cdot x_{voc,e} + G_{voc,p}}{\frac{q \cdot \rho_{a,i}}{3600}} \quad (6)$$

Assuming the sovent concentration in the outdoor air to be 0, then we get:

$$x_{voc,i} = \frac{\left(\frac{q \cdot \rho_{a,i}}{3600}\right) \cdot 0 + G_{voc,p}}{\frac{q \cdot \rho_{a,i}}{3600}} \Leftrightarrow x_{voc,i} = \frac{G_{voc,p}}{\frac{q \cdot \rho_{a,i}}{3600}} \quad (7)$$

$$G_{voc,p} = A \cdot \frac{p_{voc,fungal} - p_{voc,i}}{Z} \quad (8)$$

$$v_{voc,i} = x_{voc,i} \cdot \rho_{a,i} \quad (9)$$

The VOC vapour pressure in the room air, $P_{voc,i}$, was solved iteratively by:

$$x_{voc,i} = \frac{m_{voc}}{m_{air}} = \frac{p_{voc,i} \cdot M_{voc}}{(P - p_{voc,i}) \cdot M_{air}} \cong \frac{p_{voc,i} \cdot M_{voc}}{(M_{air} \cdot P)} \Leftrightarrow P_{voc,i} = \frac{x_{voc,i}}{\left(\frac{p_{voc,i} \cdot M_{voc}}{(M_{air} \cdot P)}\right)} \quad (10)$$

Where,

- $G_{voc,entering}$ and $G_{voc,leaving}$ are the VOC vapour entering and leaving the room [kg/s]
- $G_{voc,p}$ is the VOC vapour penetrating the insulation system in [kg/s]
- $x_{voc,e}$ and $x_{voc,i}$ are the VOC vapour ratio in the outdoor and room air [kg/kg]
- q is the ventilation flow [m^3/h], which is the product of the room volume and the ACH.
- $\rho_{a,i}$ is the density of the room air [kg/m^3], at 21.3 °C
- $p_{voc,fungal}$ is the VOC saturation pressure behind the insulation system [Pa]
- $p_{voc,i}$ is the VOC vapour pressure in the room air [Pa]
- P is the atmospheric pressure 101325 Pa
- Z is diffusion resistance of insulation systems [$m^2 \cdot s \cdot Pa/kg$]
- A is the assumed fungal growth area behind the insulation system [m^2]
- $v_{voc,i}$ is the VOC vapour content in the room air [kg/m^3]
- m_{voc} and m_{air} are the mass of the VOCs and of dry air respectively [kg]
- M_{voc} is the molar mass of the solvents [g/mol]; 58.08, 46.07 and 114.19 g/mol respectively for acetone, ethanol, and 2-heptanone
- M_{air} is the molar mass of dry air [g/mol]; 28.96 g/mol

3 Results

3.1 Experiment 1: Decontamination methods

The results of decontamination methods show high levels of fungal growth in all masonry specimens using the “hand-power” decontamination method with the paint scraper (Table 2). For one wall using the Microclean method it was found that the Mycometer Surface Value (MSV) results were just above background level. Results from the remaining masonry specimens were within normal background level.

3.2 Experiment 2: Development of fungal growth

3.2.1 Hygrothermal measurements

Results show that the average temperatures in the interface between the masonry specimens and insulation systems were between 18.4 and 19.5 °C, except for the walls with Phenolic foam where temperatures ranged from 20.6 to 22.7 °C due to the aquarium heaters. The average a_w in the interface were between 0.99 and 0.999 for all masonry specimens except the four Phenolic walls (where three were around a_w 0.86-0.88 and one at at 0.964) and one CaSi wall (at a_w 0.959). The final a_w were between 0.995 and 0.999 for all walls except for three of the four Phenolic walls, which varied from 0.934 to 0972. The final moisture content for the adhesive mortars and insulation materials are listed in Table 3. The measured hygrothermal conditions for the interface were considered very favourable for the occurance of fungal growth [3].

3.2.2 pH and fungal growth testing

The result of the material tests performed after one year of application showed that the internal renders had pH-values of 12.2 to 12.6, and the adhesive mortars from 12.4 to 12.7.

375 The Mycometer surface and bulk material tests for all the 17 masonry specimens showed that
376 the fungal biomass was below background levels, which was the case for both fungal sampling
377 rounds (after 6 and 12 months), see Table 4. In contrast to the Mycometer tests, the agar imprints
378 of the drilled-out core samples found viable spores present in the interface of nearly all masonry
379 specimens. Primarily *Aspergillus versicolor* and *Penicillium chrysogenum* colonies were found
380 after transference to the agar media, with the vast majority of the viable spores being *A.*
381 *versicolor*. None or few viable *Acremonium murorum* and *Wallemia sebi* spores were found
382 after transference to the agar media. Comparison of the core samples from the different
383 insulation systems showed a significantly larger number of viable spores in the interface of the
384 Phenolic system compared to the other systems. A comparison between the two sampling
385 rounds showed differences in the amount of viable spores, and in some corner samples (round
386 2) the spore count was higher than the central samples (round 1) where the spore suspension
387 was placed originally. No differences were seen between insulation systems or the
388 decontamination methods.

389 **3.3 Experiment 3: VOC diffusion**

390 The VOC vapour flow rate density of the examined material samples are presented in Figure 6,
391 and the derived permeability values are available in [30]. It was seen that the vapour flow rate
392 density of acetone was 5-6 times higher than that of ethanol, 27-28 times higher than water, and
393 55-57 times higher than 2-heptanone. For ethanol the vapour flow rate density was 5 times
394 higher than that of water, while for 2-heptanone the vapour flow rate density was 40% lower
395 than water. The diffusion similarity factor, $\kappa_{diff,voc}$ for acetone, ethanol and 2-heptanone
396 determined through the similarity approach are shown for the six examined materials in Figure
397 7. The average $\kappa_{diff,voc}$ values for the three VOCs were 1.16, 1.21 and 0.35 respectively.

398 The vapour diffusion resistance, *Z*, for the five systems based on the derived permeability values
399 in [30] and the system configurations (Table 1) are listed in Table 5. It was observed that the

Phenolic and PUR-CM systems were considerably more diffusion tight against VOC transport compared to the CaSi, AAC and Cork plaster systems. In the case that the fungal growth was to occur in the interface between the adhesive mortar and insulation instead of between the internal lime render and adhesive, the diffusion resistance of the insulation system against transport of the examined VOCs decreases by: PUR-CM 1.3-3.7%; CaSi 25.4-27%; AAC 12.8-13.6%, and Phenolic < 0.3%.

3.4 Theoretical VOC mass balance for a room scenario

Table 6 shows the VOC vapour content in the room air obtained through the VOC mass balance calculations for three VOCs and the five insulation systems. It was seen that the VOC content in the room air was higher for the CaSi, AAC and Cork plaster systems compared with the tighter PUR-CM and Phenolic systems. In addition, the VOC content in the room air seemed to be higher in the case of the more volatile acetone.

4 Discussion

4.1 Experiment 1: Decontamination methods

In the experiment with the three decontamination methods it was found that the simple hand-power method using a paint scraper was insufficient for removal of all fungal biomass (spores and mycelium) on the masonry specimens. This was probably due to the hand-power method only removed fungal mycelium and spores in/on the wallpaper and glue, while the mycelium penetrating into the internal render layer would remain. In one masonry specimen a high level of fungal biomass using the Mycometer test was found in one location, and below detection range in another, which suggest an uneven distribution of growth or effectiveness of the hand-power decontamination of the wall surface. It also highlights the importance of performing several and different tests (agar growth and Mycometer). In contrast to the hand-power method, the mechanical method with hammer and chisel was found to be very effective as it also

removed potential growth in the internal render layer. For the MicroClean method, it was found that the Mycometer Surface results were below normal background level, which indicates that the heat treatment with dry steam was effective at removing of fungal growth on the masonry specimens.

4.2 Experiment 2: Development of fungal growth

In the experiment with added insulation systems no active fungal growth was found in the interface between the masonry specimens and the insulation systems despite favourable temperature and a_w and the presence of fungal spores. The lack of fungal growth as tested with the Mycometer method was probably due to the high pH of the internal render and the adhesive mortars, which seemed to hamper germination and growth, as concluded in [13,17]. On the other hand, as a result of the agar imprint tests it was found that large numbers of *A. versicolor* and *P. chrysogenum* spores survived the high pH in the interface and formed colonies when transferred to V8 and DG18 agar. The spores were seen to survive better in the adhesive mortar used for the Phenolic system compared to the other adhesive mortars despite similar pH levels. The results indicate that the moisture weight-% in the adhesive mortars could be an important factor in terms of the amount of surviving fungal spores in the interface, where the four Phenolic walls were among the ones with the highest moisture content. The measured a_w in the masonry specimens, were close to what would be expected in the interface between a masonry wall and added internal insulation in real case buildings, as illustrated in the large field experiment presented in [17] where similar a_w were observed in the interface using these exact insulation systems. The results suggest that the CaSi systems was the most robust in terms of lowest moisture content in the adhesive mortar and least number of fungal spores surviving in the interface. In the case of no "pre-contamination" of the masonry specimens, the CaSi, AAC, PUR-CM and Cork-plaster systems seem to be equally robust.

As stated in Section 3.2.2, the number of viable spores were seen to differ between sampling locations on the same walls. This was possibly caused by the application of the adhesive mortars for the insulation systems that was added and spread out using a notched trowel, which could have caused the spores to get mixed into the adhesive mortar and then become unevenly spread around the wall surface. It was also observed that a number of agar plates had an area nearly free of fungi colonies which was probably caused by the Mycometer surface tests had been taken prior, see [30].

As a result of the Mycometer tests in the interface it was also found that after 6 and 12 months of application of the insulation systems there was no difference between the decontamination methods in terms of fungal survival. Although the masonry specimens decontaminated using the hand-power method had a large fungal biomass after the decontamination, the results indicate that the choice of decontamination methods may be of minor importance when the insulation systems are installed using adhesive mortars with very high pH (>12).

In terms of the long-term perspective, it is yet to be determined if fungal spores would be able to survive until the pH has dropped to more favourable levels or if they would become unable to germinate before this was to occur. In [17] it was found that the decline of pH seems to depend on the water vapour diffusion resistance of the system and could take several years, especially for the more diffusion-tight systems where the high pH levels were maintained for at least 4½ years. Similar to the work presented in [17], the short experimental period is a limitation in terms of assessing the long-term performance of the insulation systems using highly alkaline adhesive mortars to prevent fungal growth. It is therefore still recommended to limit the amount of mycelia, spores and organic residues in critical locations such as the masonry/insulation interface through thorough decontamination, and to not use insulation systems with organic elements or additives.

4.3 Experiment 3: VOC diffusion

The result of the VOC diffusion experiment, mimicking the production of volatile compounds (VOCs) from fungal growth, showed that the three VOCs were able to diffuse through most of the examined materials, so in the case of fungal growth behind the applied internal insulation systems the VOCs could potentially affect the indoor air quality negatively. The Phenolic and PUR-CM foam insulation systems with closed cell structure were found to be considerably tighter against VOC diffusion compared to the CaSi, AAC and Cork plaster systems – as it is the case for diffusion transport of water vapour through the systems.

It was found that the VOC vapour flow rate density for the samples generally were within 20-25% of each other for the individual materials, with the exception of the more diffusion tight materials (Phenolic and PUR-CM insulations, and the aluminium membrane), where the vapour flow rate density varied considerably. The discrepancies were probably caused by leaky sealings resulting in excessive vapour flows results for the tight materials. The actual vapour flows through the material samples were probably closer to the lowest measured values than the largest values, as the only cause of an unintentional increase of the diffusion resistance would be an accidental spill of epoxy, which was inspected prior to the test. For this reason the permeability and diffusion resistance were determined for both the average and minimum vapour flow rates. The diffusion results could have been affected slightly by the differences in the ambient RH levels due differences in moisture inside the material pores. On the other hand, the ambient temperature would probably affect the vapour pressure differences over the material samples due to changes in the saturation vapour pressure inside the test cups. The air velocity inside the fume hood was not measured, however, it was assumed that the air movements would provide sufficient air flow to reduce the risk of a stagnant air layer forming above the test cups.

It was found from the similarity approach for transport of moisture and VOCs in materials that the diffusion similarity factor, $\kappa_{diff,voc}$ for acetone and ethanol was above 1 suggesting that the materials constrict diffusion of the VOC molecules more than the diffusion of water vapour molecules. In contrast, for 2-heptanone the average $\kappa_{diff,voc}$ was 0.35 and so the molecules are less constricted compared to water vapour molecules. It is still unclear whether it is the molar mass, saturation vapour pressure, molecule polarity or something else that determines if the $\kappa_{diff,voc}$ factor is below or above 1 and the magnitude of the difference to water vapour.

4.4 Theoretical VOC mass balance for a room scenario

As a result of the VOC mass balance calculations for the room scenario it was found that the rate of diffusion through most of the insulation systems were large, resulting in a high VOC content in the room air for the less tight systems with the more volatile VOCs. Acetone was found to exceed the recommended exposure limit by the American National Institute for Occupational Safety and Health (NIOSH) of 0.59 g/m^3 for all system but the Phenolic foam, while for ethanol and 2-heptanone none of the systems exceeded the exposure limits of 1.9 g/m^3 and 0.47 g/m^3 respectively [33]. However, as the production rate of VOCs from fungal growth is unknown, the rate of diffusion would probably be limited by the production rate resulting from the metabolism of the fungal growth behind the insulation. We assume that the resulting partial pressure for the VOCs at the fungal growth in the masonry/insulation interface would be less than the saturation values used in the hypothetical room scenario. At the present time the authors do not have a qualified estimate of what the partial pressure for the VOCs in the interface could be as more research is needed for production of VOCs. In terms of the effect on the indoor air quality, this is still unclear as there are no health-based guidelines or threshold values concerning MVOC exposure in buildings as stated in a 2009 WHO report [34].

5 Conclusions

The present paper investigated the conditions that may remove or prevent fungal growth in the interface between the solid masonry walls and the added internal insulation.

- The "hand-power" decontamination with a paint scraper was inadequate for removal of fungal growth, while the MicroClean (dry steam) and "mechanical" (removal of internal render with hammer and chisel) methods were found to be very effective.
- Choice of decontamination method was found to be of minor importance in terms of the risk of fungal growth behind the insulation system as the high pH of the adhesive mortars (>12) probably inactivated existing fungal growth on the walls and prevented new growth.
- No active fungal growth was detected in the interface of the 17 masonry specimens after 12 months due to high pH, however colony forming spores were found on transference to agar media.
- *Aspergillus versicolor* and *Penicillium chrysogenum* spores were found to survive the high pH in the interface better than *Acremonium murorum* and *Wallemia sebi*.
- *Aspergillus versicolor* and *Penicillium chrysogenum* spores were found to survive better in the interface of the Phenolic insulation systems compared to the other insulation systems, despite similar pH conditions in the interface of all five systems.
- VOCs were able to diffusion through most of the examined materials and could potentially affect the indoor air quality in the case of fungal growth behind the insulation.
- The rate of VOC diffusion through the examined insulation was high and was probably limited by the production rate resulting from the metabolism of the fungal growth.

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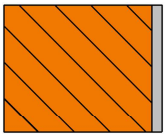
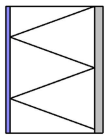
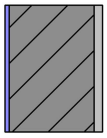
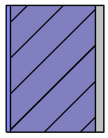
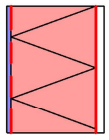
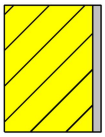
636 Table 1 Build-up of masonry specimens and the five insulation systems, and the material properties. Note that

637 insulation systems were installed on the interior side of the "Base wall".

Material layers from the exterior side to the interior side	ρ [kg/m^3]	λ_{dry} [W/(m·K)]	μ_{dry} [-]	A_w [kg/(m^2·s$^{1/2}$)]	d [mm]	R [m^2·K/W]	Z [m^2·s·Pa/kg]	
Yellow soft-moulded brick	1643	0.600	16.9	0.278	180	0.58	1.54E+10	
7.7% lime adjusted mortar (internal render layer)	1243	0.440	22.43	0.390	10	0.02	1.13E+09	
Total: for Base wall						**0.60**	**1.65E+10**	
PUR-CM adhesive mortar	1313	0.497	18.75	0.005	10	0.02	9.47E+08	
PUR-CM insulation	49	0.037	27.01	0.013	80	2.16	1.09E+10	
PUR-CM render	725	0.147	11.73	0.107	10	0.07	5.92E+08	
Total: for PUR-CM system						**2.25**	**1.25E+10**	
Casi adhesive mortar[a]	1429	0.619[1]	12.67	0.053	8	0.01	5.12E+08	
Casi insulation[b]	225	0.061	4.23	0.726	100	1.64	2.14E+09	
Casi adhesive mortar[a]	1429	0.619[1]	12.67	0.053	10	0.02	6.40E+08	
Total: for Casi system						**1.67**	**3.29E+09**	
AAC adhesive mortar	830	0.155	13	0.003	8	0.05	5.25E+08	
AAC insulation	99	0.044	3	0.006	100	2.27	1.52E+09	
AAC adhesive mortar	830	0.155	13	0.003	8	0.05	5.25E+08	
Total: for AAC system						**2.38**	**2.57E+09**	
Adhesive mortar[a]	1516	0.733[1]	41.4	0.006	5	0.01	1.05E+09	
Aluminium (AL) foil perforated					0.1			
Phenolic insulation	35	0.020	114	0.009	100	5.00	5.76E+10	
Aluminium (AL) foil			10000		0.1		5.05E+09	
Gypsum board	850	0.177	10	0.277	13	0.07	6.57E+08	
Total: Phenolic system						**5.07**	**6.43E+10**	

Cork plaster[b]	250	0.037	3	0.129	40	1.08	6.06E+08	
NHL Finish render[c]	1600	0.769	14.55		10	0.01	7.35E+08	
Total: plaster system						**1.09**	**1.34E+09**	
Additional materials:								
Wet-room membrane*			14567					

[a]Values were determined in the preliminary study. [b]Values were obtained from product datasheets. Other values were determined by Technische Universität Dresden. [c]Estimated values based of similar products tested by Technische Universität Dresden. NHL: Natural Hydraulic Lime.

Table 2 Mycometer surface results after decontamination of masonry specimens

Mycometer Surface Value (MSV)	Hand-power wall 1	Hand-power wall 2	Hand-power wall 3	Hand-power wall 4	Mechanical wall 1	Mechanical wall 2	Mechanical wall 3	Mechanical wall 4	MicroClean wall 1	MicroClean wall 2	MicroClean wall 3	MicroClean wall 4
Sample A	2388	4117	3644	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	69
Sample B	4353	2653	5794	4212	BDL	BDL	BDL	BDL	BDL	BDL	BDL	66

BDL: below detection level

Table 3 Moisture content in the adhesive mortars and insulation materials [weight-%]

Insulation system	Adhesive				Insulation[b]			
	Hand-power	Mechanical	MicroClean	Uncontam.	Hand-power	Mechanical	MicroClean	Uncontam.
PUR-CM system	13.2	9.2	9.7	6.3	12.6	18.0	6.3	3.6
Phenolic system	14.4	15.2	13.6	11.0	35.6	82.8	32.1	27.6
AAC system	12.8	10.3	9.9	7.0	31.6	39.6	27.8	11.7

CaSi system	5.9	1.8	4.0	6.0	11.3	16.6	12.5	10.9
Cork plaster system				6.2[a]				48.3

[a]Original internal render as no adhesive was used for this system. [b]Outermost 10 mm, i.e. nearest the masonry.

Table 4 Mycometer and agar imprint test results after 6 and 12 months

	Mycometer Value (MV)										Colony forming units (CFU)	
	Results after 6 months					Results after 12 months					Total CFU from V8 and DG18	
	Masonry/ insulation interface		Adhesive mortar	Outermost 10 mm insulation		Masonry/ insulation interface		Adhesive mortar	Outermost 10 mm insulation		6 months	12 months
	A	B		A	B	A	B		A	B		
PUR-CM Hand-power	46	11	6	10	5	11	15	16	3	2	3	154
Phenolic Hand-power	5	8	6	8	4	11	12	5	1	1	2	1200
AAC Hand-power	7	7	4	4	3	10	8	9	1	1	58	475
CaSi Hand-power	7	12	6	13	38	10	9	10	22	23	0	100
PUR-CM Mechanical	17	5	3	4	3	13	12	BDL	3	0	1	0
Phenolic Mechanical	1	3	8	8	5	34	41	19	2	1	634	611
AAC Mechanical	BDL	0	6	7	3	5	5	2	4	1	7	3
CaSi Mechanical	4	9	5	18	36	7	11	42	30	20	2	28
PUR-CM Microclean	14	14	5	3	4	15	16	30	3	1	2	301
Phenolic Microclean	26	6	4	6	6	9	18	21	36	10	112	1214
AAC Microclean	32	14	19	7	4	8	15	6	3	5	0	4
CaSi Microclean	20	7	6	25	26	3	13	6	36	33	228	8
PUR-CM Un-inoculated	7	7	4	20	2	11	11	2	1	3	75	4
Phenolic Un-inoculated	3	1	2	5	3	18	19	19	1	1	216	359
AAC Un-inoculated	3	2	2	5	3	6	5	4	2	2	5	13
CaSi Un-inoculated	5	5	13	18	38	9	10	9	21	21	5	168
Cork plaster Un-inoculated	19	26	NT	26	27	12	13	NT	19	19	1	3

BDL: below detection level. NT: not tested. Un-inoculated: reference specimens, which were not used experiment 1. Note that the rating scales for Mycometer Surface tests (Interface) differ from the Mycometer Bulk-material tests (Adhesive mortar and insulation), please see Section 2.3.

Table 5 Vapour diffusion resistance, Z [m²·s·Pa/kg] for the insulation systems (including adhesive mortar)

	Acetone	Ethanol	2-heptanone

	Average	Max	Average	Max	Average	Max
PUR-CM system	1.01E+10	1.04E+10	3.18E+10	4.20E+10	1.00E+10	1.00E+10
CaSi system	1.85E+09	1.89E+09	2.56E+09	2.61E+09	5.89E+08	5.89E+08
AAC system	1.89E+09	1.90E+09	2.66E+09	2.70E+09	6.01E+08	6.01E+08
Phenolic system	2.51E+12	6.16E+12	2.22E+12	2.48E+12	5.76E+10	5.76E+10
Cork plaster system	1.95E+09	2.22E+09	2.79E+09	3.22E+09	6.77E+08	6.77E+08

654

655 Table 6 VOC vapour content in the room air, $v_{voc,i}$ [g/m³]

	Acetone	Ethanol	2-Heptanone
CaSi system	3.65	0.64	0.07
AAC system	3.63	0.62	0.07
PUR-CM system	0.67	0.04	0.004
Phenolic system	0.001	0.001	0.001
Cork plaster system	3.19	0.52	0.06

656

657 Figure 1 Flow chart for the activities under the three experiments

658 Figure 2 Experimental setup for the two experiments: a) Fungal decontamination methods (experiment 1), and b)
659 Development of fungal growth in masonry specimens fitted with internal insulation (experiment 2).

660 Figure 3 Fungal sampling: (a) Taking out drilling core using hole-saw; (b) Taking Mycometer Surface samples in
661 the interface; (c) Making agar imprint for the interface; (d) Preparation of core samples for the Mycometer Bulk
662 Material test, cutting away excess insulation; and (e) Measuring pH.

663 Figure 4 Decontamination: (a) Hand-power with paint scraper; (b) Walls after removal of render with hammer and
664 chisel; (c) MicroClean dry-steam cleaning with plate mouth pieces and (d) fibred cotton cloth mouth pieces.

665 Figure 5 Parameter variations investigated in the development of fungal growth experiment

666 Figure 6 Density of VOC vapour flow rate, g, for the material samples

667 Figure 7 Diffusion similarity factor $\kappa_{diff,voc}$ for the three VOCs