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Potential impact of clay plasters on indoor air quality

Aalto university



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INTRODUCTION

Clay is the finest fraction of soil, with particles smaller than two micrometres. Unlike silt, sand and gravel, which are mechanically fragmented rock, clay particles are typically thin plates made of specific clay minerals. In earthen construction, clay works as the binder. Its very large surface area and negative surface charge let it glue other particles together and adsorb substances onto its surface. Clay plaster is an interior finish that suits almost any substrate. In its simplest form it is a mixture of clay, water and sand. Plant fibres are often added to improve workability and reduce cracking. Interest in clay plaster has grown in recent years, partly because of its environmental profile. It has a very low carbon footprint and, because it is unfired and does not contain any chemically binding substance, it can be reused by simply mixing it with water again. It is also valued for its ability to moderate indoor relative humidity. Clay is also non-combustible, which can improve the fire safety of structures. Many naturally occurring Finnish clays can serve as a raw material, including surplus soil from excavation sites. This makes clay plaster a promising use for a locally available and often wasted resource. Yet the performance of Finnish clay plasters has been studied little.

This report presents a preliminary investigation of four aspects that matter to builders, designers and occupants.

- First, it quantifies the **moisture buffering potential of a clay plaster made from local, Finnish clay**. Clay-based materials are known to exchange moisture with the environment they are exposed to, absorbing it from the air when indoor relative humidity gets higher and releasing it into the environment when indoor conditions are drier. Quantifying this performance gives an indication of the ability of the plaster in helping to keep indoor relative humidity stable (potentially contributing to improved indoor comfort and wellbeing).
- Second, it analyses **mould susceptibility of clay plasters,** considering both plasters with and without a small content of bio-fibers (which are at times used in practice). The goal is to evaluate the mould risk related to use clay plasters, compared to more conventional finishing materials. Additionally, the test aims to evaluate whether the addition of bio-fibers relevantly changes the vulnerability of clay plasters to mould growth.
- Third, the **microbiological growth on the plaster** is quantified and characterised, before and during exposure in a chamber with controlled environmental conditions and a less controlled, office space with human presence. The goal is to measure the viable microbial content of clay powder, observe changes during processing into clay plaster, and follow the microbial signals during these two different exposure scenarios. This can be the starting point to open a discussion on the microbial characteristics and probiotic potential of clay plasters in buildings with relevance to human health. Our work here barely scratches the surface but contributes to building the basis of our understanding of these aspects.
- Fourth, we explore the **adsorption of volatile organic compounds (VOCs).** Some evidence suggests that clay plaster can adsorb these indoor air pollutants. We test emissions of clay plasters and their potential for pollutant removal after exposure to toluene at two concentrations under static conditions. Studied clay plasters include “Untreated” clay that is conditioned under stable conditions and “Oven-dried” clay plaster from which the moisture was removed by oven drying. The goal is to evaluate if clay plasters could be preferable to conventional finishing materials, due to lower emissions and high adsorption capacity.

Together, these results aim to give industry a practical picture of how Finnish clay plasters can interact with indoor environments and their potential to support comfortable and healthy indoor conditions.

The results presented in this report **can be summarised as follows:**

- **Moisture buffering.** The clay plaster developed from local clay, sand and water, appears to offer an excellent performance for moisture buffering applications, ranking within the highest class possible for moisture buffering applications (according to the NORDTEST protocol). *This means this material offers promising potential for passive regulation of indoor relative humidity, ideally supporting more stable and comfortable indoor conditions, compared to conventional finishings characterized by low moisture buffering performance.*

- **Sensitivity to mould growth.** Following preliminary results observed using the Finnish Mould Model, considering the starting moment of microscopic mould growth (k1 at M=1) after natural inoculation: (I) clay plaster and clay plaster with bio-fibres fall into sensitivity class 1, "very sensitive", the same class as untreated pine sapwood and cardboard-faced gypsum board, (II) Although in the same class, fiber-free clay plasters are a safer choice, as mould is observed to take about double the time to start growing, (III) Mineral clay powder alone is medium resistant, similar to plastic and concrete. These results suggest that added sand and water raise the vulnerability to mould, when mixed with clay, in a plaster, and the fibres raise the vulnerability further (likely because they supply nutrients for mould). *Overall, clay plasters appear to be as susceptible to mould as paper-faced gypsum boards, which are commonly used in buildings. Careful moisture design is therefore advisable, as it is for any sensitive interior finishing.*

- **Microbiological growth.** Results show that the clay powder contains some levels of viable fungi and in particular of viable bacteria, including spore-forming, actinomycetes-type bacteria commonly found in soil. Processing the powder into plaster clearly adds fungi to the mix, which are likely introduced with the sand and water in the process. In the plaster, viable fungi and to a larger extent, viable bacteria were consistently present at every sampling date, irrespective of whether the plaster was exposed in a controlled chamber (20-22C, 50% RH) or in an office space with human presence. In quantitative analysis, the levels of viable fungi and bacteria in plaster exposed for 6 months in an office environment were lower compared to in fresh clay plaster, whereas microbial levels in plaster exposed to controlled conditions were higher at 6 months compared to fresh plaster. Future experiments will aim at better understanding microbial growth on clay plaster under different environmental conditions and at characterising the types of bacteria and fungi present in clay plaster.

- **Volatile organic compounds (VOCs).** Both clay plasters tested without toluene had total VOC (TVOC) concentrations below 10 µg/m^3, suggesting *low VOC emissions under the used conditions*. “Untreated” clay plaster showed minimal reduction at the lower toluene concentration, whereas toluene was not detected in the tests containing “Oven-dried” clay plaster, indicating higher adsorption capacity of “Oven-dried” samples. The result suggests that the moisture content of the clay plays a significant role in the adsorption of toluene. *Overall, the results indicate very low VOC emissions from clay plaster, consistent with its being a natural, unfired material. Clay plaster may also adsorb some VOCs, such as toluene, but so far this was observed only with oven-dried samples.* However, these tests were conducted with a limited number of samples and under specific laboratory conditions, and the results should be considered preliminary. Further testing is needed to confirm the emissions and the adsorption capacity of clay plasters, and to establish their relevance under real building usage conditions.

Detailed results follow.

1. Moisture buffering performance

Rationale. Indoor humidity has a direct effect on our comfort, health, sleep quality, and productivity. When the air is too dry, mucous membranes and skin dry out, leading to irritated eyes and a higher risk of respiratory problems. When it is too humid, discomfort from overheating increases. High indoor relative humidity can additionally lead to higher risk of joint pain and inflammatory rheumatic conditions.

Keeping humidity at a moderate level also limits the growth of bacteria, mould, and fungi, and reduces the presence of mites , which are all sources of allergens that can threaten human health. Indoor humidity also affects how easily viruses such as influenza and SARS-CoV-2 spread: they transmit more readily at very low or very high humidity than at moderate levels. For these reasons, a relative humidity of 40–60 %RH is generally considered the ideal range for healthy, comfortable indoor conditions, as shown in Figure 1.

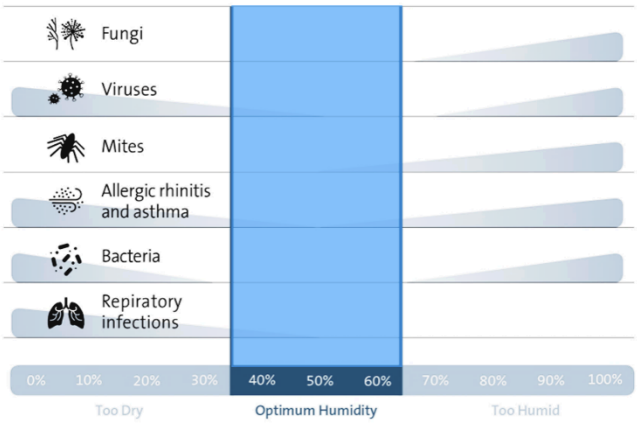

Figure 1. Sterling chart. *Optimum indoor relative humidity range (40–60%) for minimising fungi, viruses, mites, allergens, bacteria, and respiratory infections.*
Adapted from: Arundel, Anthony V., et al. "Indirect health effects of relative humidity in indoor environments." Environmental health perspectives 65 (1986): 351.

Keeping indoor humidity within this 40–60 %RH range usually relies on active systems (humidification-dehumidification, HVAC systems, …) which imply carbon emissions during both production of the systems and their operation (energy use). One sustainable alternative is the use of natural, hygroscopic building materials. Such materials are able to naturally absorb and release moisture, as so, when indoor humidity rises, they absorb moisture from the air. When the air dries, they release the moisture back, avoiding it becoming too dry. This is a material response which requires no active energy use, as it is a passive humidity-regulating solution.

Results. In this project, a clay plaster has been tested for moisture buffering performance. Experimental results show that a thin layer of clay plaster (1cm thick), made of locally sourced clay, sand, and water, has excellent moisture buffering behaviour. **The measured moisture buffering value (MBV) is 2.58 ± 0.11 g· m^{-2}· %RH^{-1}, which is classified within the best class (excellent, Figure 1) for moisture buffering applications, according to the NORDTEST protocol, which is the most common scientific reference for benchmarking finishing materials.**

Test procedure. Samples were tested for moisture buffering value performance following the NORDTEST protocol. Triplicate samples of the clay plaster (10 × 10 × 1 cm, Figure 2) were prepared, oven-dried, conditioned, sealed on all surfaces but the tested one, and then tested in a climatic chamber under cyclic conditions of 8 h at 75% RH and 16 h at 33% RH, 23°C, until dynamic equilibrium was reached. Results are expressed as the measurement of the last cycle under dynamic equilibrium, averaged across three samples ± standard deviation.

a.



b.

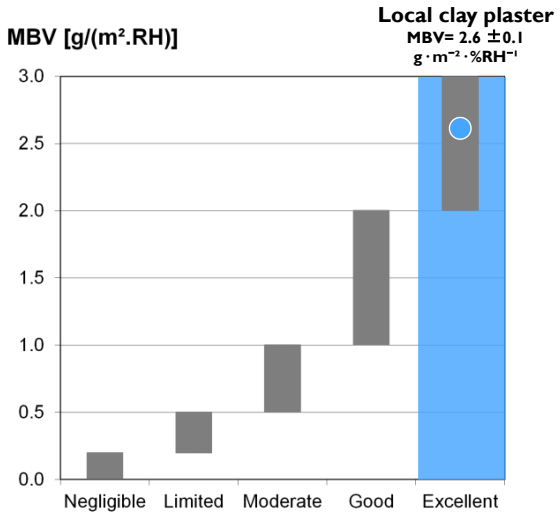

Figure 2. *Moisture buffering test: (a) clay plaster samples used in the testing (10 × 10 × 1 cm), and (b) results located in the performance class chart from the NORDTEST protocol.*

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2. Vulnerability to mould and microbial content

2.1 Vulnerability to Mould growth

Rationale. Mould growth in building materials can degrade indoor air quality, and it can release spores and allergens that are linked to respiratory symptoms and asthma. Whether mould will appear depends on several factors, including the presence of mould spores, humidity and temperature conditions, and sensitivity of the material to mould growth. Mould growth is highly relevant when working with natural materials, as they can show higher risk of mould growth compared to more conventional materials. This risk should be evaluated, to know how to best use them and when careful design is necessary due to mould risk.

Results. The following results should be intended as preliminary, and more testing is required to further confirm them. The following preliminary results were observed, based on the starting moment of microscopic mould growth (k1 at M=1, Figure 3 and 4):

- Clay plaster and clay plaster with bio-fibres falls into sensitivity class 1, "very sensitive", the same class as untreated pine sapwood and cardboard-faced gypsum board. Although in the same class, fiber-free clay plasters are a safer choice, as mould is observed to take about double the time to start growing.
- These results indicate that clay plaster finishes require careful moisture design, as already applied to common materials of the same classes, such as paper-faced gypsum boards;
- The clay matrix alone shows low susceptibility to mould, approximately corresponding to class 3, "medium resistant", like plastic-based materials, mineral wool and carbonated concrete. Mould risk increases in the plaster, compared to clay, which is likely a consequence of adding sand and water. Adding straw fibres increases the risk further, which might be a consequence of the nutrients available in the fibres.

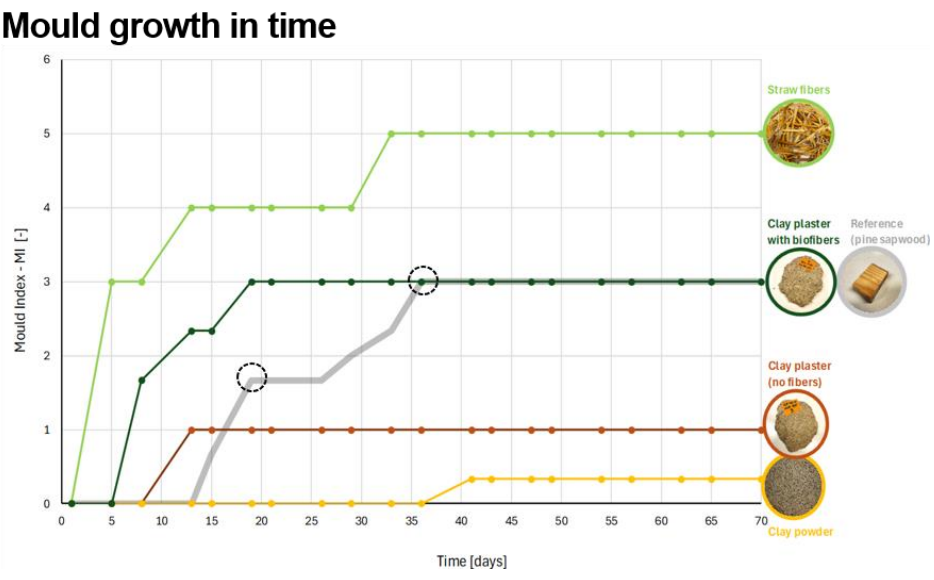

Figure 3. *Time evolution measured for the mould index on the tested material samples. Results expressed as the average from observations on 3 samples per material.*

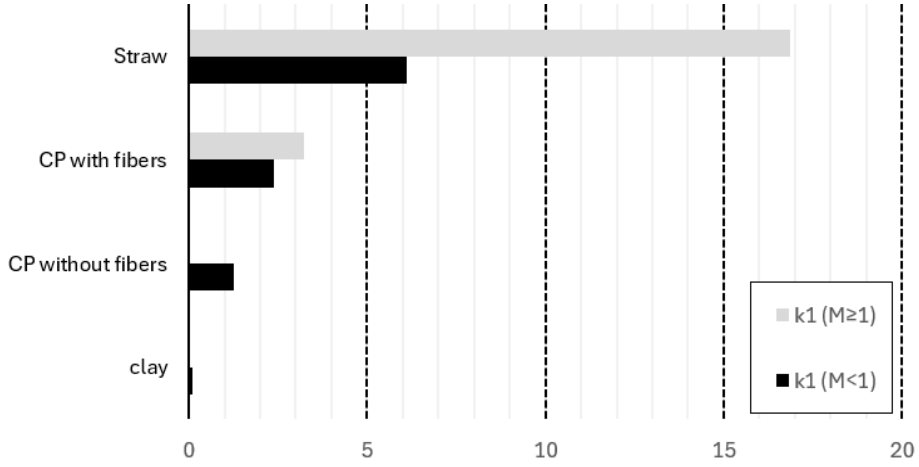

Figure 4. *Results expressed in terms of sensitivity classes, following the Finnish Mould Model. The classification is based on values of k1 measured for M=1, as M=3 was reached only in two materials (straw, and clay plaster with bio-fibers).*

Test procedure. Cylindric samples with about 7cm diameter and 1cm thickness were prepared in triplicate and conditioned at 20 °C and 45 %RH (Figure 5). Natural inoculation was performed by keeping the samples for 12 days in a mould-contaminated environment, reproducing the way materials are contaminated during handling and storage on a real construction site. They were then kept in sealed in containers (one single box for 3 samples of one material) above a saturated potassium sulphate solution, giving approximately 97 %RH at 20 °C test conditions, and kept there for 10 weeks. The top surface of every sample was inspected twice weekly and scored on the 0–6 mould index scale, using a microscope at 50× magnification for the early stages and unaided visual assessment once growth became visible. Pine sapwood was tested in the same run under the same conditions to serve as the reference material.



Figure 5. *In the top: pictures of the samples of clay and plasters tested, together with the setup box with saturated salt solutions used for each triplicate of samples of each material.*
In the bottom: a view over the microscope visual assessment of mould growth, and an example of what is seen during the test.

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2.2 Microbial content

Rationale. Indoor surfaces are relevant as both, sinks and sources of microbes in indoor spaces. The role of microbes, including those from outdoor environments, from humans and animals, and also from indoor environments, for human health is ambiguous. For example, moisture damage in buildings can result in microbial growth, which is linked to respiratory symptoms and other adverse, mostly respiratory health effects. Pathogens can be deposited on surfaces through coughing and sneezing, or the hands of infected people on frequently touched surfaces, and such contaminated surfaces can contribute to infectious disease transmission. On the other hand, exposure to a diverse indoor microbiota, particularly when of environmental rather than of human origin, is thought to benefit human health, by supporting immune system development. Building materials contribute to which microbes are present indoors. Clay plaster is a natural, minimally processed material, and little is known about its viable microbial content or how that content develops once the plaster is in use.

This pilot study addresses three questions:

1. What is the viable microbial content of clay powder, and how does it change, if at all, after processing into clay plaster?
2. How does the viable microbial content of clay plaster develop over time under controlled conditions (50% RH, 20-22 °C) with minimal human interaction?
3. How does it develop over time when the plaster is exposed in an occupied office-type space?

Results. In the following, the preliminary results are structured based on these three study questions.

Re 1) Clay powder contains low levels of viable fungi and higher levels of viable bacteria (Figure 6). Total bacteria were present in a similar range in the powder ($1.1–7.3 \times 10^4$ CFU/g) and in fresh plaster ($5.5–13 \times 10^4$ CFU/g). Fungal viable levels were low and variable in the powder, while in fresh plaster, fungal counts were more uniform, at about 1,800 CFU/g on M2 and 1,200–1,500 CFU/g on DG18. Actinomycete-type bacteria were detected in all powder replicates ($3.2 \times 10^3–2.2 \times 10^4$ CFU/g) but in only one of three plaster replicates (450 CFU/g). Processing seems to have changed the community, with fewer actinomycetes and more consistently detectable fungi. The sand and the mixing water are likely sources for the added fungi, but since those were not analysed separately, we cannot confirm this here.

Re 2,3) In direct plating and cultivation, total bacteria scored 3 (clear microbial growth) in every sample of clay plaster, in both environments and through all timepoints 0, 1, 3 and 6 months (*data not shown*). The scale is semi-quantitative and does not resolve exact changes in bacterial numbers. Fungal growth stayed at moderate to high levels, with similar or slightly lower scores for samples from the occupied office space than from the controlled environment. Actinomycete-type bacteria were absent in the controlled environment throughout the observation period and were detected only once, at 3 months, at minimal levels and in two of three replicates. The results from bacterial and fungal counts derived from dilution plating are more informative, even if only performed in clay powder, clay plaster at timepoint zero and clay plaster at the timepoint 6 months, in that they represent quantitative values (Figure 6). We found that the levels of viable fungi and bacteria in plaster exposed for 6 months in an office environment were about 10-15 times lower compared to in fresh clay plaster. In contrast, fungal and bacterial levels in plaster after 6 months under controlled conditions were ~5 and ~25-times, respectively, higher compared to fresh plaster. Future experiments will aim at better understanding microbial growth on clay plaster under different environmental conditions and at characterising the types of bacteria and fungi present in clay plaster.

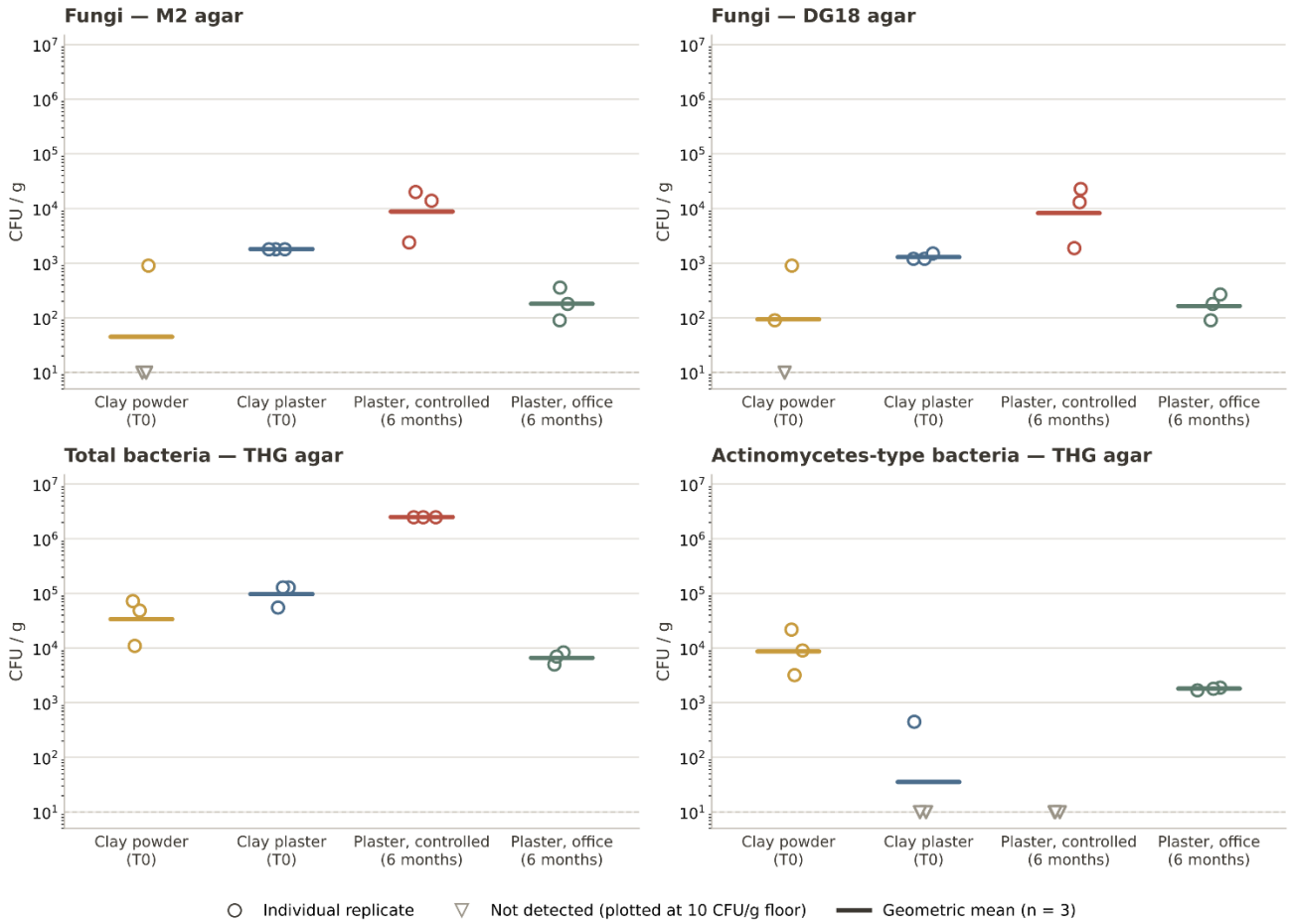

Figure 6. *Viable fungi (on general M2 agar medium and DG18 agar medium supporting growth of more xerophilic fungi) and viable bacteria (total bacteria and Actinomycetes-type bacteria on THG agar medium) on clay powder and fresh clay plaster, as determined via dilution plating and cultivation.*

Test procedure. A graphical overview of the design of these experiments is provided in Figure 7, example pictures in Figure 8.

Clay plaster was prepared by mixing clay powder, sand and water and letting it dry. Viable bacteria and fungi were determined by cultivation in clay powder (raw material) and in fresh plaster at time zero using dilution plating (fully quantitative) as well as direct plating method (semi-quantitative) and cultivation. The plaster pieces were then exposed in two settings: in the first, a controlled environment, they were kept in closed chambers at 20–22 °C and 50% RH with minimal human interaction; in the second, an occupied office space, they were placed in a cafeteria/rest space at Aalto University, with somewhat variable environmental conditions and human presence. Three plaster pieces per setting were sampled at time points zero and after 1, 3 and 6 months with semi-quantitative direct plating (*data not shown*) and with quantitative dilution plating method (Figure 6). Fungi were cultivated on M2 agar (a general fungal growth medium) and DG18 agar (for growth or xerophilic fungi). Total and actinomycete-type bacteria were cultivated on THG agar. Growth was scored semi-quantitatively from 0 (no growth) to 3 (clear growth) using direct plating from triplicate samples at each timepoint (data not shown) and quantitatively using dilution plating method (expressed as colony forming units (CFUs) per gram material) on triplicate samples of clay plaster at timepoints zero and 6 months, in addition to clay powder.

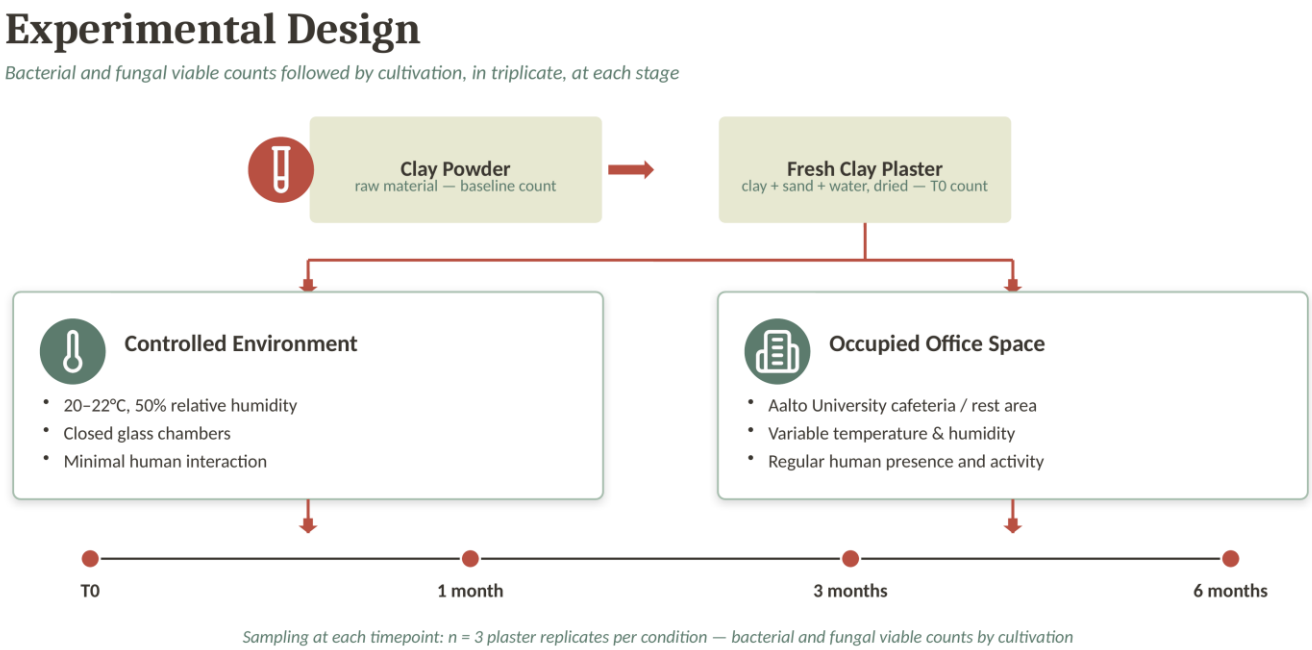

Figure 7. *Experimental design of microbial studies.*

A



B



Figure 8. *Clay plaster exposure in a controlled chamber (A) and in office space (B).*

3. Volatile organic compounds (VOCs)

Rationale. Volatile organic compounds (VOCs) are common indoor pollutants emitted from a wide range of building materials, furniture, and consumer products. Their concentration and persistence in indoor air can influence indoor air quality and occupant exposure. The adsorption of VOCs by building materials could be used indoors to passively reduce airborne concentrations and the persistence of pollutants.

This pilot study investigated the ability of clay plaster to adsorb toluene under static laboratory conditions and examined the effect of moisture content. Zeolite was included as a reference material with established adsorption properties. Given the limited number of samples and specific experimental conditions, these results should be considered preliminary results. Further testing with a larger number of samples and controlled experimental conditions are needed to confirm the adsorption capacity of clay plaster.

Results. The results of the adsorption tests are presented in Figure 9. Baseline toluene concentrations measured in the empty bottles were 53 µg/m^3 following the 60 ng injection and 110 µg/m^3 following the 120 ng injection. The "Untreaded" clay plaster samples showed minimal (1 µg/m^3) reduction at the lower initial toluene concentrations, whereas no measurable reduction was observed at the higher concentration. Zeolite reduced the concentration by 42% and 24% at the lower and higher initial concentrations. Toluene was not detected in the tests containing "Oven-dried" clay plaster, indicating that the concentration after exposure was below the analytical detection limit. Both samples tested without toluene had TVOC concentrations below 10 µg/m^3, suggesting that the tested clay plasters had low VOC emissions under the conditions used. However, these emission tests were not conducted according to standardised emission testing method, and therefore, the results cannot be directly compared with emission data from other materials.

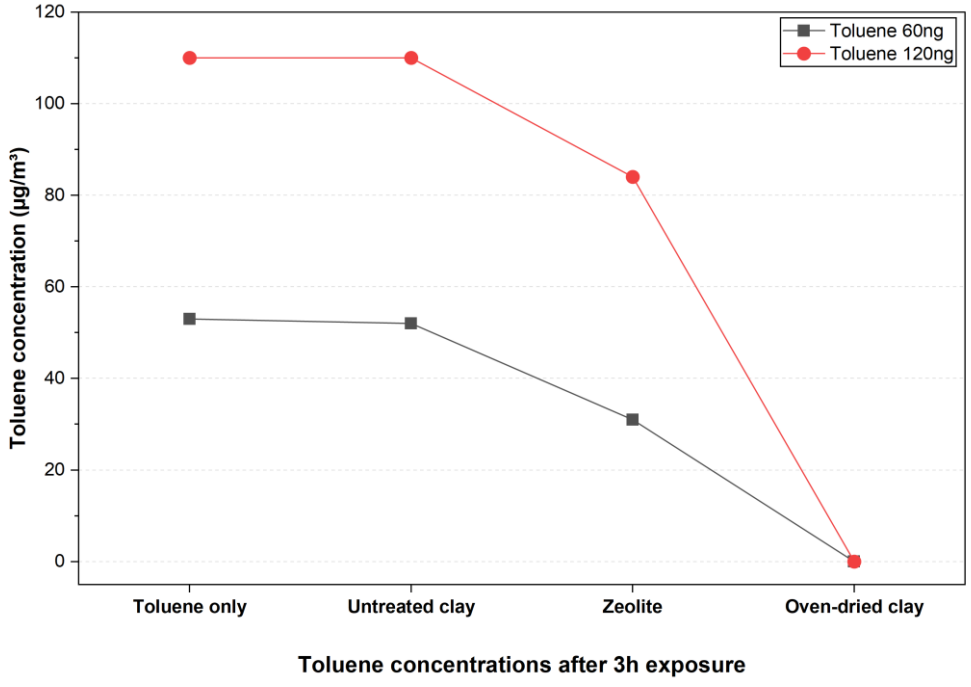

Figure 9. *Measured toluene concentrations after exposure to tested materials.*

Test procedure. VOC adsorption by clay plasters was tested under static conditions using a 3-hour exposure to toluene at two concentrations. The tested material included "Untreated clay" plaster, which was conditioned under stable conditions before testing, and "Oven-dried" clay plaster from which moisture was removed by oven drying. Zeolite

was used as a reference because of its known adsorption capacity. The test specimens were placed in 0.6L glass humidifier bottles, and liquid toluene solution was injected into vials attached inside the bottles (Figure 10). Toluene-only tests were conducted to determine baseline toluene concentrations in the bottles. and "Untreated" and "Oven-dried" clay samples were tested without toluene to assess potential VOC emissions. After injection of the toluene, the bottles were closed and sealed for three hours. The bottle air was then actively sampled onto Tenax TA sorbent tubes using air pumps with a flow rate of 200 ml/min for three minutes. To compensate for the sampled air volume, replacement air was filtered through another Tenax TA tube that was placed before the inlet of the bottle. VOC concentrations were analysed by thermal desorption gas chromatography-mass spectrometry (TD-GC-MS) according to ISO 16000-6:2021 in a FINAS accredited laboratory.

Sample preparation. Crushed material samples with a grain size of 4-8 mm were used to increase the exposed surface area. "Untreated clay" plaster samples were conditioned in a desiccator under stable conditions (22°C, 69% RH) before testing. Three clay samples were dried in an oven at 110°C until a constant mass was reached to remove moisture. The water content of the "Untreated clay" plaster was calculated from the difference in sample mass before and after drying and was 1.6wt%. Zeolite (ZeoLith Plus, Ubbink) was purchased from a local hardware store and kept in the original packaging until testing. The external surface areas of the material samples were estimated based on the grain size and density. Sample masses of 30 g for clay and 36 g for zeolite were selected to provide similar estimated external surface areas of approximately 0.02-0.03m^2.

Target chemicals. A toluene–methanol solution was prepared to ease the handling of the toluene and its introduction into the test bottles. 12 and 24 µL of solution were used, corresponding to 60 and 120 ng of toluene, respectively. Based on the injected amounts and bottle volume, the calculated target toluene concentrations were 100 and 200 µg/m3. The measured baseline concentrations were lower, at 53 and 110 µg/m3, respectively, but approximately doubled between the two test concentrations as intended.



Figure 10. *Clay plaster and zeolite exposure.*

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