



Investigation on material properties and hygrothermal performances of 3D-printed silica aerogel-based thermal insulation

Samuel Pantaleo^{*}, Fenne Adriaanse, Florent Gauvin, H.J.H. Brouwers

Department of the Built Environment, Vertigo, PO BOX 513, Eindhoven, 5600 MB, the Netherlands

ARTICLE INFO

Keywords:

3D-printing
Thermal insulation
Innovative building materials
Silica aerogel
HAM simulation

ABSTRACT

The construction industry continuously seeks to improve building efficiency, productivity, and sustainability. Within this context, 3D printing has emerged as a promising technology to accelerate construction, reduce costs, and support housing development in regions facing rapidly increasing demand. However, to fully realize the potential of additive manufacturing in the building sector, all structural components, including insulation layers, must be printable. Currently, no fully integrated, printable insulation solution exists, as insulation is typically installed adjacent to walls after printing.

This study investigates the performance of a 3D-printed bio-based insulation composite incorporating silica aerogel. Key printing parameters are systematically evaluated, and the insulation properties are compared to those of manually cast reference samples. Coupled heat, air, and moisture simulations are then performed to assess the hygrothermal performance of conventional and 3D-printed wall assemblies integrating the insulating material. Finally, the material's susceptibility to mold growth is examined, and strategies are proposed.

1. Introduction

Current constraints (e.g., resource depletion, increasing of global population, environmental breakdown ...) imply the need to investigate new technologies, especially in the construction sector, which accounts for approximately 37% of the global greenhouse gas (GHG) emissions (United Nations Environment Programme, 2022). Within this context, three-dimensional (3D) printing has emerged as an interesting solution to address these challenges. While additive manufacturing is already widely used in several industries such as plastics, aerospace, and medicine, its application in the building sector is still in its early stages of development. The main advantages of this new technology are cost and time reduction, improved design freedom, and reduced environmental impact compared to conventional methods.

3D printing directly addresses some of the most pressing challenges faced by the building sector today, such as the demand for affordable housing that keeps rising, especially in developing countries (Moghayedi et al., 2024) and the need for emissions reduction associated with the building sector. Housing demand and the need for sustainability create high expectations for 3D printing in the building sector. 3D printing relies on the automated, computer-controlled addition of materials layer by layer to form walls and structural elements of

houses (Bici and Yunitsyna, 2023). Early applications were targeting cement-based mixtures, but the latest research has emphasized expanding the range of potential printable materials, such as fly ash or furnace slag (Arash et al., 2025). Among the most promising alternatives are geopolymers, clay- and soil-based composites (Long et al., 2021), as well as biopolymer blends (Long et al., 2021), each of which offers distinct advantages in terms of sustainability, performance, or local availability. To meet the specific requirements of 3D printing for the building sector mainly pumpability, extrudability, and rapid setting, researchers are also investigating dedicated additives. However, achieving the right balance between material properties, environmental impact, and cost remains a central challenge.

In addition to material innovation, 3D-printing also brings important operational benefits. Automation reduces reliance on manual labor (Hossain et al., 2020), thereby lowering exposure to hazardous environments and improving worker safety. Demonstration projects and current technologies show two main possibilities, either the production of entire houses via the use of robotic arms on-site, or the quick and standardized production of modules using large-scale printers (Hossain et al., 2020; Everett et al., 2022). Several technologies are available, based on the needs. A robotic arm is able to produce high complexity geometry, but suffers mainly from a limited printing area. Its upgraded

^{*} Corresponding author.

E-mail address: s.m.pantaleo@tue.nl (S. Pantaleo).

<https://doi.org/10.1016/j.dibe.2026.100980>

Received 11 February 2026; Received in revised form 10 April 2026; Accepted 15 June 2026

Available online 23 June 2026

2666-1659/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).



Fig. 1. House assembly, project Milestone (Wolfs et al., 2023).



Fig. 2. Addition of insulation material within printed wall (Palazzo, 2025).

version is a telescopic arm that can be transported on-site, yet suffers from its precision. Looking at bigger system, gantry systems are dedicated to wall and house printing, without the need of high operating skills. Yet, it suffers from important installation and assembly time. Also devices, such as modular crane, also suffer from a lack of precision, but can enable large and complex printing projects (Everett et al., 2022). From a sustainability perspective, 3D printing contributes in several ways. The precision induced by the method minimizes material waste (Khan et al., 2021). In addition to the potential use of recycled or bio-based materials (Kromoser et al., 2022), it further reduces the embodied energy of construction. Current investigations focus on mixtures incorporating waste-derived aggregates or renewable fillers, as well as on enhancing the recyclability of printed elements. The reduced time needed to build a house, the use of recycled or waste-based materials (Dweib et al., 2006), and the reduction of waste production should imply lower costs, which is crucial for promoting this construction technique, especially in developing countries. Yet, the technology itself remains expensive, due to the novelty of the technology and because it still requires significant labour work, on top of high-skilled staff, as seen in Fig. 1.

In addition, the current state of the technology emphasizes the non-fully automated process, the technology being still relying on labour work to install additional components of the wall, such as insulation layers (Aldawi et al., 2013), as seen in Fig. 2.

These layers are needed to add properties to the printed wall, on top of meeting specific building regulations (Bazli et al., 2023). The printing of the insulation, or the additional layers of a wall, using the same

technique, and/or simultaneously with the house shells, is the next step to fully take advantage of the printing technology. This has the potential to improve the efficiency of this building method, reduce the costs, improve the building speed and overall encourage its adoption.

Among the different approaches targeting thermal insulation applied to buildings, several categories can be observed. The first one is to play on the composition of the structural material, usually concrete or mortar, and trying to optimize its composition or the printing parameter (Sovetova and Calautit, 2024) to play on the thermal conductivity. Yet, this improvement of thermal conductivity usually results in a reduction in mechanical properties. The second common option is the shape optimization of the printed layer (Liu and Du, 2025; Dziura et al., 2023), by bringing via specific shapes and geometry air cavities or shapes lowering the thermal conductivity. In addition, formed voids can be filled with thermal insulation, during an extra step. With a similar approach, the design of printed block can be found (de Rubeis, 2022), with easy filling of the voids and important freedom for the shapes. Yet, all these approaches are targeting a reduction of thermal conductivity via 3D printing, but yet are not directly processing the thermal insulation material via 3D-printing, therefore limiting the target of fully automated house building via 3D printing. Lastly, several papers reports the use of 3D-printing for the insulation layer, yet current products usually implies post-processing operations, such as important and long drying steps (Ma et al., 2022) or sintering in an electric oven (Dutto et al., 2023). These steps are difficult to imagine for an on-site printing. Therefore, the investigation of the printability of the thermal insulation alone, or side-to-side with a structural layer, could path the way to more automation for housing construction. Most of the traditional insulating material appears difficult to process via 3D-printing technology, therefore the use of a composite seems mandatory. Bio-based materials such as cork and cellulose fibers are a straight forward way to design thermal insulating composites, yet the final properties can be not as low, due to the concessions needed to develop the composite. On the other hand, silica aerogel appears as the best material for thermal insulation. Due to its properties and especially its high porosity, silica aerogel has many applications, from battery safety (Huang et al., 2025) to thermal protection. Yet, it uses its characteristics at its best when considering thermal insulation. For this application, this material is usually mixed into composites, as pure thermal insulating material (Pantaleo et al., 2024; Borzova et al., 2024) or into structural materials (Lamy et al., 2021; Khamidi et al., 2014), for example in mortars (Yao et al., 2026). It can also be mixed into coatings, again mainly for thermal applications, when silica aerogel in the shape of powder is used (Li et al., 2025). Following a previous study, where a slurry of silica aerogel and bio-based thermal insulation material was developed (Pantaleo et al., 2025) ($\lambda = 22 \text{ mW/m}\cdot\text{K}$), this study aims to

Table 1
Composition of the printed sample.

Water (wt%)	Xanthan Gum (wt%)	Glycerol (wt%)	Loose Cellulose Fiber (wt%)	Silica aerogel granulates (wt%)
72.0	2.0	8.0	3.0	15.0

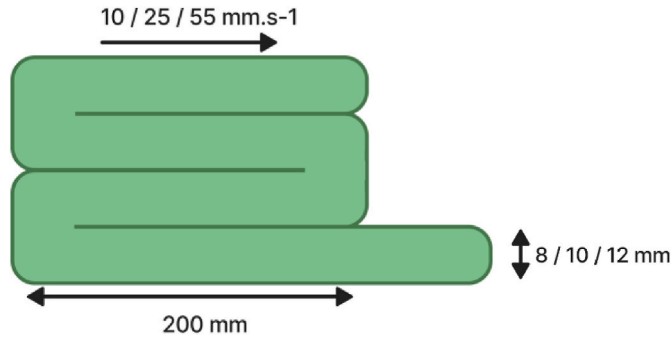


Fig. 3. Printing parameters – Side view.

understand its processability via additive manufacturing. Preliminary results show a great potential for additive manufacturing, thanks to the good processability observed, and a mix design with important amount of water, making the material mix design easy to adapt, depending on the properties needed. Building upon these developments, the present study explores the use of this slurry in the 3D printing process. Starting from testing its printability, with a focus on potential dual side-to-side printing with concrete, the printed material properties is then compared to the conventional process. A comprehensive overview of the properties of the material place in walls will be made, via heat, air and moisture simulations. Lastly, an assessment of mold development and will be carried out, due to the presence of bio-based materials and the conditions of on-site printing, being long drying time at low temperatures. The effect of an antifungal is also investigated on this slurry.

2. Materials and methods

2.1. Materials

Silica aerogel granulates are obtained from Cabot Corporation, USA (Aerogel Particles P100® – Size from 0.1 to 4.0 mm). Xanthan Gum (Analytical grade) and Glycerol (Analytical grade) are purchased from VWR Chemical, the Netherlands. Cellulose (Cyclin® Cellulose Sound Insulation) is purchased from De IsolatieShop B.V., the Netherlands, and shredded to obtain loose cellulose (heterogeneous). Weber Beamix (Saint-Gobain) was used as the binder for the concrete 3DP layer. Antifungi agent is provided by Groupe Berckem.

Insulating material is based on a previous study (Pantaleo et al., 2025), and its composition is listed in Table 1.

2.2. 3D-printing

Two methods are used in this study to produce the samples. At first, samples are printed using a caulking gun (Makita - DCG180ZXX) equipped with a custom nozzle at size 100 * 10 mm, and printings are made freehand. The second setup is based on the same caulking gun but mounted on a robotic arm (ABB - IRB1200-5/9). Sample shapes are designed in Rhino, using the Grasshopper® extension, and logged onto the robot arm interface. Layer length was set at 200 mm before overlapping. Additionally to this, the height position of the nozzle was adapted to find the ideal printing parameter, on top of the extrusion rate directly monitored on the caulking gun. The tested printing speed varies from 10 to 55 mm s⁻¹. Fig. 3 depicts the different printing parameters.

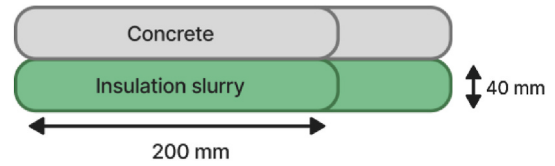


Fig. 4. Printing parameters, concrete, and insulation layer.

Lastly, a side-to-side 3D printing is done, using concrete and the insulation slurry, to mimic a dual 3D-printing. For the concrete, the layer height is set at 40 mm, 200 mm length, and printed at 10 mm s⁻¹, as seen in Fig. 4.

The concrete layer is printed at first due to its capacity of hardening faster than the slurry. The insulating slurry is printed a few minutes after the printing of the concrete layer.

2.3. Thermal properties

To measure thermal conductivity, different techniques are employed. The transient plane source method (Hot disk Thermal Constant Analyser) is used to measure materials with lower thermal conductivities and will provide, in addition, the specific heat capacity value. Prior to measurements, the device is calibrated using an EPS reference sample provided by the manufacturer, with a declared thermal conductivity of 25.3 mW/m·K. Measurements are conducted at room temperature (20 ± 2 °C). The thermal conductivity of printed samples is measured using a heat flow meter device (ThermTest HFM 100), at different mean temperatures (30 °C, 20 °C, 10 °C, and 0 °C). Before any measurement, samples are dried overnight at 40 °C in an oven (Memmert universal oven UF260).

2.4. Compression tests

Mechanical strengths of the printed insulation layer are tested through compression tests, using an MTS Criterion equipped with a 30 kN load cell, at a test speed of 2 mm/min, and at room temperature. A minimum of 5 samples (30 mm * 30 mm * 10 mm – BS EN 826), cut from the core of the printed layer, are tested.

2.5. Rheology tests

The rheological behaviour of the prepared inks was investigated using a strain- and stress-controlled rheometer (Anton Paar® MCR 102e) using parallel plates geometry. Amplitude sweep experiments were performed at a constant frequency of 10 rad s⁻¹ by increasing the amplitude of the applied oscillatory shear strain from 0.0001% to 1000%. The apparent yield point of the suspensions and foams was taken from the intersection of the storage and the loss moduli obtained from these oscillatory measurements. Measurements with de.

2.6. Heat, air, and moisture (HAM) simulation

For the HAM simulations, one-dimensional non-steady heat and moisture transport processes are solved by coupled differential equations using the software WUFI Pro (WUFIa), i.e., heat transport and moisture transport by

$$\frac{\partial H}{\partial T} \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left[\frac{\partial T}{\partial x} \right] + h_v \frac{\partial}{\partial x} \left[\frac{\delta}{\mu} \frac{\partial p}{\partial x} \right] \quad (1)$$

and

$$\rho_w \frac{\partial w}{\partial \varphi} \cdot \frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x} \left[\rho_w D_w \frac{\partial w}{\partial \varphi} \frac{\partial \varphi}{\partial x} \right] + \frac{\partial}{\partial x} \left[\frac{\delta}{\mu} \frac{\partial p}{\partial x} \right] \quad (2)$$

respectively, where D_w (m².s⁻¹) is the liquid transport coefficient, H (J.

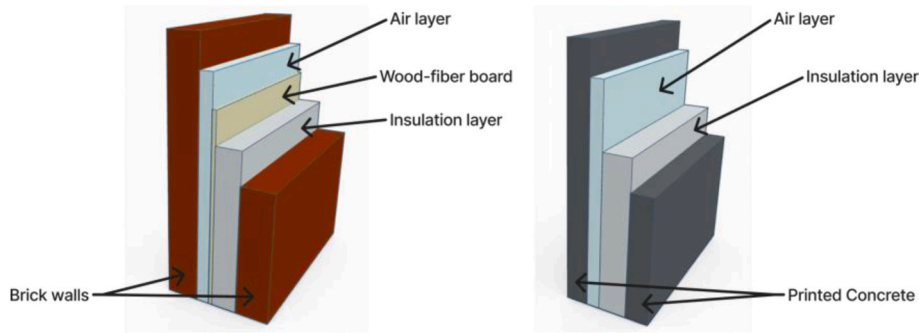


Fig. 5. Schema of simulated walls – Left: Brick wall, Right: Dual 3D-printing Insulation/Concrete.

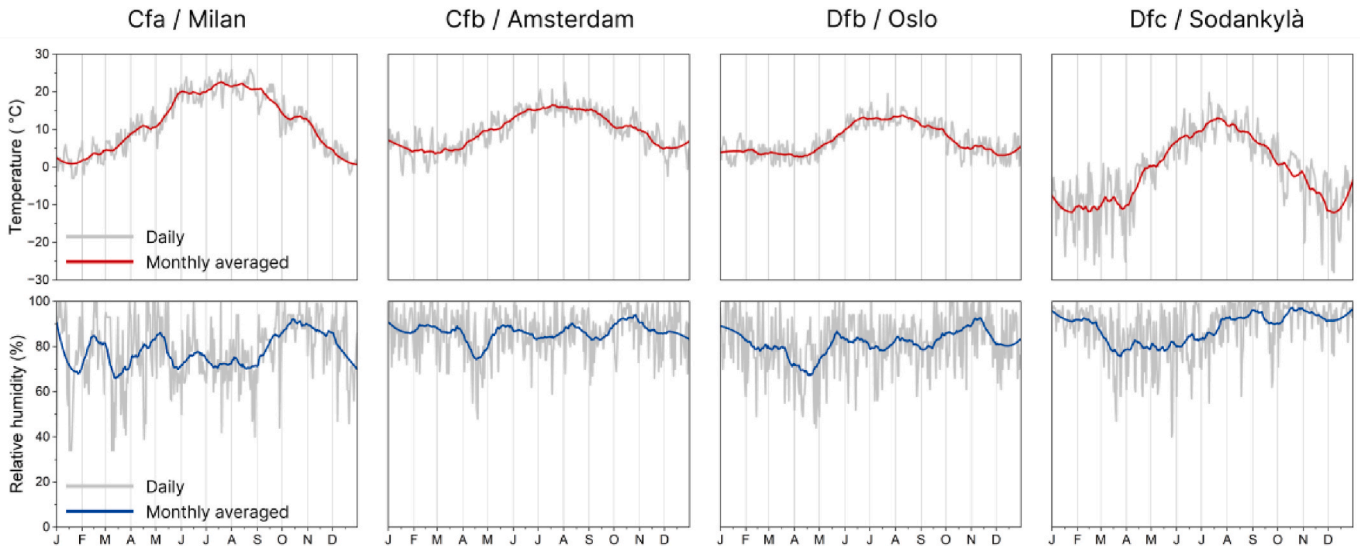


Fig. 6. Temperature and Relative humidity variation over one year for selected climates.

m^{-3}) the enthalpy, h_v ($J \cdot kg^{-1}$) the evaporation enthalpy of water, p (Pa) the water vapour partial pressure, w ($m^3 \cdot m^{-3}$) the water content, δ ($kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$) the water vapour diffusion coefficient in air, T ($^{\circ}C$) the temperature, λ ($W \cdot m^{-1} \cdot K^{-1}$) the thermal conductivity, μ (dimensionless) the vapour diffusion resistance factor, ρ_w ($kg \cdot m^{-3}$) the density of water, and ϕ (dimensionless) the relative humidity RH. The initial and boundary conditions are given in [Appendix A](#).

Two designs of walls are investigated. The first one ([Fig. 5](#)), considered as a standard brick wall structure for cold climate zones ([Koh et al., 2022](#); [SINTEF Community, 2020](#)), is composed of brick layers for exterior and interior walls (thickness = 0.1 m), an air cavity layer (thickness = 0.04 m), a wood fiber board (thickness = 0.013), and the insulation layer. The second one ([Fig. 5](#)) is composed of 3D-printed concrete layers (thickness = 0.07 m, based on project Milestone in the Netherlands ([Wolfs et al., 2023](#))), an air layer (thickness = 0.04 m), and the printed insulation layer. Material properties, listed in [Appendix B](#) and [Appendix C](#), are extracted from WUFI Pro 7 Database ([WUFI, 2025](#)). Insulation layer properties are measured and added as a new material in the software database. Specific heat capacity and thermal conductivity are obtained using the transient plane source method, and bulk density is calculated by

$$\rho_{bulk} \text{ (g / cm}^3\text{)} = \frac{\text{Mass (g)}}{\text{Volume (cm}^3\text{)}} \quad (3)$$

where the mass is obtained on overnight dried samples. The porosity is obtained via

$$\text{Porosity (\%)} = 1 - \frac{\rho_{bulk}}{\rho_{apparent}} \cdot 100\% \quad (4)$$

where $\rho_{apparent}$ is measured using a helium pycnometer (Micromeritics AccuPyc II 1340). The water relative humidity behavior is obtained using dynamic vapour sorption measurement. In addition, the developed insulation is compared to two standard insulating materials, namely EPS and cellulose.

To investigate the performance of the insulation material, four different locations within Europe with different Köppen climates were selected: Milan, corresponding to a humid subtropical climate (Cfa), Amsterdam for a Marine west coast climate (Cfb), Oslo for a warm humid climate (Dfb), and Sodankylä to represent a subarctic climate (Dfc). Climate properties are listed in [Appendix D](#) and are applied to the exterior wall. In addition, the walls are facing the main driving rain direction ([Appendix D](#)) of each climate. The climate applied to the interior walls is set as per ISO 13788 ([ISO 13788 Hygrothermal Performance of, 2013](#)) with humidity class 3, representing a building with unknown occupancy, and a constant temperature set as 20 $^{\circ}C$. The simulations are run over 5.5 years to reach equilibrium, with a time step of 24 h. Yearly averages are presented in [Fig. 6](#).

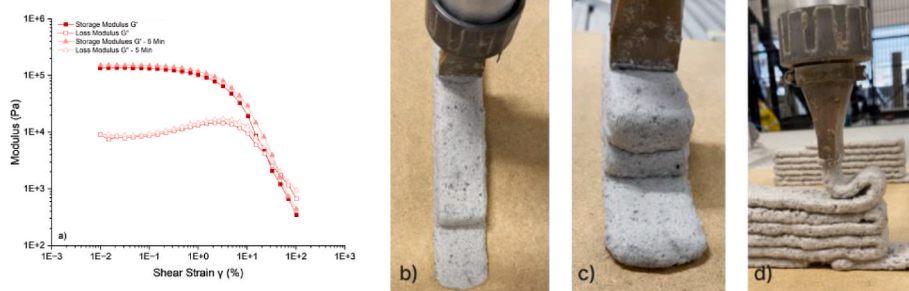
2.7. Mold development simulation and assessment

For the first time, and using the results from the HAM simulations, mold development was simulated, using WUFI Pro with the WUFI Bio Extension, which employs Sedbauer's bio-hygrothermal model ([Klaus](#)

Table 2

Composition and conditions for mold development assessment.

Sample Name	Water (wt%)	Antifungi (wt%)	Xanthan Gum (wt%)	Glycerol (wt%)	Loose Cellulose Fiber (wt%)	Silica aerogel granulates (wt%)
Reference	72.0	0.0	2.0	8.0	3.0	15.0
Antifungal_3	69.0	3.0	2.0	8.0	3.0	15.0
Antifungal_6	66.0	6.0	2.0	8.0	3.0	15.0

**Fig. 7.** Hand-free printing of insulation material.**Fig. 8.** a) Rheology of the slurry and examples of 3D-printing using a robotic arm – Robotic arm layer height settings: b) 8 mm, c) 10 mm, d) 12 mm.

et al.). The selected occupant exposition class is “Surfaces inside constructions without direct contact to indoor air”, with an initial relative humidity in spores of 0.5%. The substrate classes chosen are class 1 for the slurry and the cellulose, which correspond to substrates that facilitate the development of mold, and class 2 for the EPS, which correspond to less bio-utilizable substrates (WUFib). Simulations are run over 5.5 years, on all the insulation layers, and for the two types of wall simulated.

On a second time, freehand samples were printed and placed in a climatic chamber, set at 30 °C and 80%RH, for a month. An antifungal agent, known for its efficiency with bio-based materials, is tested with different amounts. The antifungal agent is a microemulsion in water of plant extract. A FT-IR measurement is displayed in Appendix E. It is assumed that the water amount in the samples remains equal. All the compositions are displayed in Table 2.

Two conditions are tested, oven-dried samples (7 days, 50 °C - Memmert Universal Oven UF260) and wet samples (conditionnement starting right after printing) are compared. Pictures and optical microscopic observations are made over the duration of the conditioning. In addition, wet samples will also be kept wet at room temperature, and observed over 30 days as well.

3. Results and discussions

3.1. 3D-printing – thermal insulation

Initially, preliminary printings were carried out using the caulking

gun in a hand-held, free mode to assess the feasibility of the process (Fig. 7).

The material was extruded smoothly from the gun, with no spreading observed after deposition, as it remained stable while still wet. This was confirmed by the measured layer heights, which were close to the nozzle opening (~10 mm), resulting in a total height of approximately 30 mm for three printed layers. However, due to the manual nature of the process, the depositions lacked precision, leading to non-uniform layer formation. Therefore, scaling up with a controlled deposition system was required. Rheology measurements were conducted using a robotic arm to investigate key printing parameters. Representative results are presented in Fig. 8.

Firstly, oscillatory shear measurements (Fig. 8 - a)) show that the slurry displays viscoelastic properties, with a storage modulus G' higher than the loss modulus G'' at low shear strains, with a cross-over observed at higher shear strain, around $\gamma = 200\%$. In addition, the slurry, made with a significant amount of water, does not settle fast and therefore remains stable over time. This is confirmed by the rheology curve, with no differences observed with delayed samples. Secondly, the two main parameters influencing the process were identified as the nozzle height and the printing speed. A too small layer height (8 mm in this case) led to material overflow on the sides and in front of the nozzle. In addition to reduced homogeneity due to side flows, the accumulation of material in front of the nozzle resulted in excessive compaction of the deposited layer. On the opposite, an excessively large nozzle height (12 mm) prevented proper layer packing. After printing the first layer, a significant gap was observed between the nozzle and the previously deposited

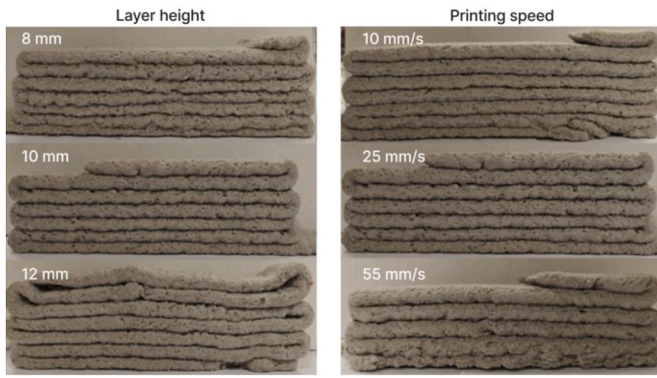


Fig. 9. Printed samples for every printing conditions.

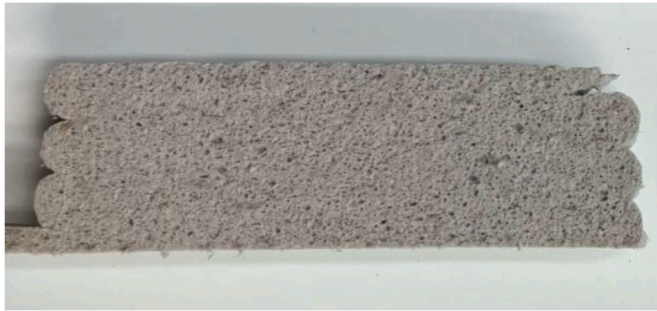


Fig. 10. Side cut of printed samples.

material (Fig. 8 – d)). Considering the slurry viscosity, a layer height of 10 mm, corresponding to the nozzle opening, provided the most suitable condition. Regarding printing speed, three different values were tested, and representative samples are shown in Fig. 9.

The influence of printing speed on the final shape was found to be less significant than that of nozzle height. All samples were printed correctly and did not exhibit major defects or material accumulation. Among the tested conditions, a printing speed of 25 mm s^{-1} appeared to offer the best balance, producing well-defined and consistent samples. In 3D-printing applied to buildings, extrudability and buildability are important and well-established requirements to consider a mortar useable in 3D-printing. The similar criteria described by Rangel et al. (Rangel et al., 2024; Tripathi et al., 2022; Wolfs et al., 2018) will be applied to our material, while not having a similar end goal. For the extrudability, a 10 mm layer height printed at 25 mm s^{-1} displayed no clogging. The deformation after drying sometimes goes above 10% of the initial width (40 mm), but will barely go above 25% deformation ($\sim 10 \text{ mm}$). Additionally, the material is considered buildable if the bottom layer withstands a yield stress of at least 896 N m^{-2} ³⁶, calculated from

$$\tau_{0,0} = \frac{\rho \cdot g \cdot H}{\sqrt{3}} \quad (5)$$

where ρ ($\text{kg} \cdot \text{m}^{-3}$) is the density of the printed material, H (m) the height, and g ($\text{m} \cdot \text{s}^{-2}$) the gravity constant. With $H = 0.08 \text{ m}$ (8 layers) and $\rho = 176 \text{ kg m}^{-3}$, a yield stress of 79.8 N m^{-2} is achieved, far away from the minimum value required. Yet, this insulating material is not designed to provide strength to a structure, but rather as a layer providing extra properties. Beyond the visual aspect, the internal homogeneity of the printed samples is critical to preserve their mechanical performance. Cross-sections were prepared by cutting approximately 1 mm from the sides of the samples, as shown in Fig. 10.

The inner core revealed a homogeneous phase with no visible distinction between successive layers. The layers merged seamlessly,

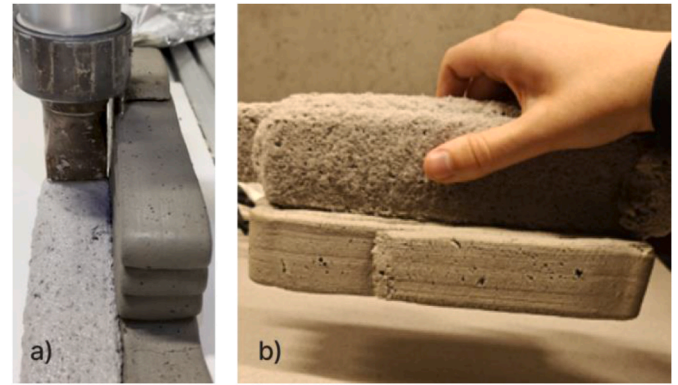


Fig. 11. a) Side-to-side double printing, b) Adhesion between layers.

forming a continuous structure comparable to cast samples, where material compaction eliminates potential voids. This observation, particularly evident near the edges, confirms the overall structural uniformity of the printed specimens. The printed samples also met the mechanical requirements for insulation materials, with a compressive strength at 10% deformation measured at 22.9 kPa, compared to 33.1 - 41.3 kPa for cast counterparts, depending on the composition. This strength is a result of the good affinity between the cellulose fibers and the xanthan gum (Pantaleo et al., 2025).

3.2. 3D-printing – double-layer concrete/insulation

To mimic a simultaneous double-layer printing process, the insulation layer was printed adjacent to a freshly printed concrete layer, immediately after its deposition and before any drying step. Examples are shown in Fig. 11 – a). The slight lateral flow of the insulation material allowed close contact with the concrete, effectively filling potential air gaps between the two materials. Although the adhesion between the materials was not quantitatively measured, it appeared sufficiently strong for the insulation layer to support the heavy concrete layer, as illustrated in Fig. 11 – b).

The interfacial bonding between the two layers was generally good, although some very narrow gaps could be observed at the interface, as seen in Fig. 12.

These gaps are likely due to shrinkage of either the concrete or the slurry during the drying phase, water evaporation, or the printing process itself, and depend on the position observed, as no gaps can be observed in Fig. 12 – b).

3.3. Thermal conductivity of the printed sample

The thermal conductivities of the printed insulation samples were in first place compared to those of the cast samples to evaluate the potential effect of the printing process. Measurements were carried out over a temperature range of 0 to 30°C , and the results are presented in Fig. 13.

The thermal conductivity of the printed samples increased slightly with temperature; however, the variation remained small, with a maximum difference of about $2 \text{ mW/m} \cdot \text{K}$ across the tested range, as seen in Fig. 13 – a). In addition, printing the slurry led to a slight increase in thermal conductivity compared to the cast samples. This increase was observed at all temperatures, with the largest difference reaching approximately $3 \text{ mW/m} \cdot \text{K}$. This is a consequence of the increased density measured for the printed layer. An average density of $0.176 \pm 0.017 \text{ g cm}^{-3}$ is obtained, against 0.147 g cm^{-3} previously measured (Pantaleo et al., 2025) on cast samples. Overall, these differences remain very small. Thermal conductivities of the combined concrete–insulation printed systems were also measured and are shown in Fig. 13 – b). The high thermal conductivity of concrete was strongly

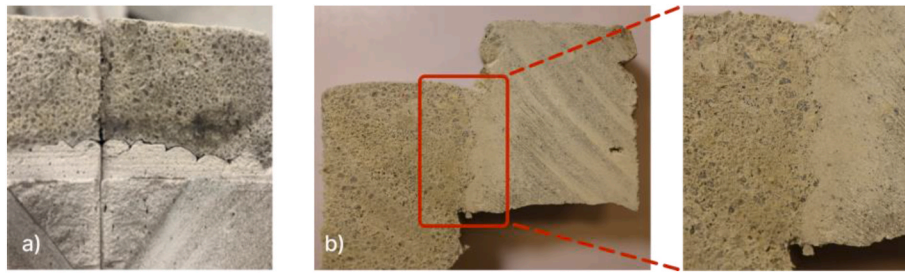


Fig. 12. Interface cement/insulation - a) Position A, b) Position B.

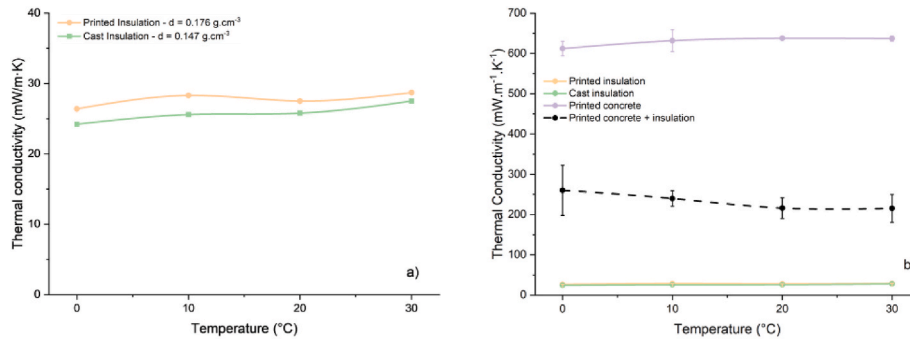
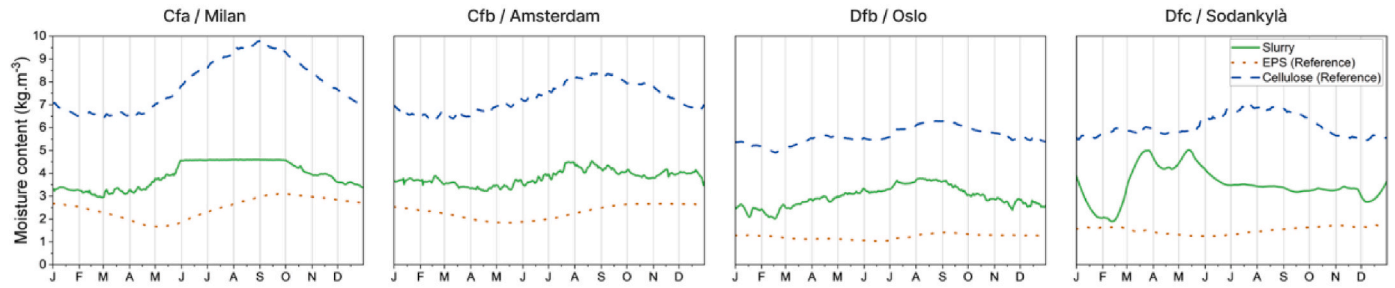


Fig. 13. Printed sample for thermal conductivity measurements – a) Comparison mold/printed, b) Comparison to concrete wall.

Brick wall



Printed wall

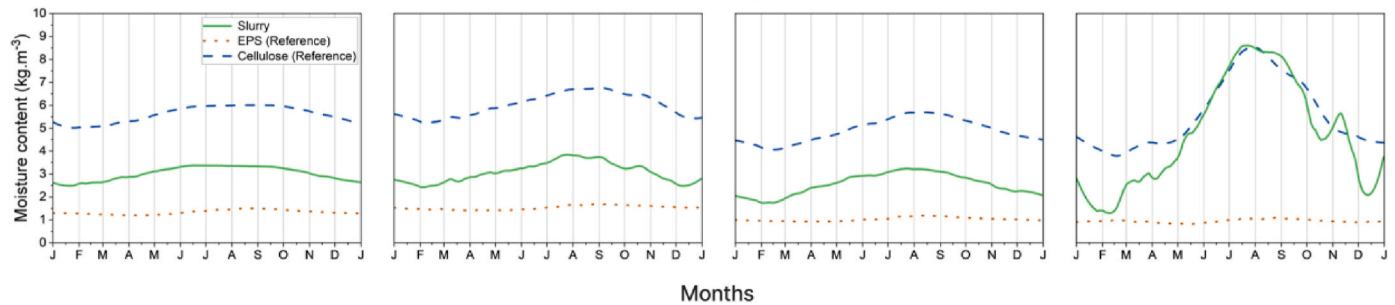


Fig. 14. Moisture content - Brick wall and Printed wall. Slurry and cellulose curves have been smoothed (Savitzky-Golay).

mitigated by the addition of the insulation layer. Starting from approximately 600 mW/m·K for the plain concrete, the effective thermal conductivity was reduced by about 60%, reaching around 250 mW/m·K after the addition of the insulation layer. As previously observed, the influence of measurement temperature remained minimal. This value is lower than related works in the literature. Ma et al. produced a 3D-printed concrete filled with silica aerogel, and achieved a thermal conductivity of 300 mW/m·K, and Rachel et al. 400 mW/m·K with mortar filled with cork. This work results fall a bit lower than other

studies, while having a better and easier freedom to improve even more the insulation capacity. A first and simple step could be to increase the width of the insulation layer, as the thermal-resistance R_{value} is described as

$$R_{value} = \frac{L}{\lambda} \quad (6)$$

where L (m) is the thickness and λ (W/m·K) the thermal conductivity.

Table 3

Insulation layer thicknesses and total wall's width in brackets.

	Slurry	EPS (reference)	Cellulose (reference)
Brick Wall (mm)	77.5 (331)	158 (411)	141 (394)
3D printed Wall (mm)	87.5 (268)	178 (358)	159 (339)

3.4. HAM simulations

3.4.1. Moisture content

The equilibrium moisture content of the different insulating materials under various climatic conditions over a simulated year is presented in Fig. 14.

The influence of climate is clearly visible in the results, with differences of up to 4 kg m^{-3} observed between Milan (Cfa climate) and Oslo (Dfb climate). These observations are a direct consequence of the important difference in rain quantity, respectively 747 and 604 mm.a^{-1} , and highlight the importance of climate when choosing an insulation material. This trend was also observed by Koh et al. (2022). Furthermore, the printed wall exhibited a consistently lower moisture content within its insulation layer compared to the cast wall, for the same time of year and under identical climatic conditions. On average, a difference of approximately 2% was observed between the two wall configurations. However, the moisture behavior under the subarctic climate of Sodankylä strongly affected the insulation layer made from bio-based materials, leading to pronounced seasonal variations. The simulated minimum moisture content reached 2 kg m^{-3} , while the maximum increased to 9 kg m^{-3} (Fig. 14).

3.4.2. Thermal behavior

Based on the thermal conductivity of the insulation materials, and in order to meet the requirement of an overall U-value of $0.205 \text{ W/m}^2\text{K}$, the insulation thickness was adjusted according to the wall configuration. All thicknesses, together with the total wall widths, are listed in Table 3.

Only transient U-values during the “heating period” (from October to March) are considered, as U-values under warmer conditions would yield non-representative results and are not relevant to this study.

Fig. 15 presents the simulated U-values for the different climates and wall structures. Overall, the developed slurry exhibits U-values comparable to those of EPS, both being lower than those obtained with cellulose, indicating good thermal efficiency of the new material. All insulation materials performed better under continental climates Dfb (Oslo) and Dfc (Sodankylä), with U-values remaining close to or matching the target value of $0.205 \text{ W/m}^2\text{K}$. Months at the beginning of the heating period (October and November) showed higher U-values regardless of the climate. Under temperate conditions, however, all insulation materials displayed U-values above the target, with the highest value reaching $0.32 \text{ W/m}^2\text{K}$ in Milan (Cfa). Regarding the effect of wall structure, the printed wall consistently led to lower U-values across all climates (Fig. 15). The slurry again demonstrated behavior similar to EPS, remaining very close to the target U-value of $0.205 \text{ W/m}^2\text{K}$, regardless of the month considered. Yet, these results are obtained with an insulation layer two times thinner than the reference used. As a comparison, with a similar thickness and in climate Cfb (Amsterdam), U-values of EPS and cellulose insulation reach $0.348 \text{ W/m}^2\text{K}$ and $0.322 \text{ W/m}^2\text{K}$. When comparing climates, the same trends persisted, with printed structures performing better in continental than in temperate climates. This finding highlights the potential of 3D-printed wall systems to reduce wall thickness while improving thermal performance. Moreover, the developed slurry appears to be a competitive alternative to conventional insulation materials. Both wall structures made with the developed slurry have an important thickness reduction (Table 3) compared to the references, while having comparable or better U-values, and being less sensitive to moisture sorption.

In addition, temperatures within the insulation layers were measured, at the extremities and in the core, and results are displayed in Fig. 16. Again, no major behavioral differences can be observed among the different materials used as an insulation layer. The type of climate, via its differences in temperature over the years, remains the most important factor influencing the results. The climate also shows an important variation of relative humidity, both among them and over the months. Relative humidity can lead to moisture absorption, especially for bio-based materials, which are the main component of the mix. High moisture absorption could lead to aging or mold development; it is therefore important to understand the way the slurry behaves to mold.

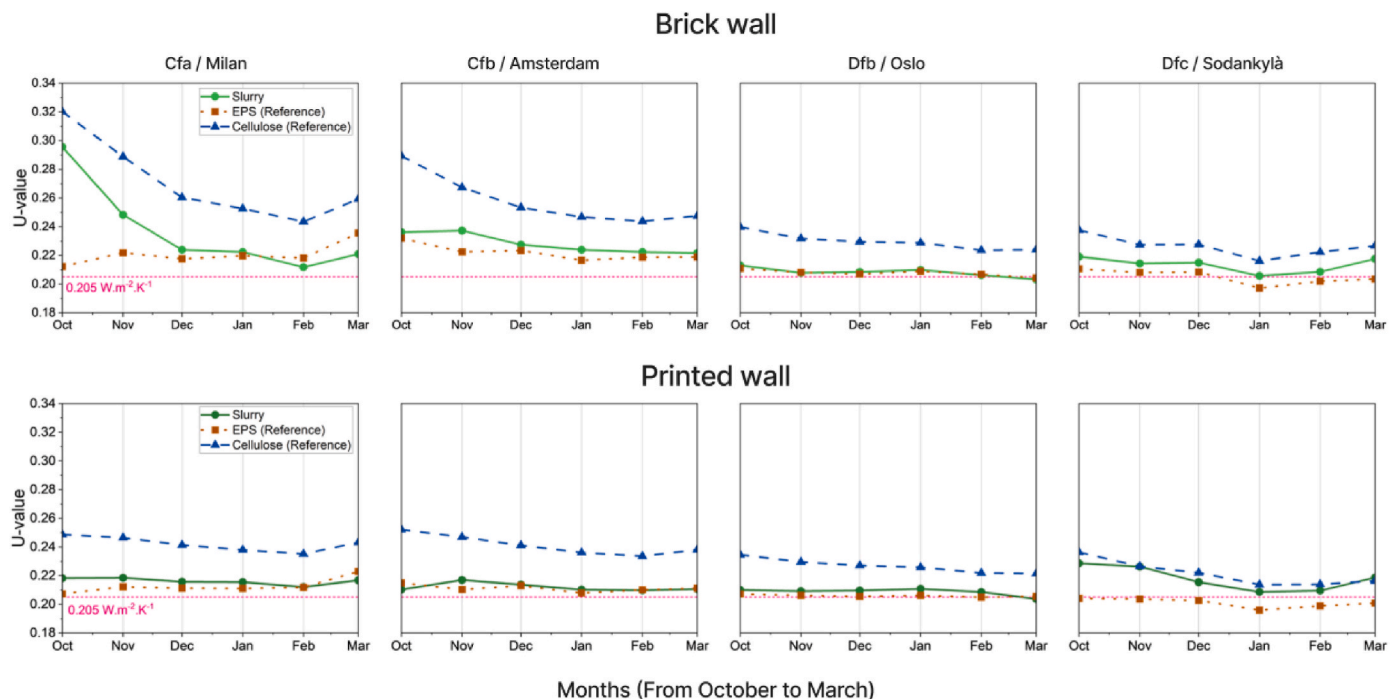


Fig. 15. U-values – Brick wall and printed walls.

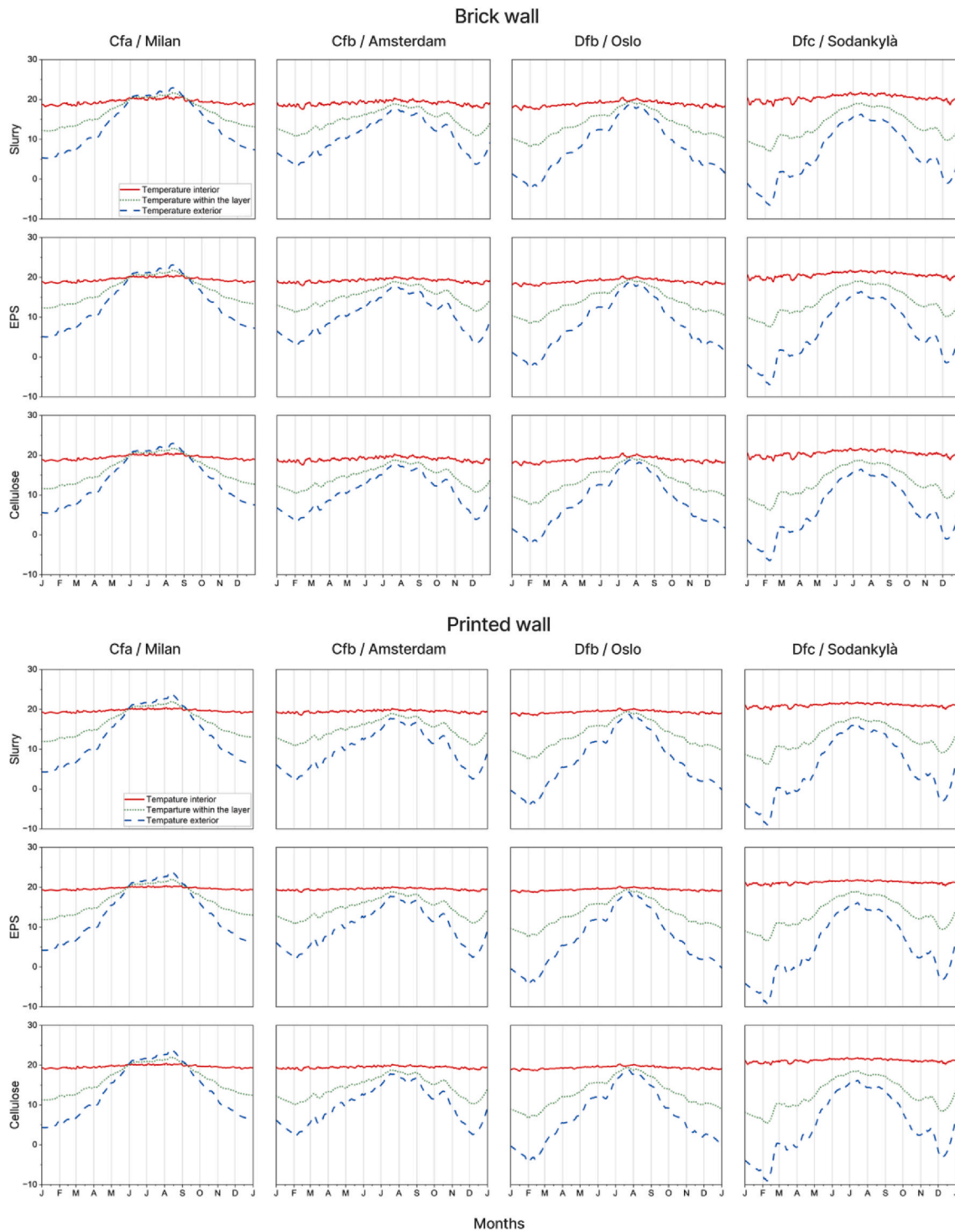


Fig. 16. Temperature comparison of the insulation layer, close to exterior wall, at the center of the layer, and close to interior wall – a) Brick Wall, b) Printed Wall.

development.

3.5. Mold growth assessment

Durability and mold growth are known thanks to a previous study (Pantaleo et al., 2025), which revealed a rapid and significant development of mold on the samples. This way mainly results in the presence of materials with high moisture-absorption capacity, such as glycerol and xanthan gum. This effect was further enhanced by the predominance of untreated bio-based materials in the mixture. Consequently,

printing the insulation material adjacent to a wet concrete layer implies prolonged exposure to moisture, which may further promote mold growth. Controlling mold development is therefore essential. Firstly, using WUFI-Bio, the mold growth indexes of the tested insulation layers are simulated and are displayed in Fig. 17.

On the brick wall, the majority of the mold indexes reached level 4 or above, corresponding to a visual coverage of more than 10% (WUFIb). Most indices reached these levels within the first year of simulation, indicating the ease with which mold can develop. Among the results, the developed slurry and the cellulose show similar averages, indicating that

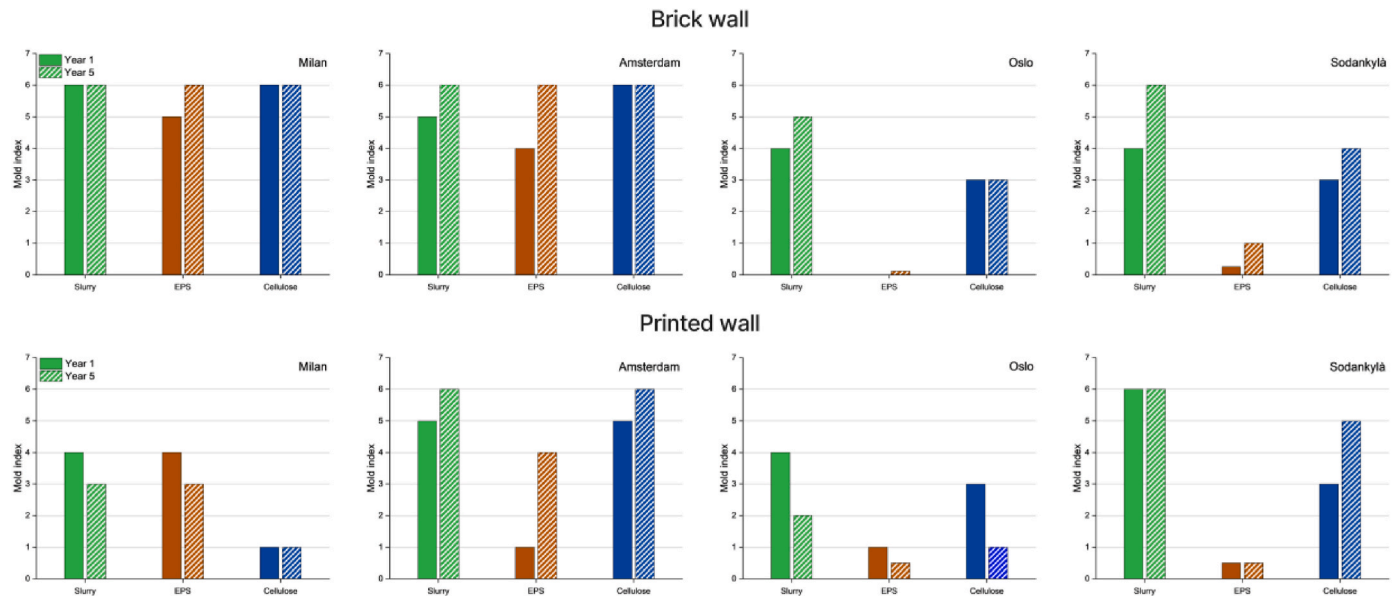


Fig. 17. Mold index under different climates, at Year 1 and Year 5 of simulation.

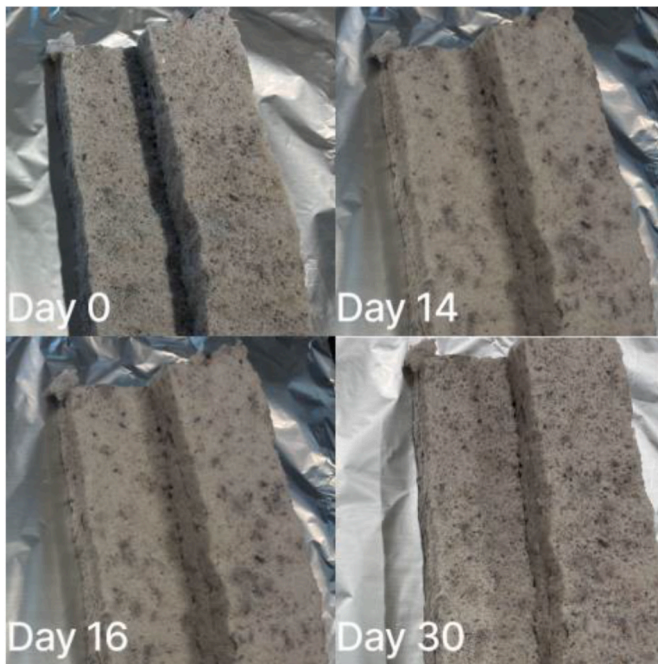


Fig. 18. Dried samples in conditioning climate chamber – Reference.

the silica aerogel has no significant effect on mold growth. Conversely, the EPS layer remains at least one level below, regardless of the climate. Yet, some important levels are reached, for example index 5 in Milan

(Appendix F). This observation highlights the effect of the climate on the mold development, which appears more influential than the substrate itself.

In the dry climates (Dfb and Dfc), almost no level-6 index is reached, even after 5 years of simulation. Moreover, for the non-bio-based layer, EPS, minimal or no growth can be observed, even after 5 years of simulation. This confirms the combined impact of relative humidity and temperature on mold growth. Now, looking at the printed wall, the mold indexes are more widely distributed. The most significant change is observed for bio-based materials: Cellulose drops from class 6 after one year in the brick wall, to class 1 after 5 years, in the printed wall. This decrease is seen for most of the simulation points. However, a high-humidity climate (Cfb/Amsterdam) still shows high mold indexes, whether the insulation is bio-based or non-bio-based. This is a consequence of the air layer next to the insulation layer for the printed wall. This layer, even though it exposes the insulation to variation in relative humidity, also prevents moisture accumulation and, therefore, adsorption on the surface layer. The opposite phenomenon occurs in the brick wall, where the wood-fiber board initially limits the influence of the relative humidity on the insulation yet prevents the renewal and removal of moisture from its surface.

Another way to address mold development is through the addition of an antifungal agent to the mix. Previous studies have examined different antifungal additives, but maintaining a bio-based approach remains crucial to preserve the material's low environmental footprint (Identification, 2025). Comparisons between dried samples are presented in Fig. 18, while untreated wet samples exhibited extensive mold growth (Fig. 20).

On the dried sample, non-treated, the mold is developing after 30 days on only a few spots on the surface. The effect of the antifungal agent

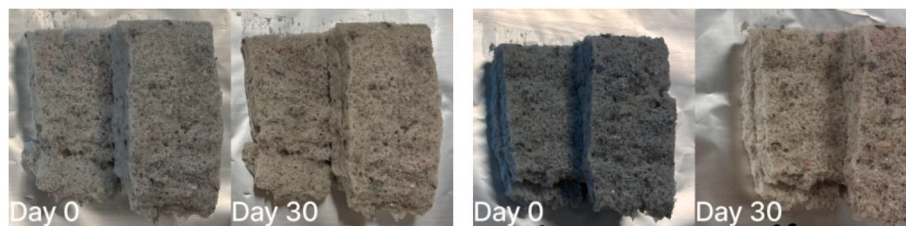


Fig. 19. Dried samples in conditioning climate chamber – Left: Antifungal_3, Right: Antifungal_6.



Fig. 20. Wet samples in conditioning climate chamber – Reference.

and, therefore, its need remains quite low here. Fig. 19 shows samples with antifungi added to the composition.

The effect of the antifungal agent is highlighted on dried samples, since no mold could be observed after 30 days. Yet, considering 3D-printing and on-site processing, the material remains wet for a certain period of time, and mold development could occur. Wet samples, with and without anti-fungi, are placed directly after processing in a climate chamber, at 30 °C and 80%RH, to assess the mold development. Fig. 20 shows the aspect of untreated wet samples.

The first visible signs of mold development appeared within 15 days. The fast development of molds confirms the results from the simulations, where most of the mold indexes for the slurry were at 4 or above, corresponding to important mold development, even within the first year of

simulation. These wet samples are the closest to on-site printing conditions, and addressing the mold development, especially on wet samples, is critical. Samples made with an antifungal agent, at two different weight concentrations were made, and the results of the conditioning can be seen in Fig. 21.

The antifungal agent appears to be efficient, as no sign of mold development could be observed on the surface of the samples, no matter the antifungal agent amount added. The main reason is the presence of polyphenols in the antifungal agent, which are known for their efficiency against mold (Davidova et al., 2024; Lin et al., 2025). The quantity needed could also be investigated, yet it appears that only a small amount should be sufficient. Finally, wet slurries were stored in sealed containers for 30 days to evaluate their preservation stability. As shown in Fig. 22, the antifungal additive significantly improved the storage behavior of the slurry, allowing it to remain stable and free of mold growth.

This could allow to prepare in advance the slurry, and only use it onsite for printing, promoting even more its use.

4. Conclusions

This study examines the development of a 3D-printable bio-based insulation. Key parameters related to printability were investigated, alongside comparative analyses using heat, air, and moisture simulations with a standardized brick wall. Additionally, the study evaluates mold development and proposes strategies to mitigate its occurrence. The findings reveal several key trends:

- The insulating material demonstrates significant potential for house printing. Its composition allows for straightforward modifications to meet specific requirements. Furthermore, it exhibits strong adhesion to other construction materials, such as concrete, thereby enhancing the speed and advantages of 3D-printed house construction by allowing potential double-nozzle printing.
- Printability has minimal impact on the insulation material's properties. Thermal conductivity increases by only 10%, with the lowest measured λ value at 26 mW/m·K. While the compression stress at 10% displacement is lower than that of the cast samples, it remains above the minimum requirement for insulating materials, averaging 23 kPa.

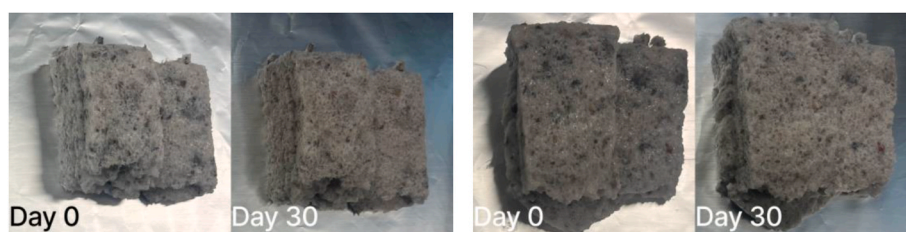


Fig. 21. Wet samples in conditioning climate chamber – Left: Antifungal_3, Right: Antifungal_6.

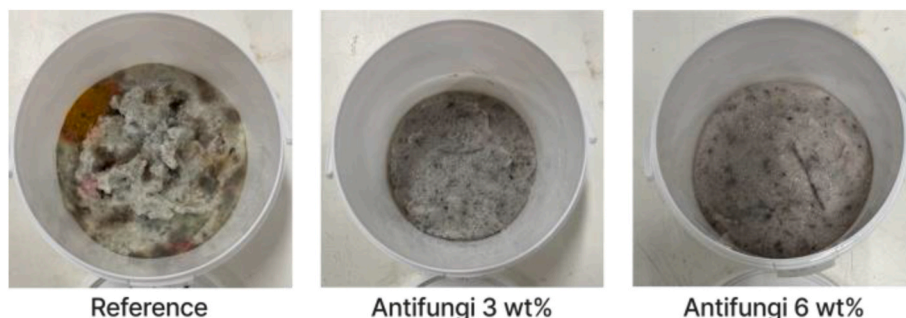


Fig. 22. Wet samples aspects at 30 days.

- Through heat, air, and moisture simulations, the new insulation material exhibits superior performance to bio-based material, though it remains slightly less efficient than petroleum-based alternatives. Its behavior under varying climatic conditions is similar to that of conventional materials. These results are obtained for a layer thickness two times smaller than the reference materials used.
- Mold growth, which readily occurs when the insulation dries adjacent to a wet concrete layer, can be effectively addressed using antifungal agents. Due to the slurry's composition and high water content, incorporating small quantities of antifungal agents proves both practical and efficient.

CRediT authorship contribution statement

Samuel Pantaleo: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Fenne Adriaanse:** Conceptualization, Investigation. **Florent Gauvin:** Supervision, Writing – review & editing. **H.J.H. Brouwers:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.dibe.2026.100980>.

Data availability

Data will be made available on request.

References

- Aldawi, F., Date, A., Alam, F., Khan, I., Alghamdi, M., 2013. Energy efficient residential house wall system. *Appl. Therm. Eng.* 58 (1–2), 400–410. <https://doi.org/10.1016/J.APPLTHERMALENG.2013.02.023>.
- Arash, M., Mohammad Abu Hasan, K., Golam, K., 2025. Assessing the environmental impact of building houses in remote areas: 3D printing vs. traditional construction techniques. *J. Build. Eng.* 102, 111968. <https://doi.org/10.1016/J.JOBE.2025.111968>.
- Bazli, M., Ashrafi, H., Rajabipour, A., Kutay, C., 2023. 3D printing for remote housing: benefits and challenges. *Autom. Construct.* 148, 104772. <https://doi.org/10.1016/J.AUTCON.2023.104772>.
- Bici, A., Yunitsyna, A., 2023. Analysis of 3D printing techniques for building construction: a review. *Construct. Robot.* 7 (2), 107–123. <https://doi.org/10.1007/S41693-023-00108-4>, 2023 7:2.
- Borzova, M., Schollbach, K., Gauvin, F., Brouwers, H.J.H., 2024. Sustainable ambient pressure-dried silica aerogel from waste glass. *Curr. Res. Green Sustain. Chem.* 9, 100425. <https://doi.org/10.1016/J.CRGSC.2024.100425>.
- Davidova, S., Galabov, A.S., Satchanska, G., Davidova, S., Galabov, A.S., Satchanska, G., 2024. Antibacterial, antifungal, antiviral activity, and mechanisms of action of plant polyphenols. *Microorganisms* 12 (12). <https://doi.org/10.3390/MICROORGANISMS12122502>, 2024, Vol. 12.
- de Rubeis, T., 2022. 3D-Printed blocks: thermal performance analysis and opportunities for insulating materials. *Sustainability* 14 (3), 1077. <https://doi.org/10.3390/SU14031077>, 2022, Vol. 14, Page 1077.
- Dutto, A., Zanini, M., Jeoffroy, E., Tervoort, E., Mhatre, S.A., Seibold, Z.B., Bechthold, M., Studart, A.R., 2023. 3D printing of hierarchical porous ceramics for thermal insulation and evaporative cooling. *Adv. Mater. Technol.* 8 (4). <https://doi.org/10.1002/ADMT.202201109>.
- Dweib, M.A., Hu, B., Shenton, H.W., Wool, R.P., 2006. Bio-based composite roof structure: manufacturing and processing issues. *Compos. Struct.* 74 (4), 379–388. <https://doi.org/10.1016/J.COMPSTRUCT.2005.04.018>.
- Dziura, P., Maroszek, M., Góra, M., Rudziewicz, M., Pławiecka, K., Hebda, M., 2023. Influence of the In-Fill pattern of the 3D printed building wall on its thermal insulation. *Materials* 16 (17), 5772. <https://doi.org/10.3390/MA16175772>, 2023, Vol. 16, Page 5772.
- Everett, B., Soto, J., Bakhshi, P., Pourmoghhtarian, A., 2022. Exploring 3D printing potentials for sustainable. *Resilient Afford. Hous.* 296–306. <https://doi.org/10.3311/cc2022-038>.
- Hossain, Md A., Zhumabekova, A., Paul, S.C., Kim, J.R., Hossain, Md A., Zhumabekova, A., Paul, S.C., Kim, J.R., 2020. A review of 3D printing in construction and its impact on the labor market. *Sustainability* 12 (20), 1–21. <https://doi.org/10.3390/SU12208492>, 2020, Vol. 12.
- Huang, Y., Fan, Y., Sun, L., Shen, X., Zhao, Y., Cao, Y., Wang, J., Wang, Z., 2025. Mechanism of heat transfer suppression and safety evaluation of high-performance aerogel insulation materials in the thermal runaway propagation of lithium-ion batteries. *Energy* 334 (2), 137684. <https://doi.org/10.1016/j.energy.2025.137684>.
- Identification, 2025. Quantification and mitigation of mold development. In: 4th ICBBM Proceedings.
- ISO 13788 Hygrothermal Performance of Building Components, 2013, p. 40.
- Khamidi, M.F., Glover, C., Farhan, S.A., Puad, N.H.A., Nuruddin, M.F., 2014. Effect of silica aerogel on the thermal of cement paste for the construction of concrete buildings in sustainable cities. *WIT Trans. Built Environ.* 137, 665–674. <https://doi.org/10.2495/HPSM140601>.
- Khan, S.A., Koç, M., Al-Ghamdi, S.G., 2021. Sustainability assessment, potentials and challenges of 3D printed concrete structures: a systematic review for built environmental applications. *J. Clean. Prod.* 303, 127027. <https://doi.org/10.1016/J.JCLEPRO.2021.127027>.
- Klaus KRUS Martin Breuer Ing Sedlbauer Klaus, S. K.; Martin, K. Mould Growth Prediction with A New Biohygrothermal Method and its Application in Practice.
- Koh, C.H., Gauvin, F., Schollbach, K., Brouwers, H.J.H., 2022. Investigation of material characteristics and hygrothermal performances of different bio-based insulation composites. *Constr. Build. Mater.* 346, 128440. <https://doi.org/10.1016/J.CONBUILDMAT.2022.128440>.
- Kromoser, B., Reichenbach, S., Hellmayr, R., Myna, R., Wimmer, R., 2022. Circular economy in wood construction – additive manufacturing of fully recyclable walls made from renewables: proof of concept and preliminary data. *Constr. Build. Mater.* 344, 128219. <https://doi.org/10.1016/J.CONBUILDMAT.2022.128219>.
- Lamy-Mendes, A., Pontinha, A.D.R., Alves, P., Santos, P., Durães, L., 2021. Progress in silica aerogel-containing materials for buildings' thermal insulation. *Constr. Build. Mater.* 286, 122815. <https://doi.org/10.1016/J.CONBUILDMAT.2021.122815>.
- Li, Z., Chen, Z., Duan, Y., Chen, J., Yao, S., Peng, L., Chen, W., Menshutina, N., Liu, M., 2025. A review of silica Aerogel based thermal insulation coatings: preparation, properties and applications. *Prog. Org. Coating* 208 (6), 109449. <https://doi.org/10.1016/j.porgcoat.2025.109449>.
- Lin, H., Yang, H., Yang, J., Wang, D., Shi, Z., Shi, C., 2025. Green synthesis of tea polyphenol grafted epoxypropyl polymer with enhanced mechanical and antifungal benefits for bamboo protection. *Chem. Eng. J.* 520, 165991. <https://doi.org/10.1016/J.CEJ.2025.165991>.
- Liu, R., Du, H., 2025. Optimizing thermal insulation through geometric design: comparative analysis of normal and lightweight 3D printed concrete Wall patterns. *Energy Build.* 348, 116437. <https://doi.org/10.1016/J.ENBUILD.2025.116437>.
- Long, W.J., Lin, C., Tao, J.L., Ye, T.H., Fang, Y., 2021. Printability and particle packing of 3D-Printable limestone calcined clay cement composites. *Constr. Build. Mater.* 282, 122647. <https://doi.org/10.1016/J.CONBUILDMAT.2021.122647>.
- Ma, G., A. R., Xie, P., Pan, Z., Wang, L., Hower, J.C., 2022. 3D-Printable aerogel-incorporated concrete: anisotropy influence on physical, mechanical, and thermal insulation properties. *Constr. Build. Mater.* 323, 126551. <https://doi.org/10.1016/J.CONBUILDMAT.2022.126551>.
- Moghayedi, A., Mahachi, J., Lediga, R., Mosiea, T., Phalafala, E., 2024. Revolutionizing affordable housing in Africa: a comprehensive technical and sustainability study of 3D-Printing technology. *Sustain. Cities Soc.* 105, 105329. <https://doi.org/10.1016/J.SCS.2024.105329>.
- Palazzo, A., 2025. How 3D printers for houses can reduce CO2 emissions. *Buildings* 15 (4). <https://doi.org/10.3390/buildings15040599>.
- Pantaleo, S., Adriaanse, F., Gauvin, F., Brouwers, H.J.H., 2025. Use of bio-waste for silica aerogel composites. *Dev. Built Environ.* 24, 100780. <https://doi.org/10.1016/J.DIBE.2025.100780>.
- Pantaleo, S., Gauvin, F., Schollbach, K., Brouwers, H.J.H., 2024. Development of latex/silica aerogel composites for thermal insulation applications. *Dev. Built Environ.* 20, 100576. <https://doi.org/10.1016/J.DIBE.2024.100576>.
- Rangel, C.M., Guimarães, A.S., Salet, T.A.M., Lucas, S.S., 2024. 3D printing lightweight mortars with Cork to improve thermal efficiency in buildings. *Constr. Build. Mater.* 425, 136008. <https://doi.org/10.1016/J.CONBUILDMAT.2024.136008>.
- SINTEF Community, 2020. Byggetaljer 523.231 skallmurvegger. In: Byggeforskserien. SINTEF.
- Sovetova, M., Calautit, J.K., 2024. Influence of printing parameters on the thermal properties of 3D-Printed construction structures. *Energy* 305, 132265. <https://doi.org/10.1016/J.ENERGY.2024.132265>.
- Tripathi, A., Nair, S.A.O., Neithalath, N., 2022. A comprehensive analysis of buildability of 3D-Printed concrete and the use of Bi-Linear stress-strain criterion-based failure curves towards their prediction. *Cem. Concr. Compos.* 128, 104424. <https://doi.org/10.1016/J.CEMCONCOMP.2022.104424>.
- United Nations Environment Programme, 2022. 2021 Global Status Report for Buildings and Construction: towards a zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi. www.globalabc.org, 2023-05-03.
- Wolfs, R., Bos, D., Salet, T., 2023. Lessons learned of project milestone: the first 3D printed concrete house in the Netherlands. *Mater. Today Proc.* <https://doi.org/10.1016/J.MATPR.2023.06.183>.
- Wolfs, R.J.M., Bos, F.P., Salet, T.A.M., 2018. Early age mechanical behaviour of 3D printed concrete: numerical modelling and experimental testing. *Cement Concr. Res.* 106, 103–116. <https://doi.org/10.1016/J.CEMCONRES.2018.02.001>.
- WUFI, 2025. WUFI Material Database.

WUFI, WUFI pro 7.1 online help, basics - moisture transport in building materials, Appendix 6.
WUFI, WUFI-Bio 4.0 Online Help.

Yao, S., Duan, Y., Chen, W., Chen, J., Zhang, H., Peng, L., Wu, X., Li, Z., 2026. Performance-driven design of aerogel-perlite cement mortars: particle packing optimization and building energy assessment. *J. Build. Eng.* 120, 115567. <https://doi.org/10.1016/j.jobee.2026.115567>.