

Innovative silica aerogel-based core sandwich panels

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ABSTRACT

Silica aerogel, despite its exceptional properties (low thermal conductivity, high porosity, and low density) still faces significant drawbacks, including high processing costs and poor structural integrity, which limit its widespread use. As a result, reinforcement is therefore essential. A promising approach involves using silica aerogel as the core layer in sandwich panels. These panels combine materials with complementary properties to mitigate individual weaknesses and unlock new applications. In this study, sandwich panels with silica aerogel cores were fabricated using external layers such as Oriented Strand Board (OSB), gypsum board, and expanded cork. The goal was to achieve low thermal conductivity while maintaining acceptable strength. The study also evaluated additional properties relevant to building applications, such as moisture sorption and mechanical resistance. Moreover, strengthening strategies were developed to enhance the core layer's performance. Various designs were tested to assess both mechanical and thermal insulation behavior. The results emphasized the need for structural reinforcement when maximizing the quantity of silica aerogel in the core layer. Among the tested materials, OSB panels offered the best structural properties, while cork panels delivered the best thermal insulation, achieving a thermal conductivity as low as $0.040 \text{ mW}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$. Additionally, the cork panels demonstrated interesting structural properties, as the skin being soft, the load is directly applied to the reinforcement rather than on the layer itself.

1. Introduction

The use of high-performance and efficient materials for thermal insulation remains the primary strategy for energy conservation of buildings. Such materials can help lowering greenhouse gases emissions and the operational energy of buildings. Ideally, these efficient materials are lightweight, feature low thermal conductivity, and are easy to process and install. Nowadays, thermal insulation is mostly fossil based. However, as seen in Fig. 1, many other alternatives exist, including as organic materials and emerging materials.

However, these materials are difficult to use as a stand alone and need supportive materials to achieve optimal efficiency. This necessity not only increase resource consumption but also adds to the time required for installation. Thus, developing materials able to combine the strength and stiffness needed for building materials with excellent thermal insulation capabilities is critical. In this context, sandwich panels have emerged as a compelling solution, offering a good balance of lightweight construction, thermal performance, and structural versatility.

A sandwich panel [2] consists of two outer layers (skins) that enclose a distinct material (core). This design aims to merge the

Abbreviation: EPS, Expanded Polystyrene; OSB, Oriented Strand Board; RH, Relative humidity; MTPS, Modified transient plane source; PLA, Polylactic acid; PET, Polyethylene Terephthalate; PVC, Polyvinyl Chloride; T_g , Glass transition temperature.

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properties of both components. The skins, usually thin and composed of stiff and strong materials such as metal [3] or cement-based materials [4,5], provide rigidity and protection. Meanwhile, the core material, often thicker, contributes to the panel's specific properties, primarily thermal or sound insulation. Typical core materials include low-density, ranging from foams [6] and honeycomb structures [7,8] to mineral wool [9]. This unique design gives sandwich panels a high strength-to-weight ratio, making them ideal for applications where both structural integrity and weight efficiency are crucial.

However, as shown in Table 1, one of the key drawbacks remains the difficulty of achieving low thermal conductivity while maintaining a thin profile and sufficient stiffness. Therefore, new materials must be explored to develop sandwich panels that meet regulatory standards for thermal insulation. For example, in the Netherlands, the Dutch Building Decree [14] establishes target values for thermal insulation, depending on whether it is a newly built house or only a refurbishment of an existing house.

Among thermally insulating materials, silica aerogel is a lightweight material gaining interest due to its superior thermal insulation capacity [15,16], being the lowest on the current market. Its lightweight nature ensures easy integration without compromising structural integrity, while its hydrophobic properties [17,18] helps mitigate moisture-related concerns, making it suitable for humid environment. Additionally, silica aerogel is stable when exposed to fire [19–21], further enhancing its appeal for building applications. To date, scientific literature on silica aerogel in sandwich panels has primarily focused on incorporating it into the external layers, often with cement. The goal is to reduce weight, and slight improvements in thermal conductivity are observed as a result of these combination. Thermal conductivity values of $0.076 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for a cement paste [22] or $0.22 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ for concrete layer [23] can be reached.

However, the values reached achieved so far are still too high to consider these panels efficient regarding thermal insulation, considering the extra insulation needed for the future. Thus, the development of panels, using silica aerogel as main material and designed toward insulation purpose, should be investigated. Yet, since most of the current silica aerogel production is currently produced in granular or powder form [24], it cannot be serve as a standalone core layer in sandwich panels and must be combined with a binder. Previous studies have explored its use with water-based latexes or plaster [25] as binding materials.

In this study, silica aerogel will be utilized as the primary material for the core layer of sandwich panels. To evaluate performance, conventional building materials such as Oriented Strand Board (OSB), gypsum board, expanded cork will be used as skin layers. This approach will allow for a comparison of feasibility, thermal insulation properties, and structural strength of the designed sandwich panel. Additionally, strengthening strategies [2] will be implemented to enhance the core layer's mechanical properties, either by the addition of chemical additives or physical reinforcement. The resulting mechanical performance of the sandwich panels will be measured, and any potential impact on the overall thermal conductivity will be assessed to ensure that the panels retain their thermal insulation efficiency.

2. Materials and methods

2.1. Materials

OSB and gypsum boards are purchased from BMN Bouwmaterialen, the Netherlands. Expanded cork boards (PSQ3) are purchased from ProSuber, the Netherlands. Picassian® AC-126 (40.0% solid content, water-based, styrene-acrylic copolymer emulsion) is kindly

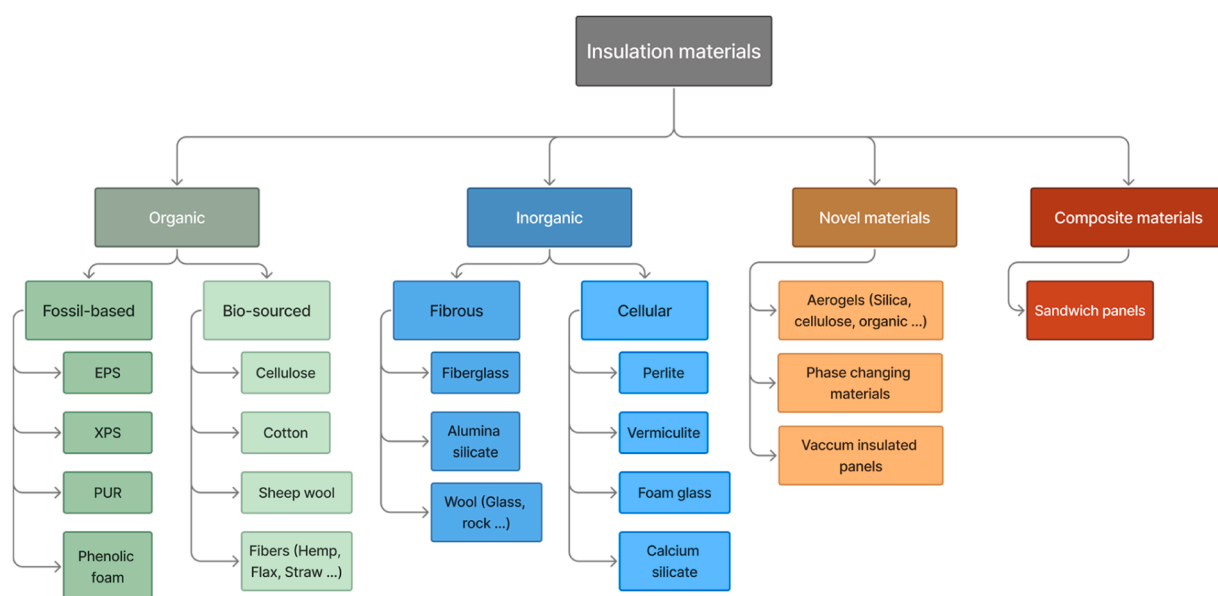


Fig. 1. Classification of material for thermal insulation – adaptation from [1].

Table 1
Example of sandwich panels.

Skin	Core	Thickness (m)	λ range (W.m ⁻¹ .K ⁻¹)	Ref.
Wood	EPS	0.035	0.070 – 0.077	[10]
Concrete	EPS	0.200	0.250 – 0.460	[11]
Wood sheet	Expanded cork	0.015 – 0.045	0.049 – 0.077	[12]
Autoclaved aerated concrete	Calcium silicate	0.030 – 0.100	0.125 – 0.287	[13]

provided by Stahl®, the Netherlands, and VINNAPAS® EAF-67 (58.0 – 62.0% solid content, water-based, vinyl acetate, ethylene, and acrylate emulsion) is kindly provided by Wacker Chemie, Germany. Silica aerogel granulates are from Cabot Corporation, USA (Silica Aerogel particles P100®, size from 0.1 to 4.0 mm). Dodecyltriethoxysilane (analytical grade) and absolute ethanol (analytical grade) are purchased from Sigma-Aldrich, Germany. 3D Printing filament made of Polylactic Acid (PLA) (Ultrafuse PLA) is purchased from BASF, Germany. Skin layers are cut using a bandsaw, and samples are molded to reach the desired dimensions.

2.2. Moisture sorption

Moisture uptakes of the samples are measured in several relative humidities (RH) conditions using saturated salt solutions, i.e., magnesium chloride hexahydrate MgCl₂·6H₂O for 33% RH, potassium carbonate K₂CO₃ for 43% RH, sodium chloride NaCl for 75% RH, and potassium chloride KCl for 85% RH. Before analysis, samples are dried overnight in an oven (Mettler universal oven UF260). For each RH, samples are left in the desiccator for at least 48 h before the first measurement. After that period, measurements are done every 24 h, over a week. The water uptake is computed by:

$$\text{Water Uptake} = \frac{m_x - m_0}{m_0} * 100 \quad (1)$$

Where m_x stands for the mass at various times, and m_0 stands for the initial mass. Weight measurements are taken at room temperature (20 ± 2 °C).

2.3. Thermal properties

Thermal conductivity measurements were carried out using different techniques. For the external layers, the modified transient plane source (MTPS) method was employed using a thermal sensor (AP Isomet model 2104). For materials with lower thermal conductivities, the transient plane source method (Hot Disk Thermal Constants Analyzer) was employed. This method also provided the specific heat capacity value. Prior to the measurements, the device was calibrated using an EPS reference sample provided by the manufacturer, with a declared thermal conductivity of 25.3 mW.m⁻¹.K⁻¹. Measurements were performed at room temperature (20 ± 2 °C). The thermal conductivity of sandwich panels was measured using a heat flow meter device (ThermTest HFM 100), at several temperatures (30 °C, 20 °C, 10 °C and 0 °C). Before any measurement, samples were either dried overnight at 40 °C in an oven (Mettler universal oven UF260) or conditioned in desiccators at various RH, as previously described.

2.4. Mechanical properties

Three-points bending tests were performed on all the materials separately as well as on the sandwich panels. The tests were performed using an Instron® 5900 Series universal testing machine, equipped with a 30 kN load cell and operated at a crosshead speed of 1 mm/min. A span length of 80 mm was applied, in accordance with ASTM C203–05A. At least five samples were tested for each condition.

2.5. Samples design

2.5.1. Skins choice

The materials selected for the outer layers were chosen to represent a broad spectrum of conventional building material. This includes one inorganic material with gypsum boards, which account for an annual production of ~ 11000 M m²/y [26], and two bio-based materials, with OSB as a widely used conventional material (40 M m³/y [27]) and expanded cork as an emerging material (production of 200 tons/y [28]).

2.5.2. Sample dimensions

Dimensions of the samples are determined using the Dutch Building Decree (Bouwbesluit 2012 [14]), providing different thermal resistance per unit area for new buildings (R_{new}) as well as renovation (R_{renov}) (Table 2).

Thermal resistance R (m².K.W⁻¹) of a material is defined as:

$$R = e / \lambda \quad (2)$$

With λ = thermal conductivity of the material ($\text{W.m}^{-1}.\text{K}^{-1}$) and e = thickness of the layer (m).

Applied to sandwich panels, it results in the sum of the consecutive layers:

$$R(\text{sandwich}) = \sum R(\text{layers}) \quad (3)$$

For the design of the panels, thermal conductivities of the outer layers are obtained from ISO 10456:2007 [29], and the thicknesses are measured using a caliper. Both values are used to determine the specific thermal resistance values. This article will explore the case of facade renovation, therefore, $R = 1.4 \text{ m}^2.\text{K.W}^{-1}$ will be used. Table 3 summarizes the sample composition and the targeted R-values.

Therefore, the thickness of the core layer made of silica aerogel composite is calculated as follows:

$$R_c(\text{sandwich}) = R_c(\text{skin}) + R_c(\text{core}) + R_c(\text{skin}) \quad (4)$$

$$R_c(\text{core}) = R_c(\text{sandwich}) - 2 R_c(\text{skin}) \quad (5)$$

$$e_{\text{core}} = [R_c(\text{sandwich}) - 2 R_c(\text{skin})] * \lambda_{\text{core}} \quad (6)$$

Every thicknesses are summarized in Table 4.

The target thermal conductivity value of $0.025 \text{ W.m}^{-1}.\text{K}^{-1}$ for the core layer composed of silica aerogel is chosen, based on a previous study [30]. Silica aerogel granulates are mixed with the latex (Picassian® AC-126) at a different latex to silica aerogel ratios (v/v) in a container using a spatula for around five minutes, until a viscous slurry is obtained. The sandwich panel samples are assembled with the help of a 3D-printed mold. During the fabrication process, a thin layer of adhesive (VINNAPAS® EAF-67) is applied to the skin layer to enhance the bonding between the core and the skin layer. This additional layer became necessary after initial tests revealed that the latex used in the core layer does not sufficiently adhere to the external layer, a common step for sandwich panels [2, 31]. The process is summarized in Fig. 2.

The height of the molds is adjusted according to the size of the core layer (e_{core}) shown in Table 4 and the material used for the skin layers. The slurry is compacted with the help of the mold. Samples are unmolded while still being wet, and placed in an oven (40°C) for a week, to ensure that all the latex is dried. As a result of the core layer's mix design, it is treated as a whole and is considered homogeneous for the rest of the study.

2.6. Strengthening strategies

Different strengthening strategies are explored to enhance the mechanical performances of the sandwich panels. Since the selected skin layers are standard materials, modifications will focus solely on the core layer. The first approach involves chemically modifying the core layer composition, while the second strategy consists of the addition of a reinforcement positioned between the skin layers.

2.6.1. Chemical addition

Building on a previous study [30], the addition of silane (Dodecyltriethoxysilane) was found to enhance the cohesion between latex and silica aerogel. This enhancement results in significantly better composite cohesion during bending tests as well as a modest improvement in mechanical response. This approach is applied to reinforce the core layer of sandwich panels. Sandwich panels with OSB as the external layer are tested using this reinforced core layer. Two different silane ratios are evaluated: a "low ratio" of 1:42 (v/v) and a "high ratio" of 1:17 (v/v) silica aerogel to silane.

2.6.2. 3D printed reinforcement

Reinforcements are designed as a proven strategy to strengthen sandwich panels. The brace designs are inspired by honeycomb structures [7,32], specifically square and hexagonal patterns. These designs are intentionally simplified for two main reasons: First, the samples are filled manually, the core layer needs to allow for easy uniform distribution, thus only vertical planar shapes are considered. Second, the goal is to evaluate the influence of varying core materials on thermal conductivity and to investigate potential thermal bridging that may occur caused by the reinforcement layer connecting to the skins. three different reinforcement shapes are made. Details are presented in Fig. 3.

Polymer 3D printing is chosen for its capacity to produce complex geometries with high precision. Polylactic acid (PLA) is selected as the printing material due to its widespread availability and lower environmental impact compared to fossil-based polymers, such as Polyethylene Terephthalate (PET) or Polyvinyl Chloride (PVC), which are commonly used in 3D printing [7,32]. It also has great hydrophobicity [33], low water absorption [33] and medium fire behavior [34].

Table 2

Thermal diffusivity values for building construction, from the Dutch Building Decree [14].

Construction	$R_{\text{new}} (\text{m}^2.\text{K.W}^{-1})$	$R_{\text{renov}} (\text{m}^2.\text{K.W}^{-1})$
Façade	4.7	1.4
Roof	6.3	2.1
Floor	3.7	2.6

Table 3

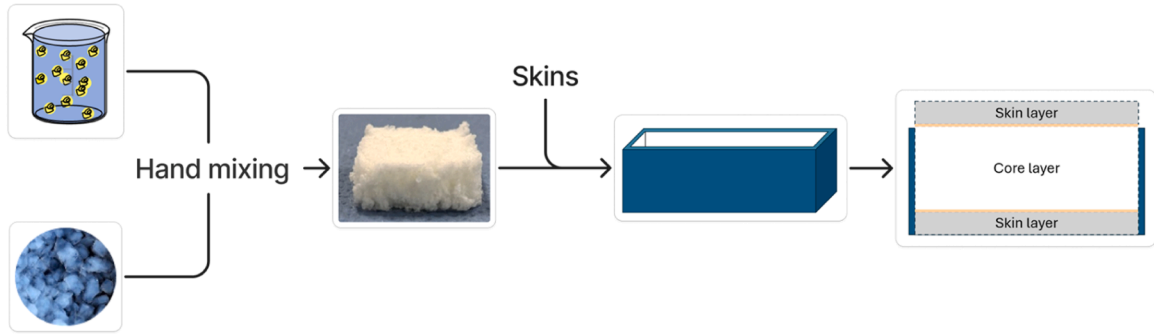
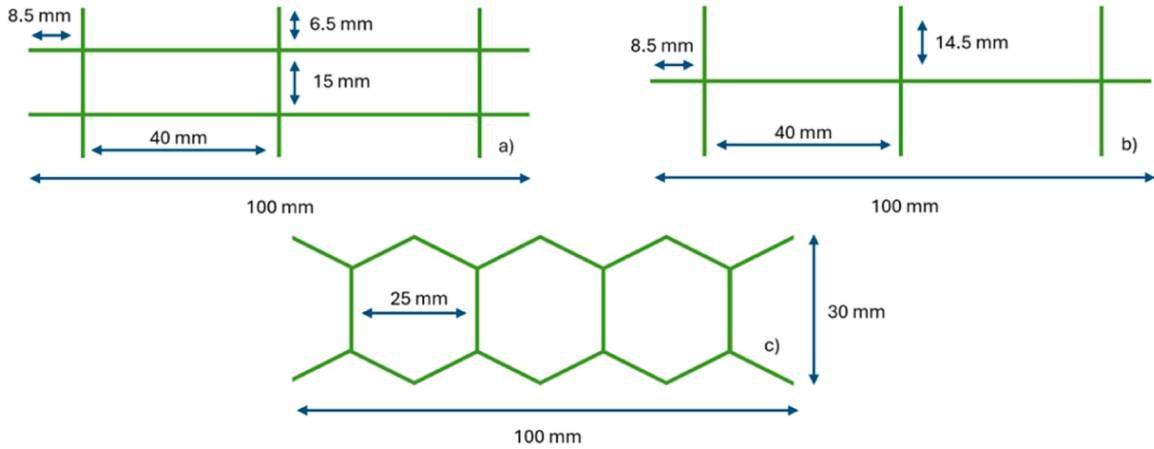
Characteristic values for skin layers of sandwich panels.

Material	e_{skin} (m)	λ_{skin} ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	R ($\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}$)	$2 R$ ($\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}$)	R core target ($\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}$)
OSB	0.009	0.130 [29]	0.069	0.138	1.262
Gyp. Board	0.012	0.210 [29]	0.061	0.121	1.279
Exp. Cork	0.010	0.050 [29]	0.200	0.400	1.000

Table 4

Core layer thickness for the different sandwich panels.

Material	λ_{core} ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	R targeted ($\text{m}^2\cdot\text{K}\cdot\text{W}^{-1}$)	e_{core} (m)	e_{core} (mm)
OSB	0.025	1.254	0.036	31.5
Gyp. Board	0.025	1.278	0.031	31.2
Exp. Cork	0.025	1.000	0.025	25.0

**Fig. 2.** Sandwich panels design.**Fig. 3.** 3D-printed reinforcement shapes: a) R1 - b) R2 - c) R3.

2.7. Mechanical simulation

Mechanical simulations are performed using COMSOL software. The 3D models are created in SOLIDWORKS software and then imported into COMSOL. For the simulation, the "Solid Mechanics" physics module is utilized to conduct a "Time Dependent" study. Two boundary conditions are applied to the model: an "Edge load" is positioned at the center of the top layer, and "Fixed constraints" are imposed on the bottom layer. The material parameters used in the simulations are detailed in Table 5.

The mechanical simulation, being time dependent, follows:

$$\rho \frac{\delta^2 u}{\delta t^2} = \nabla \cdot S + F_v \quad (7)$$

where ρ is the density (kg.m^{-3}), $\frac{\partial^2 u}{\partial t^2}$ the acceleration, $\nabla.S$ the stress tensor and F_V the external volume force.

Thermal simulation

Thermal simulations are performed using COMSOL software. The 3D models are created in SOLIDWORKS software and then imported into COMSOL. The simulations employ the "Heat Transfer in Solids" physics module within a "Time Dependent" study. For each simulation, measurements are recorded at six points: three within the core layer, positioned at the center of the layer at close, medium and far distances from the heat source, and three within the reinforcement at similar positions, as displayed in Fig. 4. For samples without reinforcement, only three points are measured.

The thermal simulation, being time dependent, follows:

$$\rho.C_p.u.\nabla T + \nabla.q = Q + Q_{red} \quad (8)$$

Where, for the heat convection contribution factor, ρ is the density (kg.m^{-3}), C_p the heat capacity, u the fluid velocity vector, and ∇T the temperature gradient. The heat conduction contribution is composed of q the heat flux density vector, associated to Fourier's law.

The model boundaries are defined as follows: a "Heat Flux" condition is applied to both the top and bottom surfaces, while a "Symmetry" condition is imposed on all sides of the model. Two distinct heating rates are simulated, with the corresponding parameters summarized in Table 6.

Simulations are conducted separately for each skin material. For each skin type, three distinct reinforcement configurations are evaluated, in addition to a reference simulation using only the core layer. The properties of each configuration are detailed in Table 7.

3. Results and discussions

3.1. Layer characterizations

3.1.1. External layers

The skin layer materials are tested under various humidity conditions to assess their response to relative humidity. "Dry" sample refers to specimens that were placed in an oven overnight after exposure to the highest relative humidity. This process evaluates both the weight change and the material's capacity to release absorbed moisture. For each sample, once the weight stabilizes, thermal conductivity is measured. All results are presented in Fig. 5.

As expected, bio-based materials exhibit greater sensitivity to moisture absorption. For instance, the moisture sorption of OSB reaches up to 14%, whereas expanded cork, known for its low absorption, remains below 5%. In contrast, gypsum board shows minimal weight increase, never exceeding 2%. Despite these differences, all materials demonstrate the ability to release absorbed moisture and return to their initial weight. Additionally, the thermal conductivity of the skin materials appears largely unaffected by exposure to high humidity levels. The results are summarized in Table 8. The measured thermal conductivities align with the apparent density of the materials, where lower density corresponds to lower thermal conductivity.

External layers are tested under three-points bending tests. The resulting stress-strain curves are displayed in Fig. 6, and values are detailed in Table 9. OSB and gypsum board showcase greater strength compared to expanded cork, with a flexural strength of 10.40 and 2.45 MPa respectively, but are quite brittle and show premature failure. In contrast, the expanded cork demonstrate greater ductility, due to its low flexural modulus (4.05 MPa) and does not break at all.

3.1.2. Core layer

Different ratios latex to silica aerogel (v/v) were made to identify the one corresponding to the targeted λ , and the results are displayed in Fig. 7.

The tested ratios started at 1:5 (v/v), as ratios below this threshold resulted in samples lacking the necessary viscosity for effective processing and molding. Oppositely, ratios above 1:10 (v/v) led to excessively viscous slurries, resulting in an inhomogeneous blends that became overly crumbly after drying due to the insufficient amount of binder. All the tested ratios ended up close to the design value ($\lambda = 0.025 \text{ W.m}^{-1}.\text{K}^{-1}$), and ratios of 1:9 (v/v) or 1:10 (v/v) latex to silica aerogel achieved thermal conductivity equal to or lower than the designed. Within this range, the slurry retains sufficient strength to form a layer that can be handled, remains stable, and is processable. Therefore, a ratio of 1:10 (v/v) latex to silica aerogel was selected for the remainder of the study. For the sandwich panel structure, moisture-related measurements are evaluated layer by layer. So, moisture absorption and thermal conductivity are measured for the core layer as well. The results are presented in Fig. 8.

The core layer exhibits a maximum moisture uptake of only 1% by weight. This absorbed moisture is also easily released, allowing

Table 5
Parameters for three-points bending simulation.

Material	Density (kg.m^{-3})	Poisson's ratio	Young's Modulus (MPa)
Core layer	195	0.3	0.70
OSB	1 189	0.3	87.17
Gyp. Board	651	0.3	109.59
Exp. Cork	166.9	0.3	4.05
PLA	1189	0.3	123.04

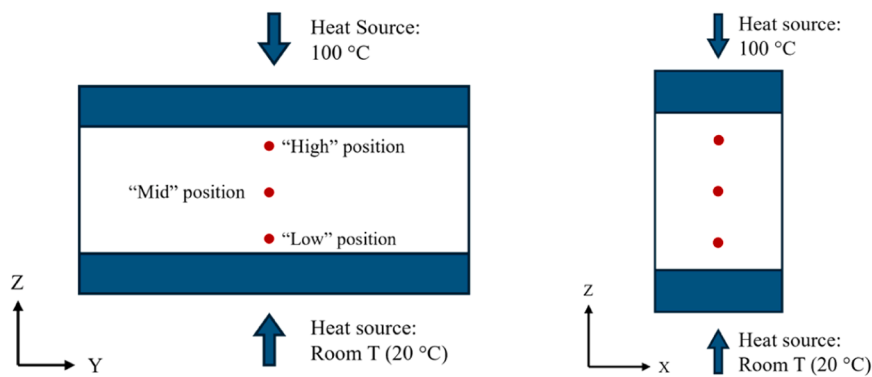


Fig. 4. Position of measurement points for thermal simulation.

Table 6
Summary of boundary and initials conditions.

Test 100–10	
Heat transfer coefficient position “high” ($\text{W.m}^{-2}.\text{K}^{-1}$)	100
Temperature position “high” ($^{\circ}\text{C}$)	100
Heat transfer coefficient position “low” ($\text{W.m}^{-2}.\text{K}^{-1}$)	10
Temperature position “low” ($^{\circ}\text{C}$)	20
Test 10–10	
Heat transfer coefficient position “high” ($\text{W.m}^{-2}.\text{K}^{-1}$)	10
Temperature position “high” ($^{\circ}\text{C}$)	100
Heat transfer coefficient position “low” ($\text{W.m}^{-2}.\text{K}^{-1}$)	10
Temperature position “low” ($^{\circ}\text{C}$)	20
Initial Temp. ($^{\circ}\text{C}$)	
Temperature in materials ($^{\circ}\text{C}$)	30

Table 7
Materials properties for thermal simulation.

	λ ($\text{W.m}^{-1}.\text{K}^{-1}$)	C_p ($\text{J.kg}^{-1}.\text{K}^{-1}$)	ρ_{bulk} (kg.m^{-3})
OSB	0.11	1421.03	471.26
Gyp. Board	0.17	1652.92	651.37
Exp. Cork	0.05	1485.65	166.93
Si. Aerogel	0.025	1229.6	195.19
PLA	0.11	797.06	1189.37

the core layer to return to its initial weight. Although thermal conductivity remains low overall, it is significantly affected even by small amounts of moisture, with the biggest difference observed being almost of 50%, from $0.022 \text{ W.m}^{-1}.\text{K}^{-1}$ to nearly $0.030 \text{ W.m}^{-1}.\text{K}^{-1}$.

3.2. Sandwich panels characterization

3.2.1. Thermal conductivity

The thermal conductivity of the sandwich panels is measured across a temperature range of 0°C to 30°C (mean temperature) to evaluate their behavior in typical building conditions. Measurements are made on all the components of the sandwich panels: core, skins, and sandwich panels as whole. The results are displayed in Fig. 9.

First, the skins show only minor sensitivity to temperature variation. Between 10°C and 30°C , a maximum increase of $0.010 \text{ W.m}^{-1}.\text{K}^{-1}$ is observed for the OSB, and barely $0.005 \text{ W.m}^{-1}.\text{K}^{-1}$ of the expanded cork. Secondly, the core layer remains unaffected by the temperature, maintaining a constant thermal conductivity of $0.024 \text{ W.m}^{-1}.\text{K}^{-1}$. Now considering the sandwich panels, the addition of the core layer leads to a decrease of material's thermal conductivity compared to skin layers alone, with both samples achieving values close to $0.100 \text{ W.m}^{-1}.\text{K}^{-1}$. The expanded cork sandwich panels are the least affected ones, as the skin itself has a thermal conductivity of $0.040 \text{ W.m}^{-1}.\text{K}^{-1}$. Additionally, the sandwich panels exhibit the same temperature-dependent behavior: thermal conductivity follows the rising measurement temperature.

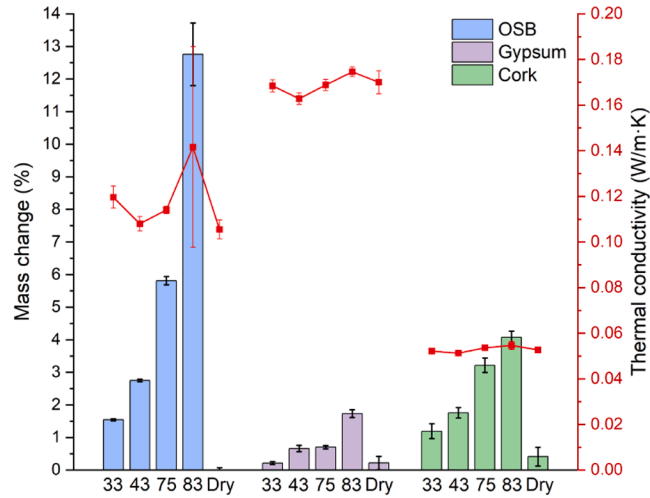


Fig. 5. Mass variation and thermal conductivity after relative humidity exposure.

Table 8

Density and thermal conductivity of the tested external layers.

Material	ρ (kg.m ⁻³)	λ_{avg} (W.m ⁻¹ .K ⁻¹)	λ_{min} (W.m ⁻¹ .K ⁻¹)	λ_{max} (W.m ⁻¹ .K ⁻¹)
OSB	580	0.12	0.108	0.122
Gyp. Board	690	0.17	0.160	0.175
Exp. Cork	150	0.05	0.055	0.055

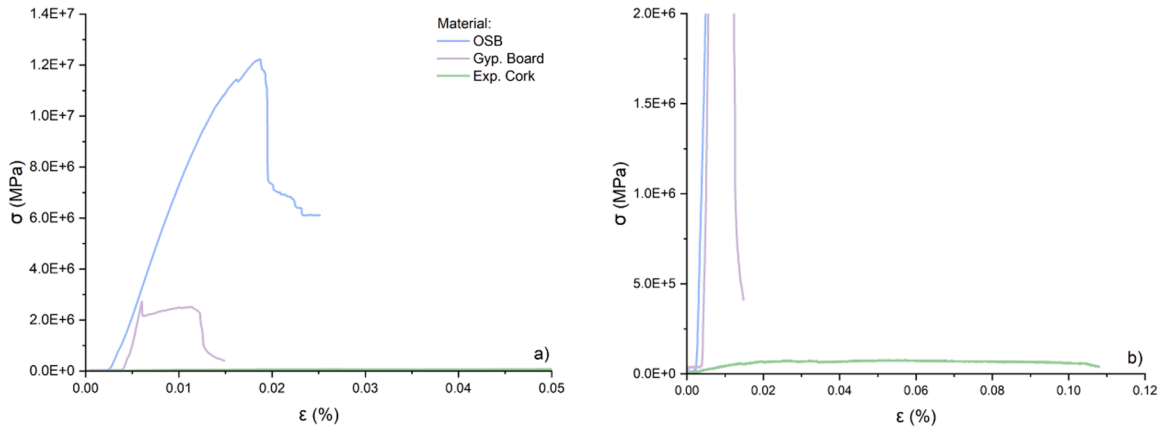


Fig. 6. Strain-stress curves for individual external layers, a) Full curves, b) Zoom-in.

Table 9

3 points bending on external layers.

Material	Flexural Modulus (MPa)	Flexural strength (MPa)	Strain at break (%)
OSB	878.72 ± 158.34	10.40 ± 1.80	0.0180 ± 0.0030
Gyp. Board	1095.93 ± 192.67	2.45 ± 0.15	0.0063 ± 0.0003
Exp. Cork	4.05 ± 0.59	0.15 ± 0.07	0.0064 ± 0.0328

3.2.2. Three-points bending

To assess the strength of the different sandwich panels, three-points bending tests were conducted. The resulting stress-strain curves, along with a representative image of a tested sample, are presented in Fig. 10.

The three-points bending tests conducted on the sandwich panels with OSB and gypsum board revealed no plastic deformation, with premature failure observed, before 0.2% deformation. All the values of the three-points bending are detailed in Table 10. These

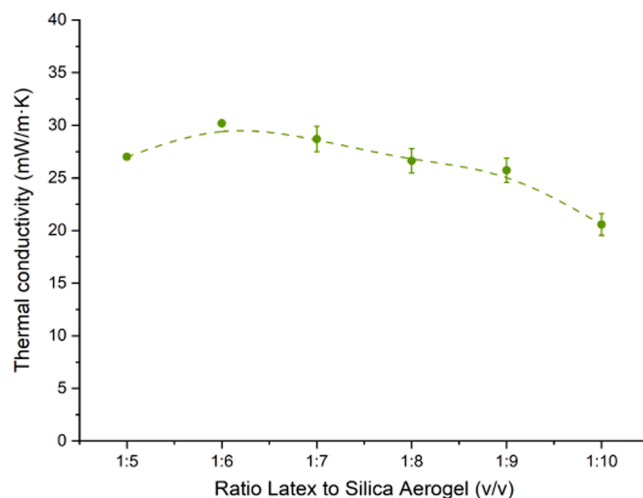


Fig. 7. Thermal conductivity for different ratios of latex/silica aerogel.

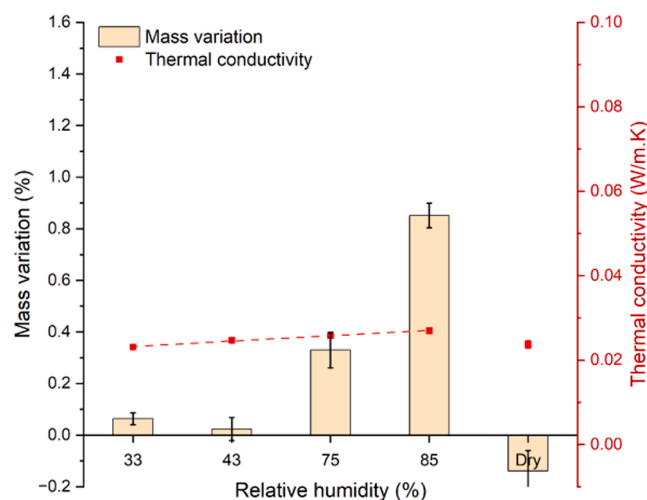


Fig. 8. Mass variation and thermal conductivity after relative humidity exposure - Silica aerogel / Latex.

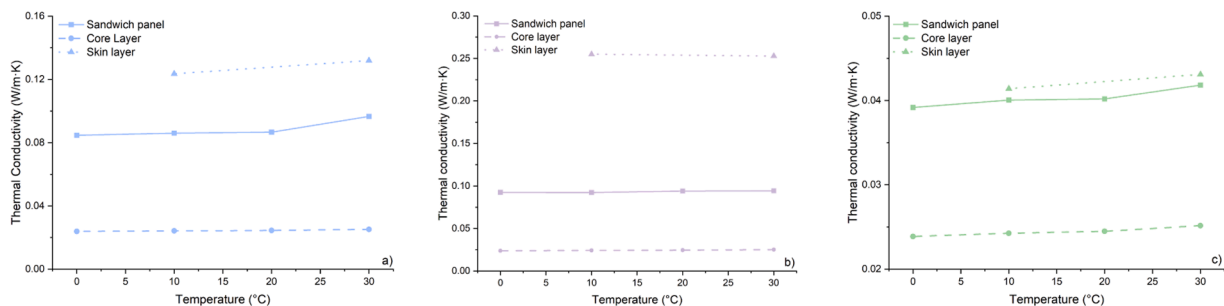


Fig. 9. Thermal conductivities of sandwich panels: a) OSB, b) Gypsum board, c) Expanded cork.

breaks occurred in the core layer, as seen in Fig. 10 – c). This behavior is attributed to the core's limited deformability, which is even more highlighted when compared to the stiffness of the skins. Cracks quickly happen in the core layer and propagate fast through it, leading to the failure of the samples. The brittleness of the core layer is a result of its composition: the latex binder has a glass transition temperature (T_g) above room temperature (55°C), and the composite does not contain reinforcements, e.g., fibers. Additionally, silica

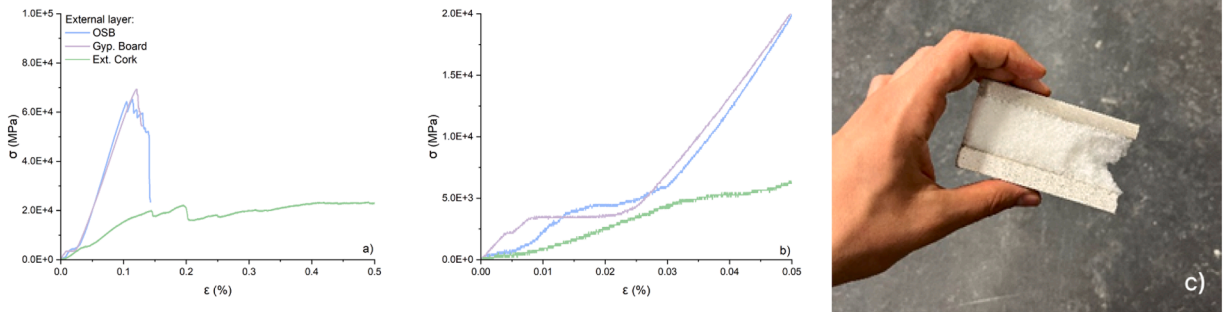


Fig. 10. Strain-stress curves for the sandwich panels, with different external layers, a) Full curves, b) Zoom in, c) Gypsum board sandwich panel after break.

aerogel is inherently brittle, further contributing to the core's fragility.

In contrast, the expanded cork panels demonstrate a markedly lower flexural modulus compared to the other two skin materials. The measured flexural modulus for the cork panel (0.17 MPa) is significantly lower than that of the OSB (0.66 MPa) and gypsum board (0.92 MPa), which explains the absence of fractures. The low stiffness allows a deformation of the external and core layers at the same time, and the samples are able to remain intact and able to handle the deformation to some extent. However, distinguishing between elastic and plastic deformation remains challenging for these samples. To better understand the force distribution during testing, bending simulations were performed, with results presented in Fig. 11.

The simulations reveal the contribution of each panel component during the bending test. Although the maximum applied load is similar across the different skin materials, it remains low, around 0.01 kPa. Only the skin layers bear these loads, indicating that the core layer's contribution to overall strength is minimal. These simulations showcased the observation made on the tested sample, as seen in Fig. 10. A strengthening strategy is needed to address this limitation.

3.3. Strengthening strategies

The first objective of these panels is not structural purposes, yet it appears with the first mechanical tests that the core is so fragile that it prevents an usage of these panels. A reinforcement of the core is therefore needed, and two strategies will be investigated to balance this major drawback.

3.3.1. Chemical addition

The first strengthening strategy relies on the addition of a chemical to the core layer to increase the cohesion of the core layer. To assess these modifications, three-points bending tests were conducted, with results presented in Fig. 12.

The addition of silane to the core layer effectively prevents premature failure during flexural testing. This improvement is observed for both silane ratios, but it is particularly pronounced in samples containing higher silane concentration. The corresponding three-points bending test values are detailed in Table 11.

Like the initial sandwich panels, those with a low silane content show comparable flexural modulus (~ 0.9 MPa) and similar flexural strengths (0.08 MPa). Although failure occurs later compared to the initial panels ($\epsilon = 0.05\%$), it still happens at a relatively low strain ($\epsilon = 0.13\%$). In contrast, a high ratio of silane significantly increases flexural strength (0.70 MPa), as shown in Fig. 12 - c). Samples with high silane content deform further before breaking ($\epsilon = 0.94\%$). However, the flexural modulus remains similar across all conditions, indicating that the silane primarily enhances core layer cohesion rather than its intrinsic strength. Thus, the mechanical strength remains low, and an alternative strengthening strategy is required to effectively increase the strength of the core layer, and therefore of the sandwich panel.

3.3.2. 3D-printed reinforcement

For the second strengthening strategy, various 3D-printed shapes are integrated to the core layer, connecting both skins. To evaluate the effectiveness of this strategy, three-points bending tests were performed, and the stress-strain curves are presented in Fig. 13.

First, the addition of reinforcement leads to noticeable increases in both stress and strain before failure. Interestingly, the shape of

Table 10

Three-points bending results of sandwich panels.

Outer layer	Flexural Modulus (MPa)	Flexural Strength (MPa)	Strain at break (%)
OSB	0.92 ± 0.03	0.08 ± 0.01	0.105 ± 0.011
Gyp. Board	0.66 ± 0.04	0.06 ± 0.10	0.117 ± 0.007
Exp. Cork	0.17 ± 0.02	0.02 ± 0.04	0.292 ± 0.095

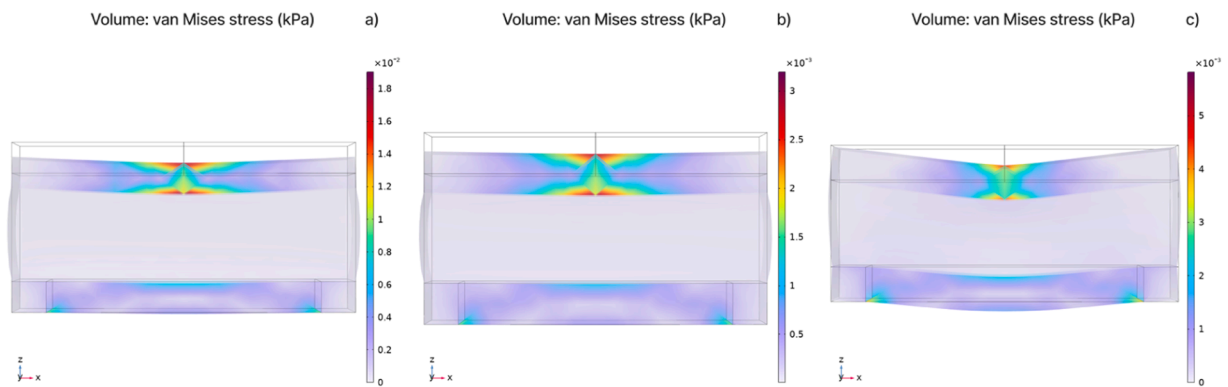


Fig. 11. Three-points bending simulations, before the break - a) OSB, b). Gypsum board, c) Expanded cork.

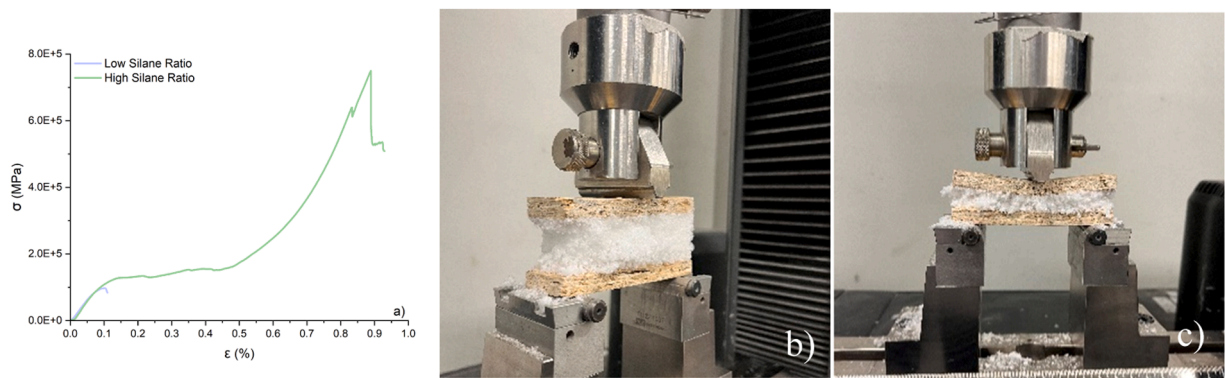


Fig. 12. Three-points bending tests - a) Low ratio Silane, b) High ratio Silane.

Table 11

Comparison of three-points bending values - External layer: OSB.

Sample	Flexural Modulus (MPa)	Flexural strength (MPa)	Strain at break (%)
No Silane	0.92 ± 0.03	0.08 ± 0.01	0.05 ± 0.01
Low Silane ratio	0.89 ± 0.15	0.08 ± 0.02	0.13 ± 0.02
High Silane ratio	0.86 ± 0.20	0.70 ± 0.08	0.94 ± 0.06

the reinforcement does not significantly influence these improvements. As observed in the unreinforced panels, those made with expanded cork do not fracture under testing. These trends are reflected in the test results, which are summarized in Table 12. For the stiffer skin layers (OSB and gypsum board), the increase in flexural modulus is substantial. The OSB panels with reinforcement R1 exhibit a maximum flexural modulus of 16.83 MPa, compared to 0.92 MPa for the unreinforced panels. The other reinforcement shapes yield values close to those of R1. A similar trend is observed for gypsum board panels, with flexural modulus increasing from 0.66 MPa to 8.40 MPa. Flexural strength follows the same pattern. The most significant improvement is seen in OSB panels with reinforcement R1, where flexural strength reaches 3.35 MPa (compared to 0.08 MPa for unreinforced panels). Gypsum board panels also show an increase, though more modest (maximum of 0.75 MPa for R1), indicating earlier failure. In contrast, expanded cork samples demonstrate smaller increases in both flexural modulus and strength. The highest recorded values are 0.85 MPa (versus 0.54 MPa for unreinforced samples) for flexural modulus, and 0.51 MPa (versus 0.25 MPa for unreinforced samples) for flexural strength.

To gain deeper insight into these mechanical values and the load distribution within the samples, mechanical simulations were performed. The results are visualized in Fig. 14 and compared with actual samples following three-points bending tests.

For the stiff skin layers (OSB and gypsum board), distinct cracks are visible within the layers after testing. The simulations reveal maximum applied loads of approximately 100 kPa for OSB panels and 10 kPa for gypsum board panels (Table 13). In contrast, the reinforcements themselves withstand loads up to 200 kPa. For expanded cork samples, the reinforcement bears most of the load, withstanding a maximum load of around 5000 kPa. Meanwhile, the skin layer supports almost no load and undergoes only deformation, as illustrated in Fig. 14.

The reinforcements effectively enhance the strength of the panels, though their shape has a limited influence on the flexural

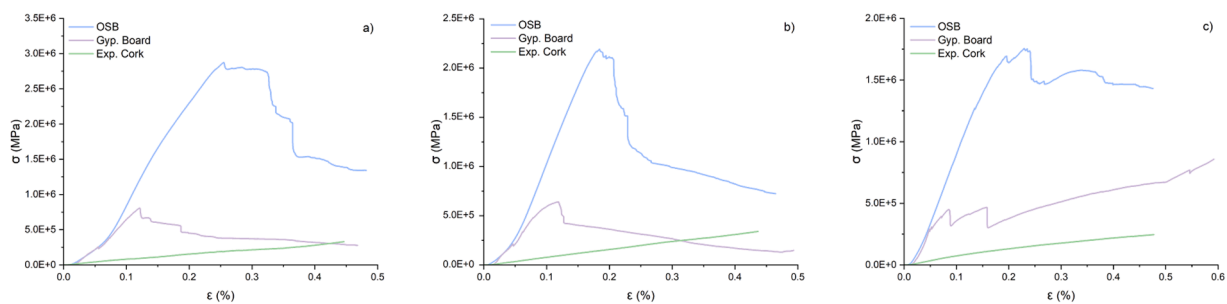


Fig. 13. Three-points bending tests - a) Reinforcement R1, b) Reinforcement R2, c) Reinforcement R3.

Table 12

Sandwich panel 3 points bending values comparison.

Reinforcement shape	Flexural Modulus (MPa)	Flexural strength (MPa)	Strain at break (%)
OSB – None	0.92 ± 0.03	0.08 ± 0.01	0.05 ± 0.01
OSB - R1	16.83 ± 3.34	3.35 ± 0.38	0.23 ± 0.03
OSB - R2	13.66 ± 0.40	2.07 ± 0.10	0.17 ± 0.04
OSB - R3	12.61 ± 1.84	2.05 ± 0.29	0.23 ± 0.05
Gyp. Board - None	0.66 ± 0.04	0.06 ± 0.10	0.05 ± 0.01
Gyp. Board - R1	6.61 ± 1.14	0.75 ± 0.04	0.16 ± 0.01
Gyp. Board - R2	8.40 ± 1.13	0.59 ± 0.04	0.09 ± 0.03
Gyp. Board - R3	6.93 ± 0.32	0.71 ± 0.11	0.089 ± 0.01
Exp. Cork – None	0.54 ± 0.04	0.25 ± 0.02	0.14 ± 0.01
Exp. Cork - R1	0.85 ± 0.55	0.51 ± 0.18	/
Exp. Cork - R2	0.86 ± 0.06	0.41 ± 0.05	/
Exp. Cork - R3	0.54 ± 0.04	0.25 ± 0.02	/

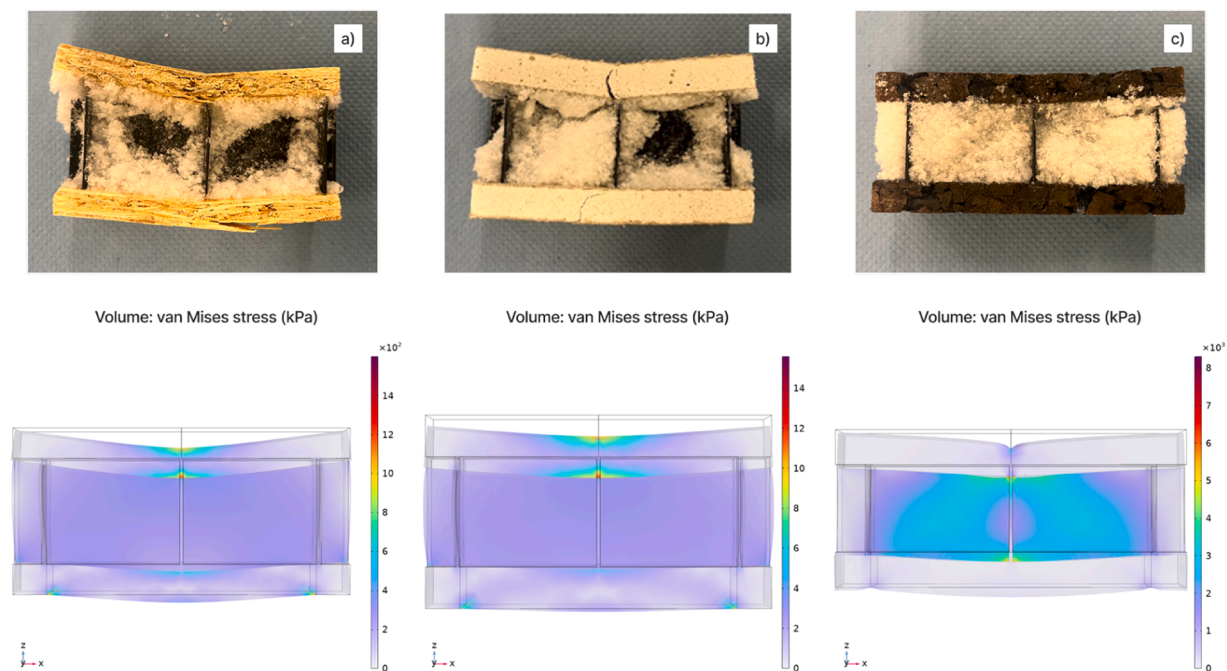


Fig. 14. Samples with R1 reinforcement, after testing - a) OSB, b) Gypsum board, c) Expanded cork, and their simulations.

modulus. At the opposite of non-reinforced panels, the skin layers now become the limiting factor for both the strength and load-bearing behavior of the panels.

Finally, the mechanical properties of the sandwich panels studied here have been compared to other sandwich panels, but manufactured using different approaches. The results are summarized in Table 14.

Table 13
Maximum load applied, from three-points bending simulations.

Sample	No Reinforcement (kPa)	Reinforcement R1 (kPa)
OSB	0.018	1400
Gyp. Board	0.005	140
Exp. Cork	0.005	6000

In terms of flexural strength, the panels from this study rank lower compared to those from other studies. Nevertheless, under optimal conditions, their performance approaches that of some competing materials, with an ultimate load reaching 1.87 kN, versus 1.90 and 2.54 kN for the least optimized conditions. Although the primary purpose of these sandwich panels of this study is not structural, they remain comparable to panels made from stronger materials, whether in the skin or core layers.

Given that the primary application of these panels is thermal insulation, it is essential to evaluate the impact of the reinforcements on thermal conductivity.

3.3.3. Thermal conductivity

To assess the effect of the addition of a reinforcement and a potential thermal bridge effect, the thermal conductivity of the reinforced panels is measured, and are displayed in Fig. 15.

The addition of reinforcements in the core layer results in an increase in the sandwich panel's thermal conductivity, effectively acting as a thermal bridge [37]. The observed increase of thermal conductivity is approximately $0.010 \text{ W.m}^{-1}.\text{K}^{-1}$ for the OSB and gypsum board, and $\sim 0.002 \text{ W.m}^{-1}.\text{K}^{-1}$ for the cork panels. These increases can be considered as important, as they account for almost 10% of the final thermal conductivity. Nevertheless, the improvements both in thermal conductivity and mechanical strength remain superior to the negative impact of the thermal bridge effect. This increase in thermal conductivity remains consistent across all tests and varies with measurement temperature, reflecting the slight increases previously observed in the individual layers of the panels. While a thermal bridge effect is identified, thermal conductivity measurements alone do not provide a complete understanding of heat diffusion within the panels. To thoroughly analyze this behavior, heat transfer simulations are performed.

3.4. Thermal simulation

The initial simulations aim to evaluate the influence of the skin layers on thermal behavior, in addition to assessing the impact of the two different heating rates. The simulated temperature curves and final results, ran on OSB skins panels, are presented in Fig. 16.

After 120 min, the stabilized temperatures differ by approximately 10°C between the high and low positions relative to the heating values (100°C vs. 90°C and 20°C vs. 30°C). For expanded cork, this difference reaches 15°C , which can be attributed to its lower thermal conductivity. Meanwhile, the temperature at the middle position remains unaffected by the skin layer, stabilizing around 60°C . No significant difference is observed among the skin materials in the time required to reach the final temperature, which is approximately 100 min. However, notable differences emerge during the early stages of simulations, with the largest discrepancy occurring between the gypsum board and the cork layers. The temperature differences of all the panels are detailed in Table 15.

When the heating rate is reduced, both the final stabilized temperature and the time required to reach it are affected. After 120 min, the temperatures at the high and mid positions differ by 5°C , regardless of the skin material used. Expanded cork continues to exhibit lower temperature measurements compared to the other materials. In contrast, the low position remains unaffected, thanks to the thermal insulation provided by the core layer, which shields it from the heat source. The time needed to reach the final temperature increases significantly, and 120 min prove insufficient to achieve stabilization. A comparative summary for OSB panels is provided in Table 16.

Given the insufficient mechanical strength of the sandwich panels, three distinct reinforcement shapes were developed to enhance their structural integrity. However, these reinforcements may compromise the panels' thermal insulation performance, due to the thermal bridge observed on the thermal conductivity test, which result from the higher thermal conductivity of the reinforcement compared to the core layer. The corresponding thermal behavior curves are presented in Fig. 17.

No significant differences are observed among the various reinforcement shapes. The time required for temperature stabilization remains consistent across all reinforcements, and the final stabilized temperatures are identical, as seen in Fig. 18. Overall, the addition of reinforcements has a limited effect on temperature diffusivity within the panel. The only exceptions are reinforcements R2 and R3 when used with gypsum board, where notable differences appear during the initial stages (Fig. 18 – b)). However, once stabilization is

Table 14
Comparison of studied sandwich panels to literature.

Type of SP	Ult. Load (kN)	Deflection at failure (mm)	Ref
OSB with silica aerogel core	0.04 – 1.87	5.30	
Gypsum board with silica aerogel core	0.05–0.60	3.30	
Expanded Cork with silica aerogel	No break	/	
Thin precast concrete sandwich panels	1.90 – 17.70	1.20 – 56.80	[35]
Epoxy resin and Polyurethane foam core	2.54 – 19.44	27.80 – 65.90	[36]

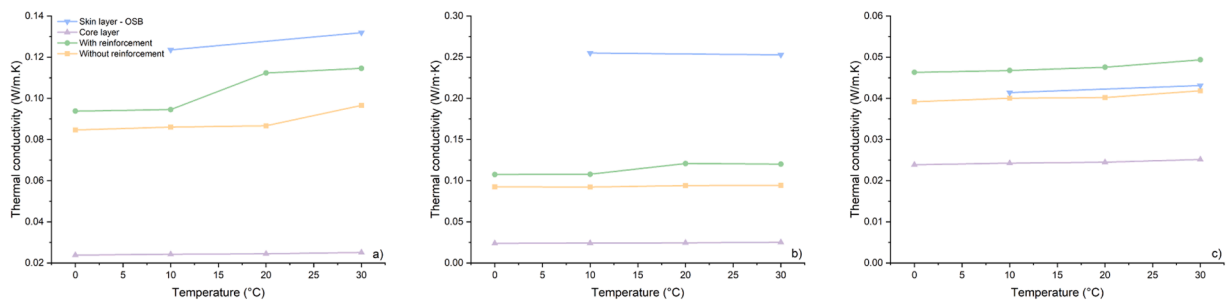


Fig. 15. Thermal conductivities of reinforced sandwich panels: a) OSB, b) Gypsum board, c) Expanded cork.

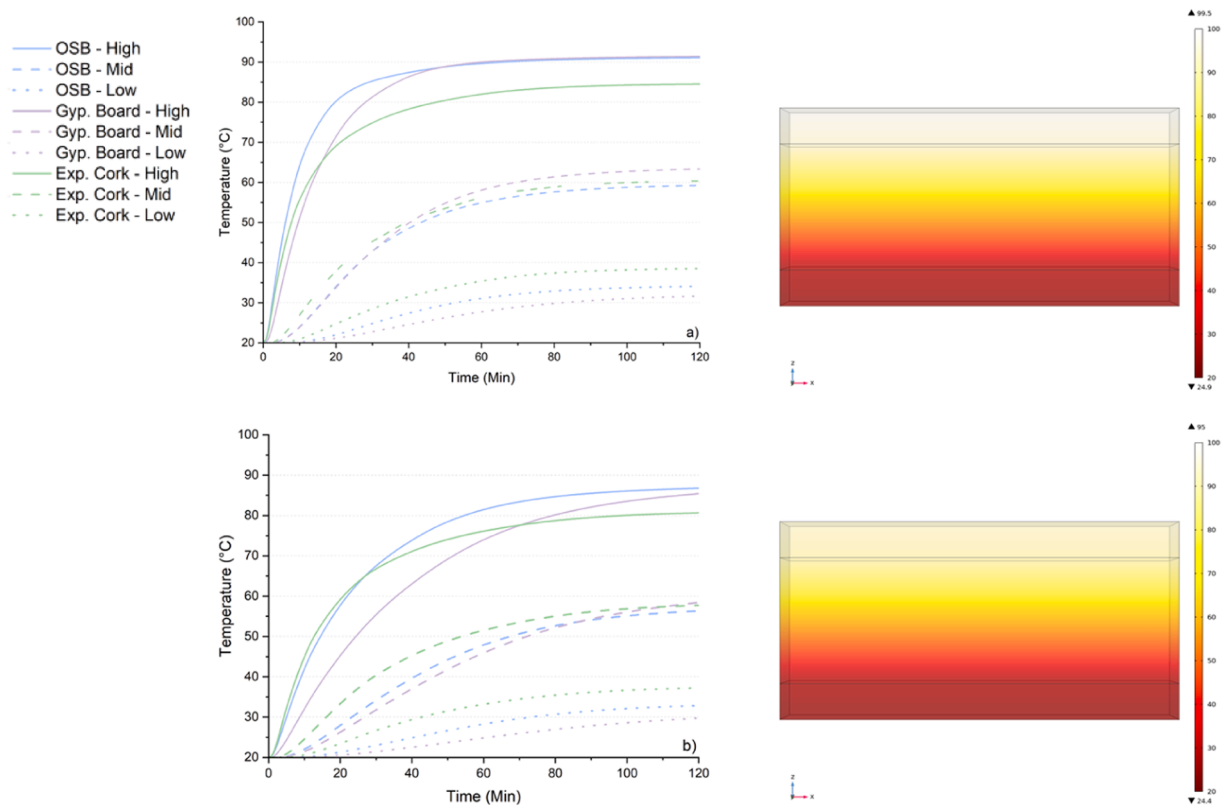


Fig. 16. Comparison of heating rates, no reinforcements, with OSB as skin layers – a) Heating rate: 100–10, b) Heating rate: 10–10.

Table 15

Temperature comparison at different time – Top position – Heating rate 100–10.

Skins	t = 20 min	t = 40 min	t = 60 min
OSB	80 (°C)	88 (°C)	90 (°C)
Gyp. Board	73 (°C)	87 (°C)	90 (°C)
Exp. Cork	69 (°C)	78 (°C)	82 (°C)

Table 16

Temperature comparison at different times, for the 2 heating rates (Skin = OSB).

	t = 20 min	t = 40 min	t = 60 min
100–10	80 (°C)	88 (°C)	90 (°C)
10–10	58 (°C)	74 (°C)	82 (°C)

reached, no differences in final temperatures are detected.

Finally, the temperatures within the reinforcement are compared to the temperature in the core layer. Results are displayed in Fig. 19.

Simultaneously, only a minimal temperature difference (up to 5 °C) is observed between the core layer and the reinforcement. This small delta is attributed to the use of PLA for the reinforcement, which has relatively low thermal conductivity ($\lambda = 0.11 \text{ W.m}^{-1}.\text{K}^{-1}$). This property also helps minimize the thermal bridge effect between the skin layers.

4. Conclusions

This study focuses on the development of sandwich panels designed for thermal insulation, utilizing silica aerogel as the core layer and various building materials as skin layers. The primary objectives are to evaluate the potential of these panels in terms of thermal insulation, mechanical strength, and other building physics properties, while also analyzing the limitations associated with the silica aerogel composite core layer.

From the findings, several key observations emerge:

- Silica aerogel, as the main component of the core layer, and of the sandwich panel, proves effective for thermal insulation applications.
- However, a core layer composed solely of silica aerogel exhibits poor resistance to bending, necessitating reinforcement strategies.
- Panels made with expanded cork achieved low thermal conductivities ($0.040 \text{ W.m}^{-1}.\text{K}^{-1}$), though OSB and gypsum board panels remain less competitive in this regard. It is worth noting that this study was conducted using the lowest R-value from the standard; further research targeting higher R-values could explore the potential for even lower thermal conductivities.
- Reinforcing the core layer with PLA significantly enhances mechanical strength, while having only a limited impact on the material's thermal conductivity.

CRedit authorship contribution statement

Pantaleo Samuel: Writing – original draft, Methodology, Investigation, Conceptualization. **H.J.H. BROUWERS:** Writing – review & editing, Supervision. **Florent GAUVIN:** Writing – review & editing, Supervision.

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.

Data availability

Data will be made available on request.

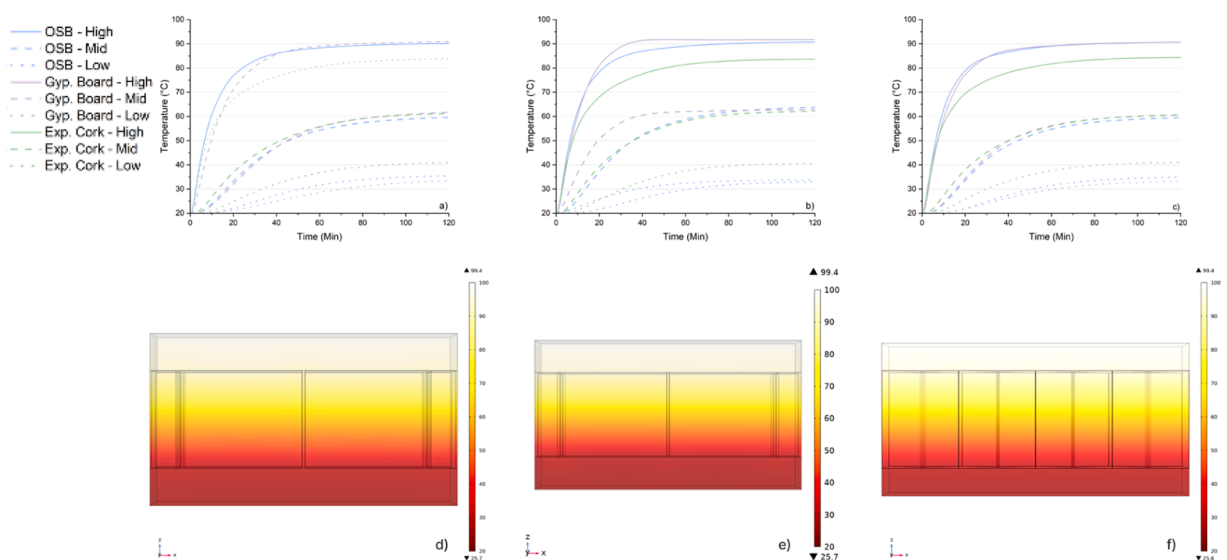


Fig. 17. Comparison reinforcement – Heating rate: 100–10 - a) R1, b) R2, c) R3, d) Simulation Gypsum + R1, e) Simulation Gypsum + R2, f) Simulation Gypsum + R3.

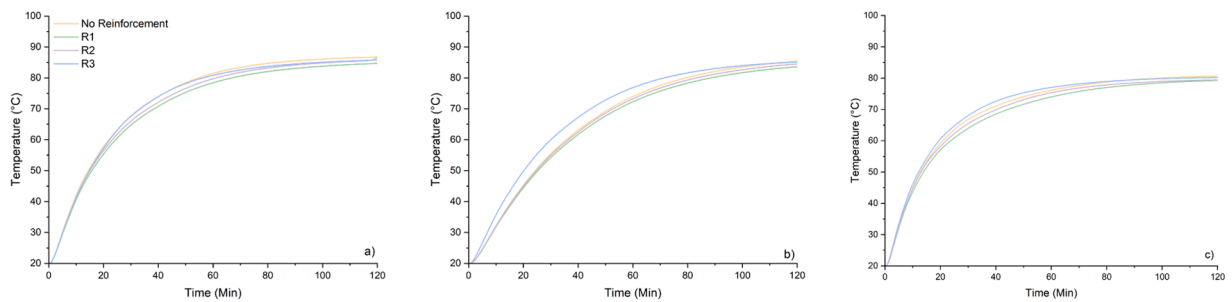


Fig. 18. Temperature comparison with and without reinforcement R1: a) OSB, b) Gypsum board, c) Expanded cork.

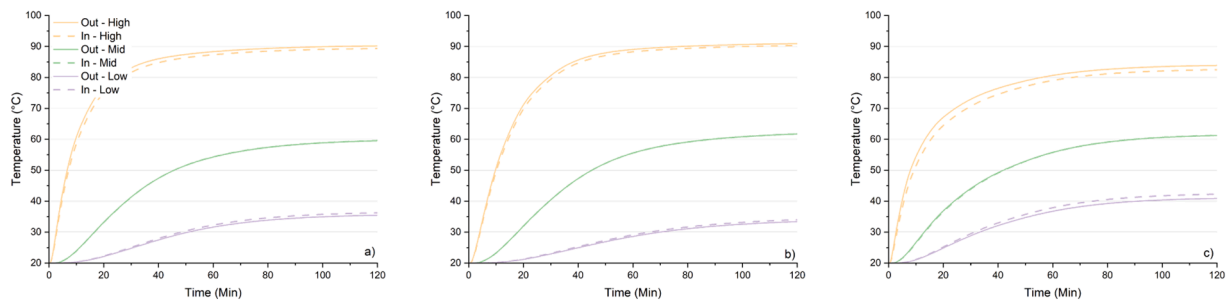


Fig. 19. Temperature comparison in and outside the reinforcement R1: a) OSB, b) Gypsum board, c) Expanded cork.

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