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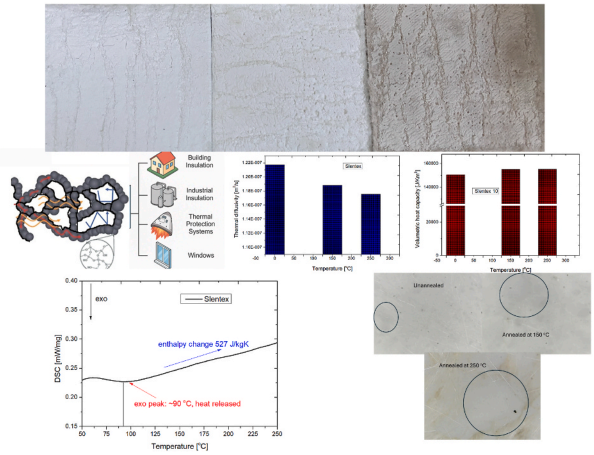
Analysis of heat treatment forced thermal and structural changes of aerogel insulation blanket – a case study

Akos Lakatos

University of Debrecen, Faculty of Engineering, Department of Building Services and Building Engineering, Ótemető str 2-4, Debrecen, H-4028, Hungary

GRAPHICAL ABSTRACT



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ABSTRACT

Aerogels, renowned for their ultralight structure and low thermal conductivity, have emerged as highly effective super-insulation materials. This paper examines their thermal properties, thermal stability, and various engineering applications. "Super Insulation Materials" such as vacuum insulation panels and aerogels, are frequently used to describe these materials. Aerogels and related super-insulation materials (SIMs) have garnered significant attention due to their ultra-low thermal conductivity and applications in building, industrial, and cryogenic insulation. Although most long-term thermal parameters are unknown, the aforementioned goods have far superior thermal insulating qualities. In the paper, we will discuss the research on the thermal

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E-mail address: alakatos@eng.unideb.hu.

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stability of Slentex aerogel blanket samples as they mature through heat treatments (150 °C and 250 °C for 1 day). Various techniques will be used to monitor the changes in the thermal characteristics (thermal diffusion and volumetric heat capacity). Thermal conductivity measurement results show a stable thermal insulation capability, while the specific heat capacity changes slightly. From these thermal values, diffusion and volumetric heat capacity were derived. The results showed a decrease in thermal diffusivity of about 3–4 %, while the volumetric heat capacity increased. Microscopic and visual analysis revealed surface oxidation, while the DSC results presented a substantial and continuous increase (strong endothermic process) in the heat flow curve.

1. Introduction

The Climate suffers as a result of the increased energy use and greenhouse gas emissions. Most energy is utilized in buildings, while transportation accounts for a substantial portion of total energy consumption. [1,2]. Over 400 major cities have been documented to have urban overheating [3]. In the context of rising energy demand and growing concerns about climate change, reducing energy use in buildings has become one of the most pressing challenges for engineers, architects, and policymakers. Buildings account for approximately 40 % of global energy consumption and nearly 30 % of global carbon dioxide emissions. Much of this energy is lost through building envelopes, especially in walls, roofs, windows, and floors. To address this, the application of efficient thermal insulation materials is critical. Most buildings are either completely or partially uninsulated [4–7] (see Table 1).

The importance of thermal insulation cannot be overstated in today's construction sector. With global targets aiming for net-zero emissions by 2050, building insulation is among the first-line strategies to reduce greenhouse gas (GHG) emissions. Insulating building envelopes not only improves thermal comfort and reduces energy bills but also plays a critical role in enabling buildings to meet or exceed energy performance standards such as EU's EPBD directives. Moreover, as building codes become more stringent, insulation is evolving from a passive element to a high-performance component that contributes to the building's overall energy system efficiency. The building sector is undergoing a profound transformation, driven by stringent energy efficiency mandates and climate goals outlined in international agreements, such as the Paris Accord and the European Green Deal. According to the International Energy Agency (IEA), heating and cooling account for approximately 50 % of total energy use in buildings. Thermal insulation is thus not only a passive element of envelope design but a vital contributor to reducing operational energy demand, greenhouse gas emissions, and long-term lifecycle costs.

Additionally, insulation is advantageous for building service systems, such as district heating channels or pipes transporting hot fluid, as found in power plants [8,9]. Thermal insulation, such as mineral wool, fibreglass, or aerogels, is recommended to withstand high temperatures. Silica aerogels exhibit extremely low thermal conductivity (∼0.02 W/m·K) [10,11].

District heating systems can be efficiently insulated using new-generation aerogels that are resistant to metallic contaminants, which can tolerate high temperatures, such as Slentex, also used by the industry and power plants. Compared to traditional insulations, such as glass wool for pipes, aerogels are far more effective in insulating against heat [8–11].

Aerogels: Extremely low-density solids with up to 99.8 % air content. Available in granular, monolithic, or blanket forms. They are used in spacecraft, cryogenic storage, and are increasingly being used in building retrofits. Slentex is a commercial brand that has been widely studied.

- Vacuum Insulation Panels (VIPs): Comprised of a porous core sealed within a gas-tight envelope under vacuum conditions. They can deliver thermal conductivities as low as 0.004 W/m·K. Their performance degrades if the vacuum seal is compromised, so edge protection is essential.
- Hybrid SIMs: Combine aerogels or VIPs with traditional materials to balance performance and cost. For instance, aerogel blankets over mineral wool can improve performance by 30–40 % with modest cost increases [12–15].

In the automotive industry, these materials are being evaluated for insulation, while in electronics, they serve as thermal interface materials due to their ability to suppress both heat conduction and electrical conductivity.

In heritage building retrofits, where changes to architectural appearance must be minimal, thin-layer aerogel plasters are deployed on interior surfaces to enhance insulation without altering facade dimensions. This is particularly valuable in Europe, where historic

Table 1
Comparison of VIPs and aerogels as application.

Property	Aerogels	VIPs
Thermal conductivity	0.015–0.020 W/m·K	0.005–0.010 W/m·K
Thermal stability	Up to ∼200 °C (limited)	Stable if edge-sealed
Moisture sensitivity	Moderate	Low (if properly laminated)
Retrofit suitability	Excellent	Excellent, with care
Structural robustness	Low–Moderate	Moderate
Ideal applications	Facade retrofits, pipes, nZEB	Building envelopes, cold storage

Table 2
Comparison of different insulation materials, based on literature [25–29].

Material	Thermal Conductivity (W/m·K)	Operating Temp Range (°C)	Environmental Notes
Silica Aerogel	0.013–0.020	−200 to 650	High-performance, energy-intensive production
VIP (Fumed Silica)	0.004–0.010	−50 to 80	Difficult to recycle, edge degradation risk
PU Foam	0.020–0.030	−50 to 100	Petrochemical origin, flammable
Mineral Wool	0.030–0.040	−200 to 700	Good fire resistance, dust concerns
Hemp Fiber	0.040–0.060	−20 to 100	Biodegradable, low embodied CO$_2$

Table 3
Results of measurements for thermal conductivity and specific heat capacity.

Measurement mean temperature [°C]	Slentex 0			Slentex 150			Slentex 250		
	Lambda [W/mk]	CP [J/kgK]	Density [kg/m^3]	Lambda [W/mk]	CP [J/kgK]	Density [kg/m^3]	Lambda [W/mk]	CP [J/kgK]	Density [kg/m^3]
10	0.0183	803	187.5	0.0185	821	189	0.0183	815	190.6
Percental change (%)				*0.65 (∼0)*	*2.24*		*0*	*1.49*	

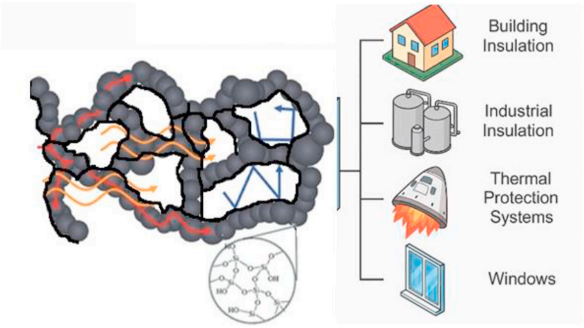

Fig. 1. Possible application of aerogels.

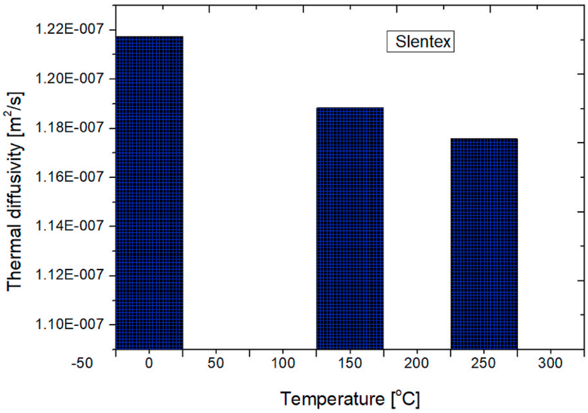

Fig. 2. Thermal diffusivity results.

preservation laws restrict the modification of exterior features. The integration of these materials into prefabricated panels is also being studied to streamline construction timelines and minimise labour costs [16–20].

The key to their insulating performance lies in the nanostructured porous network, which limits heat transfer through conduction, convection, and radiation. This effect, often attributed to the Knudsen effect, reduces gas-phase conductivity, making aerogels ideal for applications requiring extreme thermal resistance. Despite these strengths, challenges such as fragility, moisture sensitivity, and limited thermal stability in some formulations restrict their broader adoption.

Their nanoporous structure inhibits conduction, convection, and radiation—contributing to superior thermal insulation performance. These insulations should withstand temperatures of at least 300 °C, but their longevity can also be estimated from the

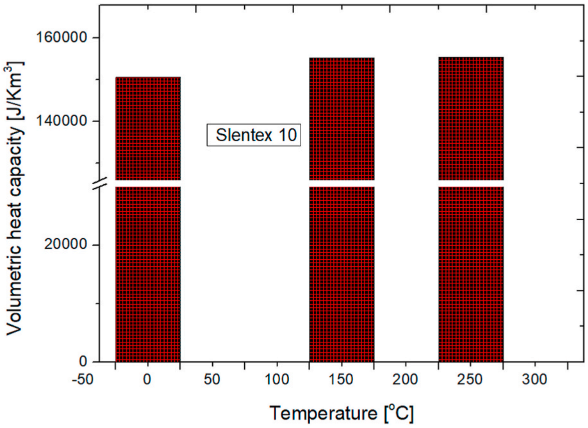

Fig. 3. Volumetric heat capacity of the samples.

Fig. 4. Photos of the samples (left to right: un-annealed, annealed at 150 °C 1 day, annealed at 250 °C 1 day.

material's ageing perspective [21–23].

1.1. *Thermal stability of aerogels*

Thermal stability is a key criterion in selecting insulation materials for high-temperature environments. Silica aerogels can withstand temperatures of up to 600 °C; moreover, some of them are also flame-retardant [24]. This makes them suitable for aerospace, industrial furnaces, and cryogenic insulation applications. It is claimed that these materials are suitable insulators for pipes carrying hot steam for power plants or district heating systems. They can withstand temperatures of up to 150–250 °C in these conditions. The insulation's thermal characteristics, including its specific heat capacity and thermal conductivity, may alter due to these temperatures. The materials' surface and structural alterations may cause these alterations. We tested the thermal conductivities and specific heat capacities of the samples after annealing them individually for one day at 150 °C and 250 °C to make them visible. Following that, the volumetric heat capacity and thermal diffusivity were computed.

1.2. *Comparative performance of insulation materials*

The table below summarises the thermal and environmental performance of selected insulation materials.

The key novelties and hypotheses are as follows:

- Exploration of the thermal, diffusivity and heat capacity for a slentex aerogel after heat treatment
- Revealing the structural changes of the material after thermal annealing
- Full exploration of the thermal stability of slentex aerogel
- Opening the relations between crystal structure and transient thermal properties

Fig. 5a. Surface photo of un-annealed sample.

2. Materials and methods

2.1. The tested material

For the experiments, we used a Slentex type aerogel, which is available on the market and widely used under different circumstances, e.g., where the requirements are extreme (e.g., elevated temperatures occur). Made entirely of mineral raw ingredients, SLENTEX® is a non-flammable and simple-to-process substance. It is currently used for various purposes in the modernisation and construction industries as a single-layer, flexible mat. An innovative inorganic aerogel for high-performance insulation. Breathable (Vapour Open); hydrophobic, highly vapour permeable, yet non-hydroscopic, providing no liquid transfer. The production of aerogels in blanket forms occurs through the sol-gel process, where the gel is placed in a fibre net. The production process consists of three steps: the sol-gel process, the drying process, and integration into a blanket form. The advantage of the fiber design is that the final product will be flexible. Slentex is a metallic-infused aerogel that we studied in our lab. This is a second-generation spaceloft aerogel of the traditional kind. Its colour is white, its fire classification is A2-s1, and its density is about 190 kg/m^3. The declared thermal conductivity is 0.019 W/mK. The following contaminants can be found in the slentex material: Methylsilylated silica, fibrous glass, calcium silicate, synthetic graphite, moreover:

Glass, oxide, $\geq$ 35.0 - $<$ 45.0 %

Silicon dioxide $\geq$ 30.0 - $<$ 40.0 %

Wollastonite (Ca(SiO3)) $\geq$ 15.0 - $<$ 20.0 %

Silanamine, 1,1,1-trimethyl-N-(trimethylsilyl)-, hydrolysis products with silica $\geq$ 5.0 - $<$ 15.0 % [20]

2.2. NETZSCH 446 heat flow meter for measuring the thermal properties (thermal conductivity and specific heat capacity)

A compact device, the Netzsch Heat Flow Meter 446, was utilized to measure specific heat capacity and thermal conductivity, which are key thermal properties of insulation materials. In the building industry, the specific heat capacity of insulation materials is just as significant as their thermal conductivity. An insulating material with a high specific heat capacity can help maintain a consistent indoor climate by mitigating temperature variations in the outside environment. Both measurements were performed in steady state.

Fig. 5b. Surface photo of un-annealed sample, magnification 5X

The accuracy of the equipment is about 1 %. This instrument was employed to assess both the prepared samples and those that underwent heat treatment. Three samples with base areas of 20 cm × 20 cm each were analysed using 1 cm thick sections. The ease with which heat can diffuse through a substance is measured by its thermal conductivity. The primary method of heat transfer through insulation is conduction, often referred to as the lambda (λ) value. A lower number indicates improved performance. The specific heat capacity of a material is defined as the amount of heat required to raise the temperature of 1 kg of that material by 1 K (or 1 °C). The upper and lower plates of the equipment are kept at precisely the same temperature to measure the specific heat capacity, or Cp, using the HFM 446 Lambda. A temperature step is started when the heat transfer between the two plates stops.

Heat-flux transducers combine and assess the signal after measuring the resulting heat flux into the sample and the plates. The system's specific heat is taken into account by conducting a so-called empty stack measurement (the system without a sample) before the sample measurement. Since it takes time for an insulator to absorb more heat before warming up (producing temperature increases) and transferring that heat, a good insulator has a larger specific heat capacity. Materials with a high specific heat capacity offer thermal mass or thermal buffering (reduction of delay). Three samples from each were tested before and after thermal annealing at 150 °C and 250 °C for 1 day.

2.3. Differential scanning calorimetry (DSC) measurements

The DSC tests were executed using a Netzsch DSC Sirius 3500 instrument with a nitrogen flow. DSC, or differential scanning calorimetry, is one of the most widely used techniques for thermal analysis. Almost any energy effect that arises in a solid or liquid after thermal treatment can be analysed using this method. A thermoanalytical method called differential scanning calorimetry (DSC) calculates the difference in heat absorbed or released by a sample and a reference material when they are heated or cooled at the same rate. This method provides information on the sample's melting point, glass transition temperature, crystallisation temperature, and heat capacity while examining physical and chemical changes in materials. The heat-flux concept governs the operation of the DSC 3500 Sirius. This technique involves applying a controlled temperature program (heating, cooling, or isothermal) to both the sample and the reference. The sample's temperature and the temperature differential between the sample and reference are the actual properties that are measured. The heat flow difference between the sample and reference, which indicates the sample's calorie changes, can be calculated from the raw data signals. In our case, we tested the slentex material between 50 and 250 °C. It clearly reveals the changes within the material's structure (see Table 2).

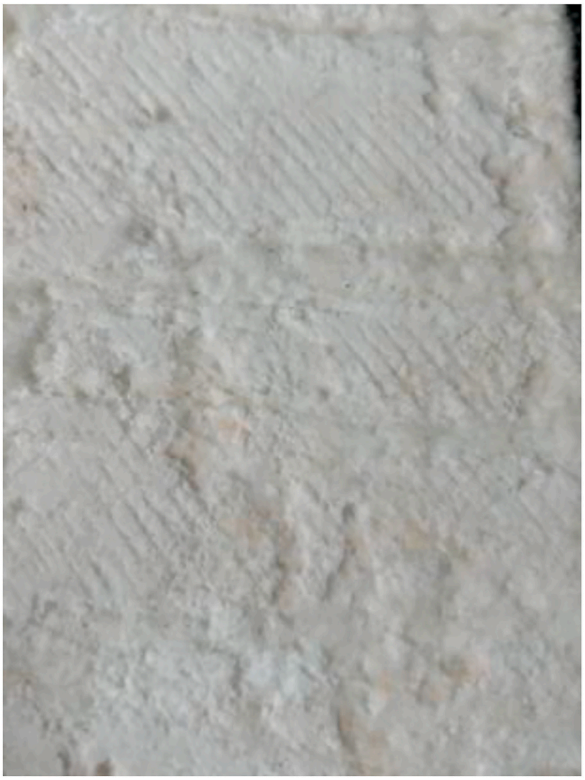

Fig. 6a. Surface photo of the sample annealed at 150 °C for 1 day.

3. Results and discussion

3.1. *The measured thermal conductivity and specific heat capacity values*

We determined the most crucial thermal characteristics of the samples using thermal conductivity specific heat capacity measurement results (see Table 3). As shown in Table 3, the thermal conductivity remained constant, while the specific heat capacity changed slightly.

3.2. *The thermal diffusivity*

The thermal conductivity divided by the density and specific heat capacity at constant pressure is known as thermal diffusivity in thermodynamics (see Fig. 1). From the results presented in Table 3, we calculated the thermal diffusivities for the samples (non-heat-treated and heat-treated). What it signifies: high thermal diffusivity means the substance absorbs heat rapidly. This implies that the substance has good heat conductivity and storage capacity. Low thermal diffusivity reflects that the substance absorbs heat slowly. This suggests that the substance is either good at storing heat or bad at conducting it. Understanding thermal diffusivity is essential. The rate at which temperature differences within a material are evened out is known as heat transfer. Material reaction to temperature variations: The rate at which materials respond to temperature changes varies depending on their thermal diffusivities. When a material is exposed to a heat source or sink, its temperature varies over time. This phenomenon is known as unsteady heat conduction. The thermal diffusivity was calculated by dividing thermal conductivity by the product of density and specific heat capacity (see Fig. 2) [30] (see Fig. 3).

One can see that the thermal diffusivity of the samples decreases with thermal annealing. The samples undergo a 3.5 % change in thermal diffusivity upon thermal annealing at 250 $^{\circ\text{C; one can see that th}}$is exceeds the accuracy of the equipment. This is a material's property. It measures a material's ability to transfer thermal energy relative to its thermal storage capacity. Heat transport is accelerated by high diffusivity [30].

As mentioned above, the rate at which heat diffuses through the material increases with the value. This indicates that the conductivity is higher, resulting in less heat being stored.

Reduced insulation results from increased heat conductivity. A higher diffusivity results in less insulation. The aforementioned variables are combined in thermal diffusivity, an equation that quantifies a material's capacity to transfer heat energy relative to its capacity to store heat energy. It functions as a gauge of thermal inertia, or "buffering."

Fig. 6b. Surface photo of the sample annealed at 150 °C for 1 day, magnification 5X

3.3. *The volumetric heat capacity*

We also calculated the volumetric heat capacity in volume. The volumetric heat capacity is the result of multiplying the specific heat capacity by the density. The amount of energy required to add one unit of heat while increasing a material's temperature by one unit is known as this quantity. Volumetric heat capacity is the quantity of heat required to raise a substance's temperature by 1 °C or Kelvin per unit volume without producing a phase shift. The meaning of this property: a) in material analysis: The amount of heat that a material can hold is determined by its volumetric heat capacity. b) In heat transfer: In thermal diffusivity calculations, it is used in conjunction with thermal conductivity to define a material's capacity to transfer heat in relation to its capacity to store it. c) In engineering, It is essential for applications involving materials that are frequently measured and filled by volume, such as solids or lubricants. The volumetric heat capacity is based on the volume of a substance, while the specific heat capacity is based on the mass of the substance.

Fig. 2 indicates that the volumetric heat capacity has increased by 3 %, which also exceeds the measurement accuracy. In this case, density and specific heat capacity are multiplied.

3.4. *Identifying the causes of changes*

To understand the above changes, we must delve deeper into the changes to the surface and structure of the material. For this visual, microscopical and DSC experiments were executed.

3.4.1. *Visual inspections of the samples*

To visualise the changes on the surface of the samples, we took photographs. At first glance, Fig. 4 shows that the surface of the bulk insulation Slenex samples becomes darker, possibly due to oxidation.

The images presented in Fig. 5a and b, 6a and 6b, as well as 7a and 7b, are at 1x and 5x magnifications. On these rows of images the surface oxidation is very well observable. Another interesting phenomenon is also visible in images 5b, 6b, and 7b. One can see that the granules of the aerogels are stick together forming aerogel fields on the surface. As further proof of this, microscopical images with 40x magnification were also imaged. These are also visible in Fig. 8. Similar results were found in Refs. [11,21] (see Fig. 7).

Fig. 8 shoes the microscopic image of both the un-annealed sample and the two annealed samples. On the downside of the image (Fig. 8), the fattened granules are clearly visible.

A possible reason for the particle growth can be the potential melting of a component. Silanamine, 1,1,1-trimethyl-N-(trimethylsilyl)-, hydrolysis products with silica is a chemical substance primarily used in applications involving surface modification and as a

Fig. 7a. Surface photo of the sample annealed at 250 °C for 1 day.

coupling agent. It's a reaction product of silanamine with silica, and its hydrolysis products can form silanol groups, which are essential for creating siloxane bonds. These properties make it useful in various industries like coatings, adhesives, and sealants. In silica aerogels, silanamine, 1,1,1-trimethyl-N-(trimethylsilyl) (also known as TMSS or hexamethyldisilazane), is used as a surface-modifying agent to improve hydrophobicity and mechanical properties. Specifically, it acts as a silylation agent, reacting with surface silanol groups on the silica network. This modification helps reduce surface energy, making the aerogel more water-repellent and less prone to particle agglomeration during the drying process.

3.5. DSC experiments

In Fig. 9, DSC experiments are presented between 50 °C and 250 °C. One can observe that at approximately 90 °C, an exothermic peak becomes visible, as heat is released into the environment. After that, the enthalpy continues to increase, absorbing heat from the atmosphere.

The increase in the heat capacity of amorphous materials stems from the fact that, due to the disordered arrangement of atoms and molecules, multiple modes of motion and energy levels are available, allowing for greater heat absorption. In contrast, crystalline materials have a more tightly bound lattice structure, where heat absorption is more limited because resonances and atomic movements are generally only associated with specific frequencies.

The volumetric heat capacity of amorphous materials is typically greater than that of crystalline materials, but this is due to the disordered arrangement of atoms and the resulting differences in thermal properties. Amorphous materials: In amorphous materials, atoms and molecules are not arranged in a regular crystal structure, but are randomly distributed. Such materials typically have a higher volumetric heat capacity because their disorder allows them to access a broader spectrum of energy quanta. As a result, amorphous materials are better able to absorb and store heat. Crystalline materials: In crystalline materials, atoms, ions, or molecules are arranged in a regular, orderly structure, which causes them to be more tightly bound to one another.

The volumetric heat capacity of crystalline materials is generally lower due to the bonds in the crystal lattice, as the movement of atoms is more restricted and only vibrations of specific frequencies can be linked to temperature changes. In amorphous materials, therefore, the volumetric heat capacity may be higher because the atoms and molecules can move more freely and thus absorb and store more energy. Kittel explains that crystalline materials may have lower heat capacity due to their orderliness and limited freedom of movement, whereas in amorphous materials, the disorder of atoms can result in a higher volumetric heat capacity [31]. This study analyses the thermal behaviour of amorphous materials and their higher heat capacity, comparing them with crystalline materials. The research highlights that the disordered nature of amorphous materials improves heat absorption and storage efficiency [32]. When a material transitions from a crystalline to an amorphous state (e.g., through heating and melting followed by rapid cooling), it absorbs

Fig. 7b. Surface photo of the sample annealed at 250 °C for 1 day, magnification 5X

energy from the surroundings to overcome the energy barrier associated with breaking the crystalline structure. This energy absorption is an endothermic process, resulting in a negative heat flow (a dip in the DSC curve). When a material crystallizes, it releases heat as the molecules arrange themselves into a more stable, crystalline structure. These factors collectively contribute to the stability of thermal conductivity, the decrease in thermal diffusion, and the increase in volumetric heat capacity.

3.6. *Environmental impact and Life Cycle Assessment (LCA)*

Environmental considerations are now a key factor in the selection and deployment of insulation materials. Life Cycle Assessment (LCA) evaluates the environmental footprint of materials from raw material extraction to end-of-life disposal. Aerogels, while high-performing in terms of insulation, require energy-intensive manufacturing processes. Their carbon footprint is relatively high compared to natural or bio-based insulations; however, this is offset by operational energy savings over the building's lifespan. Bio-based materials such as hemp, flax, and wood fibers generally exhibit low embodied energy and CO_2 emissions. For instance, hemp insulation requires up to 60 % less energy in production than EPS and has a negative carbon footprint when cultivated sustainably [33]. However, their thermal performance is lower, and durability against moisture and pests remains a concern.

VIPs present a paradox: they offer ultra-low thermal conductivity, significantly reducing energy consumption, yet their disposal and production rely heavily on synthetic polymers and aluminium layers.

4. Conclusion

Aerogels and VIPs represent the frontier of thermal insulation technology. Their **exceptionally low thermal conductivity** makes them suitable for demanding applications, ranging from ultra-thin facade retrofits to high-temperature piping. The emergence of super-insulation materials, especially aerogels and VIPs, has enabled high-performance building envelopes even in space-constrained retrofits.

Overall, the path forward includes fostering synergies between traditional and advanced materials. This includes combining the mechanical robustness of mineral wool with the ultralow conductivity of aerogels, or leveraging natural binders to reduce the embodied energy of synthetic foams.

In this paper, the following results were reached. After ageing the samples for a day at 150 and 250 °C, the thermal and physical characteristics of Slentex insulation were assessed through heat-treatment based ageing. The data enabled us to identify changes in both structural and thermal properties, and we also investigated potential correlations between these two properties. Thus, we identified the observable and quantifiable surface and structural changes for Slentex fiber. The Cp measurements supported the

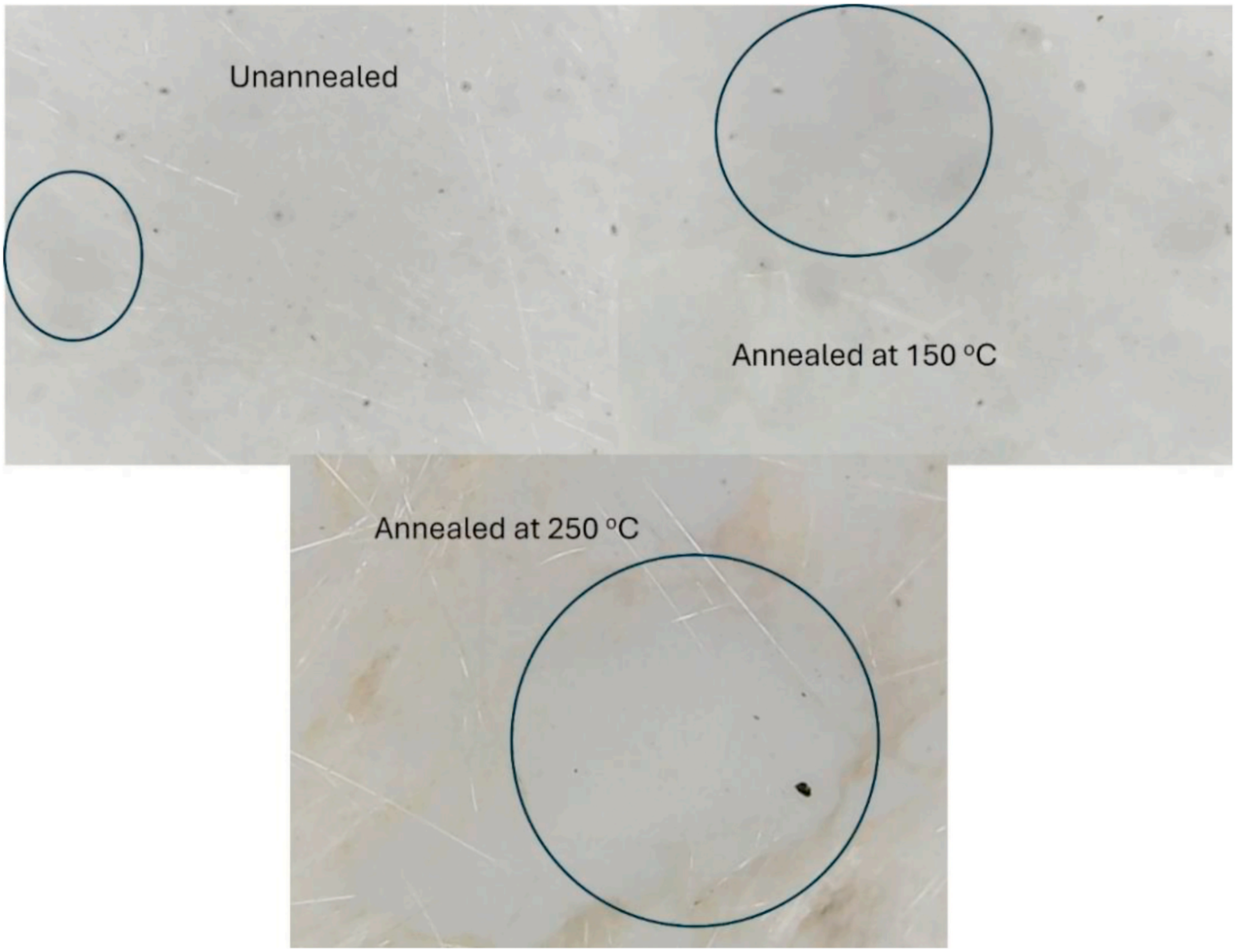

Fig. 8. Microscopic image of the samples with magnification 40X

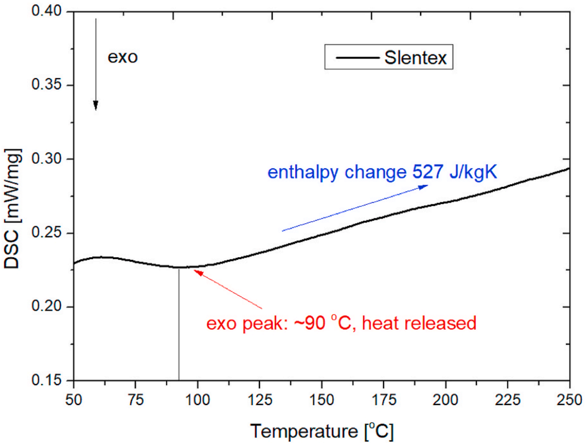

Fig. 9. DSC experiment results.

amorphisation process, which showed a 10 % change after a day of annealing at 250 °C, as well as a strongly oxidised surface on the sample. Thermal conductivity measurement results show a stable thermal insulation capability (amorphisation), while the specific heat capacity changes slightly after ageing. These are both due to the amorphous nature of the state. From these thermal values, diffusion and volumetric heat capacity were derived. The results showed a decrease in thermal diffusivity of about 3–4 %, while the volumetric heat capacity increased. Microscopic and visual analysis revealed surface oxidation, while the DSC results presented a substantial and continuous increase (strong endothermic process) in the heat flow curve.

Future work should focus on developing hybrid systems, enhancing moisture barriers, and implementing scalable low-carbon production methods for SIMs. Moreover, we plan to extend these measurement results with infrared, x-ray diffraction and Raman spectroscopy measurements.

Declaration of competing interest

The authors whose names are listed immediately below certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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Data availability

Data will be made available on request.

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