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ORIGINAL PAPER

Development of environmentally friendly lightweight aerogel composites as sustainable building materials: high insulation performance and application potential

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Abstract
In this study, inexpensive and environmentally friendly aerogel insulation composites were synthesized using diatomite. During the synthesis, raw diatomite, polyvinyl alcohol (PVA) and carboxymethyl cellulose (CMS) were used as binders and only water was used as solvent. The freeze-drying method enables the formation of an aerogel structure with low density (0.114 g/cm^3) and high porosity (91.50%), making it suitable for applications such as thermal insulation. The final LWA aerogel has a very low thermal conductivity of 0.041 W/(m.K). The synthesized aerogels were combined with ready-made plasterboard to obtain a lightweight aerogel composite. A test box with plasterboard walls was prepared with the obtained LWA composite and the internal temperatures and surface temperatures were measured. Comparative measurements with the test box without LWA composite showed a temperature difference of approximately 7 °C. The use of diatomite without any pre-treatment makes aerogel an environmentally friendly and cost-effective material. It is thought that such innovative materials will contribute to sustainability in industrial applications. In conclusion, the findings of the study reveal that diatomite-based lightweight aerogels offer new opportunities as building materials.

Keywords Aerogel · Diatomite · Thermal insulation · Composite

Introduction

The greatest problem facing humanity worldwide is climate change. The main cause of climate change is known as the release of greenhouse gases and carbon dioxide into the atmosphere, most of which are caused by energy consumption. Energy consumption, which increases with increasing population, urbanization and the increase in the need for comfort in people, is an important parameter with a potential impact on climate change (Lamy-Mendes et al. 2021; Shaik et al. 2024). Since developed countries tend to be more energy dependent, energy use is higher than in low-income countries (Duong et al. 2021a). For this reason, the applicability of methods such as energy efficiency and dissemination of clean energy use should be increased in the development of energy policies in countries. Buildings constructed with the development of the construction sector with population growth and industrialization account for more than one third of global energy demand (Gupta and Deb 2023; Zhang et al. 2024). For this reason, it is expected that increasing energy efficiency in the building sector will both contribute to the country's economy and prevent the climate problem. Thermal insulation applications in buildings come to the fore as the cheapest and most effective method that can be sustained for energy efficient use (Lee et al. 2023). It is possible to provide energy efficiency thanks to the correct insulation materials and correct applications applied in the building shell, windows,

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roofs and windows. Even the insulation applied to the exterior of the building alone can provide 25–35% energy savings (Verbeke and Audenaert 2018; Gupta and Deb 2023). Energy efficiency applications can prevent climate change and at the same time increase the comfort of life. When it comes to energy efficiency in buildings, it is a comprehensive issue that is affected by many processes starting from the design phase of the building until its use. Good building design, adequate insulation, use of energy efficient materials, efficient lighting and air conditioning systems, promotion of renewable resource utilization, use of environmentally friendly and sustainable materials play an active role in energy efficiency (Yang et al. 2022a). Lightweight building materials are materials that contribute to preserving indoor heat in buildings, ensuring more efficient operation of heating–cooling systems, reducing energy consumption and reducing energy costs (Hu et al. 2025). Although traditional thermal insulation materials such as polystyrene (EPS, XPS), glass wool and rock wool offer low thermal conductivity, they are limited by thick application requirements, moisture absorption, low fire resistance and durability problems (Xu et al. 2023). Environmental impacts should also be considered in the production and utilisation of these materials. Diatomite-based aerogels overcome these limitations with lower thermal conductivity, light weight and superior fire resistance. In addition, by using diatomite, a natural and cheap source of silica, aerogel synthesis becomes environmentally friendly and cost-effective. These properties make diatomite-based aerogels an ideal alternative in the search for sustainable and high-performance insulation materials (Adhikary et al. 2022; He et al. 2023). In addition to its advantages as an insulation material, the use of aerogels compared to traditional insulation materials has a positive impact on energy savings in the building envelope, resulting in a significant reduction in greenhouse gas emissions of up to ~ 65%. Thus, the use of aerogels in building materials can serve the goal of reducing carbon emissions in Sustainable Development Goal 13 (Climate Action) set by the United Nations Member States. (Singh et al. 2023). In addition to thermal insulation, they are materials that make a great contribution to the building sector thanks to their ease of transport and installation, conformity to green building standards, durability and low maintenance costs (Shah et al. 2021). Silica aerogels, the so-called new generation thermal insulation material, is an extremely interesting type of material with low density, low thermal conductivity, low dielectric constant, high optical conductivity, high porosity and large specific surface area (Li et al. 2023; Jia et al. 2023). In silica aerogel synthesis, wet gels prepared by sol–gel method are generally obtained by drying at ambient pressure. Chemicals of organic origin such as tetraethyl orthosilicate (TEOS), tetramethylorthosilicate (TMOS), polyethoxydisiloxane (PEDS) are generally used as silica sources (Mazrouei-Sebdani et al. 2021). During drying at ambient pressure, the surface tension of the wet gels is quite high, and the aerogel exhibits a fragile structure. Freeze drying method is preferred to overcome the limitations caused by surface tension in the drying process (Shishir et al. 2018; Xu et al. 2023). The biggest challenge to the commercialization of aerogels, in addition to processing-based optimization, is the selection of expensive chemicals as the raw material source. For this reason, it is of great importance that silica-based materials used as raw materials can be obtained from cheap materials, natural and industrial waste silicon sources (Balaji et al. 2022; Liu et al. 2025). In this way, both the recovery of industrial by-products will be ensured and the cost of the final product will be reduced by using natural materials as silica source (Shah et al. 2021; Adhikary et al. 2022).For this aim, many organic and inorganic materials such as coal fly ash, rice husk ash, perlite have been used in the synthesis of silica aerogels in recent years (Asadi and Norouzbeigi 2018; Seun Samuel Owoeye et al. 2021; Djati Utomo et al. 2022). In order to obtain silica from silicon-containing materials, methods such as calcination, chemical extraction and electrochemistry are used. Natural resources used as a source of silica are generally used by direct extraction or processing, while industrial wastes are usually recycled or other processing methods to obtain silica (Miao et al. 2022). Diatomite, which contain high levels of silicon, are rocks consisting of the fossilized remains of marine organisms, a type of single-celled algae called diatoms (Ma et al. 2014). Approximately 90% of its volume is in void structure and its thermal conductivity is very low. In this way, it is an important source of raw materials, especially for the production of silica-based materials. While diatomites mainly contain silica, they also contain small amounts of minerals such as iron oxide (Fe_2O_3), aluminum oxide (Al_2O_3) (Aggrey et al. 2021). It has a fine, light and porous structure and is used in different application areas in many industries as filtration, isolation and soil improver. Diatomite's have high chemical stability, low density (1.9–2.4 g. cm^{-3}) and large surface area (35–68 m^2 g^{-1}) (Yang et al. 2022b). The usage areas of diatomites are becoming widespread day by day. It is used as a carrier agent for pesticides and plastics in agriculture, absorbent for petroleum and its derivatives, additive material in paint and concrete,

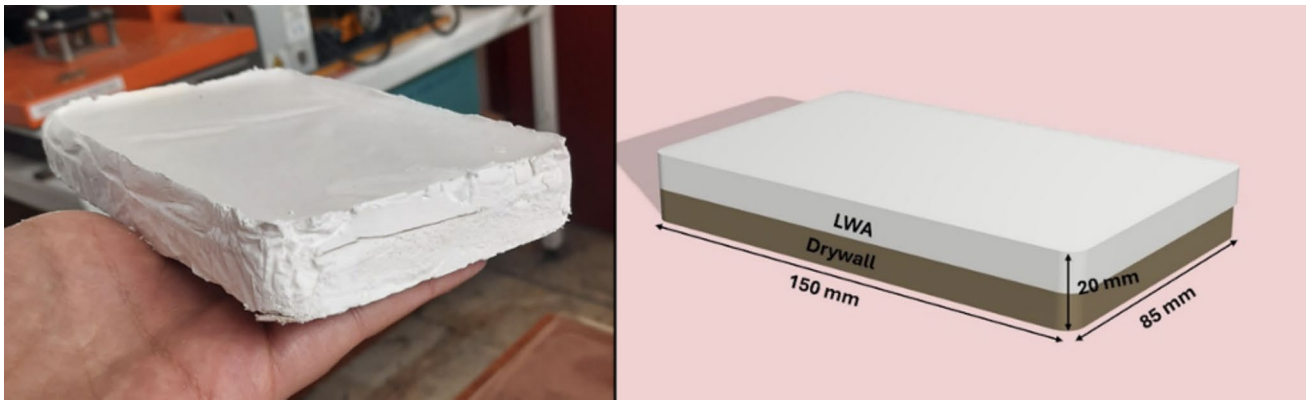

Fig. 1 LWA-plasterboard composite (left side) and 3D representation of the composite (right side)

Table 1 The mass, size, volume, density and porosity of the synthesized light aerogel

Sample name	Mass (g)	Width (cm)	Length (cm)	Height (cm)	Volume (cm^3)	ρa (g/cm^3)	ρb (g/cm^3)	Φ (%)
Diatomite (DT)	11.55	8.5	13.2	0.9	100.98	0.114	1.341	91.50

filtration and purification, sound insulation and many similar areas. (Łach et al. 2023; Pereira et al. 2024). In this study, it was aimed to synthesize environmentally friendly aerogel insulation composites from diatomite's selected as silicon source, which are cheap and free of harmful chemicals. Despite the high production cost and limited production capacity, the commercialisation of aerogels offers significant opportunities for potential markets. In particular, increasing demand in the aerospace, construction, electronics and acoustics sectors could make aerogels economically attractive (Appiah et al. 2024). The use of aerogels in cooling and thermal management of electric vehicle batteries and in light, thin and durable electronic components is also becoming widespread. Aerogels constitute an important market opportunity in acoustic insulation in automotive and construction(Visan and Negut 2025). By increasing the stability of aerogel with solutions such as vacuum packaging and inert gas environments, it will be possible to use LWAs in many fields such as pharmaceutical industry, biotechnology and environmental engineering in addition to their use as insulation materials (Jeong et al. 2024).In this context the homogeneous mixture obtained by using Polyvinyl alcohol (PVA) and carboxymethyl cellulose (CMS) as binders was poured on the plasterboard matrix and freeze dried as a mould and the product obtained was characterized. The use of synthesized lightweight aerogel (LWA) composites as thermal insulation materials in buildings was investigated.

Materials and methods

Materials

Diatomite, a type of natural stone containing high silicon, was obtained from Kutahya/Türkiye. Diatomites in coarse aggregate size were ground into powder and used directly without any pre-treatment. Polyvinyl alcohol (PVA, Mw ~ 89,000–98,000, 99% hydrolyzed, density 1.19 g/cm^3) and carboxymethyl cellulose (CMC, density 1.59 g/cm^3) were used as secondary binder.

Fabrication of diatomite aerogels composite

In this study, raw diatomites used without any pretreatment were used as a skeleton in aerogels synthesized by sol gel method. This situation contributes to reduce the cost problem arising in aerogel synthesis. During the synthesis, diatomite was used at 3% by mass, PVA at 2% by mass and CMC at 0.5% by mass. A 100 ml sol was prepared by mixing polyvinyl alcohol (PVA), carboxymethyl cellulose (CMC) and deionized water at 80 °C until homogenized (Do et al. 2021). Then diatomite was added to the sol solution at 3% by mass

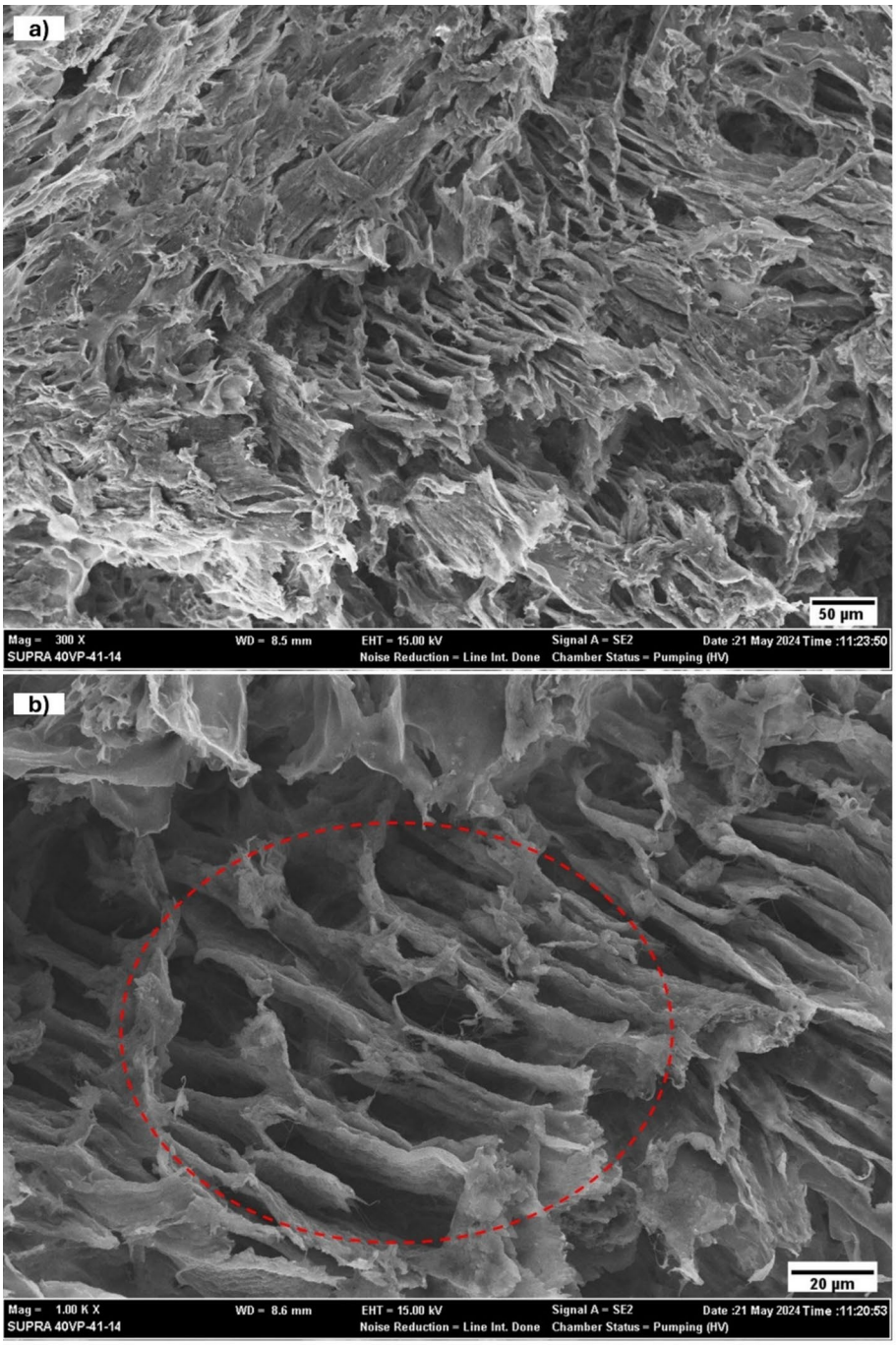

Fig. 2 SEM images are captured at 300x (**a**) and magnification of 1000x (**b**)

and stirred at 80 °C for 3 h. The prepared sol solution was homogenized in a homogenizer at a speed of 2000 rpm for about 15 min after some cooling, after mixing, each sample was poured onto a prepared plasterboard sheet with a thickness of 10 mm and a length of 85*150 mm. The composite samples in wet gel form were first frozen at −80 °C for 48 h and then freeze-dried at −60 °C for 48 h under 1×10^{-3} millibar vacuum. The dried LWA-plasterboard composite structure removed from the mould is given in Fig. 1. In the method called lyophilization, the water trapped in the pores is freeze-dried in a vacuum under low pressure (Niculescu et al. 2024). The most important advantages of the method are efficient protection of sensitive compounds used in the synthesis process, preservation of structural integrity,

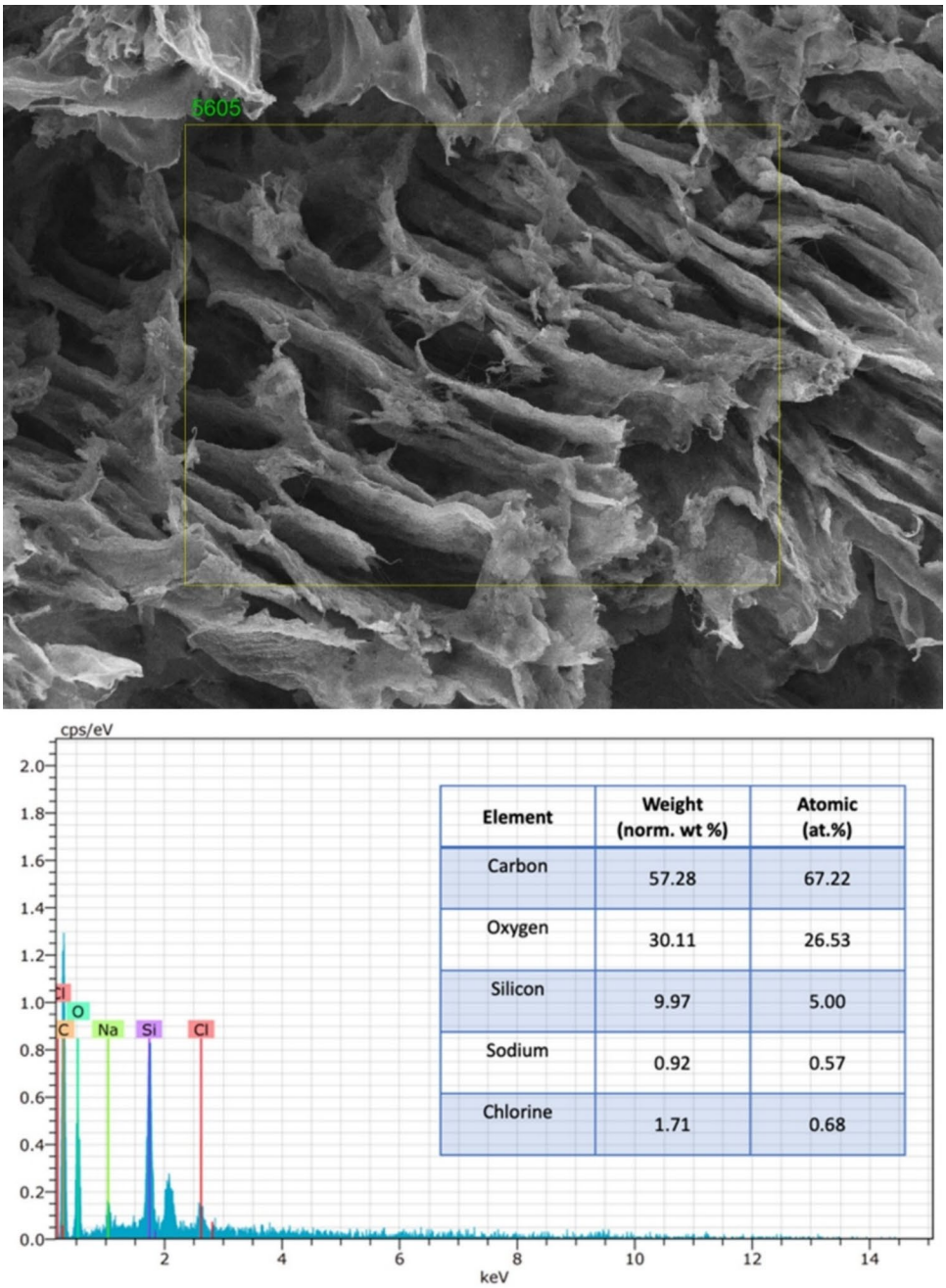

Fig. 3 EDX analysis of light weight aerogel synthesized with diatomite

control of product quality and stability (Peng et al. 2022). The method allows the water in the compounds to evaporate rapidly to the solid phase state, preserving the integrity of the structure at low temperature and achieving a homogeneous, regular porous structure (Ge et al. 2025).

Characterization

To determine the surface properties, microstructure properties and particle size of the raw diatomite and light weight aerogels obtained by using diatomite, scanning electron microscopy (SEM) was used. During the analysis, a ZEISS brand SUPRA 40 V model SEM–EDX device was used with an SE detector under a voltage of 15 kV. Before SEM analysis, the samples were coated in a Quorum mark, Q300 model coating device under Pt source for 1 min with a coating thickness of approximately 100 nm to make the samples conductive. Fourier Transform Infrared Spectrometer (FTIR/PerkinElmer—Spectrum II) and X-Ray Diffractometer (XRD/Rigaku Miniflex) were used to determine the functional groups and phase composition of light aerogels, respectively. After the light aerogel

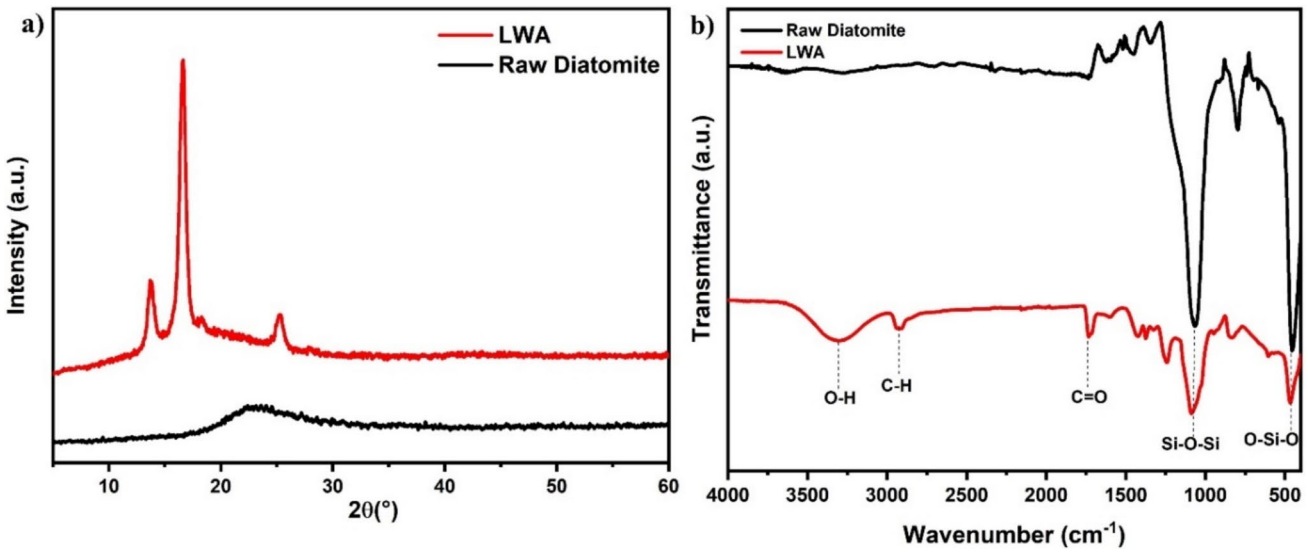

Fig. 4 XRD (**a**) and FTIR spectra of the silica aerogels from diatomite prepared using PVA/CMC (**b**)

samples were synthesized and dried, their density and porosity were calculated. Bulk densities (ρa) of the aerogel samples (Eq. 1) were determined by calculating their volumes from their dimensions and masses (Table 1).

$$\rho_a = \frac{m}{v} \tag{1}$$

m_N is the mass of raw diatomite used (g), m_{CMC} is the mass of CMC (g), m_{PVA} is the mass of PVA (g), ρ_N, ρ_{CMC} and ρ_{PVA} are the densities of the sample (raw diatomite), CMC and PVA respectively and ρ_{PVA}: 1.19 g/cm^3, ρ_{CMC}: 1.59 g/cm^3, ρ_{DT}: ~ 2.05 g/cm^3.

$$\rho_b = \frac{m_N + m_{CMC} + m_{PVA}}{\frac{m_N}{\rho_N} + \frac{m_{CMC}}{\rho_{CMC}} + \frac{m_{PVA}}{\rho_{PVA}}} \tag{2}$$

In the calculation of the porosity (Φ) ratio in %, the bulk densities (ρ_a) of the samples and the actual densities (ρ_b) of the components used during the synthesis (Eq. 2) were considered (Eq. 3).

$$\phi = \left(1 - \frac{\rho_a}{\rho_b}\right) \times 100 \tag{3}$$

(Do et al. 2020) synthesized cellulosic lightweight aerogels using pineapple leaf fibres, a type of agricultural waste, and PVA. In the synthesized aerogel, 99% porosity and 0.013–0.033 g/cm^3 density were obtained. In another lightweight aerogel sample synthesized using fly ash, 95.78% porosity and 0.072 g/cm^3 density were determined for the sample with 3% fly ash by mass (Do et al. 2021). Similarly, high porosity (95.6%) and ultra-low density (0.055 g/cm^3) were obtained in aerogels prepared by doping car tyre wastes and fly ash (Le et al. 2024), while in another study, nearly 90% porosity and 0.10–0.19 g/cm^3 density structure were obtained in aerogels doped with fly ash and PVA binder (Duong et al. 2021b).

In this study, bulk density (ρ_a) was calculated as 0.114 g/cm^3 and porosity value (Φ) was calculated as 91.5% in the lightweight aerogel sample synthesized using diatomite. It is possible to say that the results are compatible with the literature.

Results and discussion

Surface morphologies of raw diatomite (Figure S1) and lightweight aerogels synthesized using diatomite, PVA and CMC were determined by scanning electron microscopy (SEM) (Fig. 2). When the SEM image of the raw diatomite is examined in Figure S1, it is seen that the silica minerals (SiO_2) exhibit morphological features with microscopic structure, regular structure and honeycomb-shaped cell wall. The diatomite selected as the silica source has a large void volume as well as a highly porous structure. When the EDS results of raw diatomite are analyzed in Figure S2, it is possible to say that the main component of diatomite consists of silica (Si) and oxygen (O). The presence of only Si and O in the EDS spectrum indicates that the source is a pure silica source. The elemental compositions of raw diatomite (Figure S2) and silica aerogels were analyzed by energy dispersive X-ray spectroscopy (EDS) analysis. Figure 2 SEM

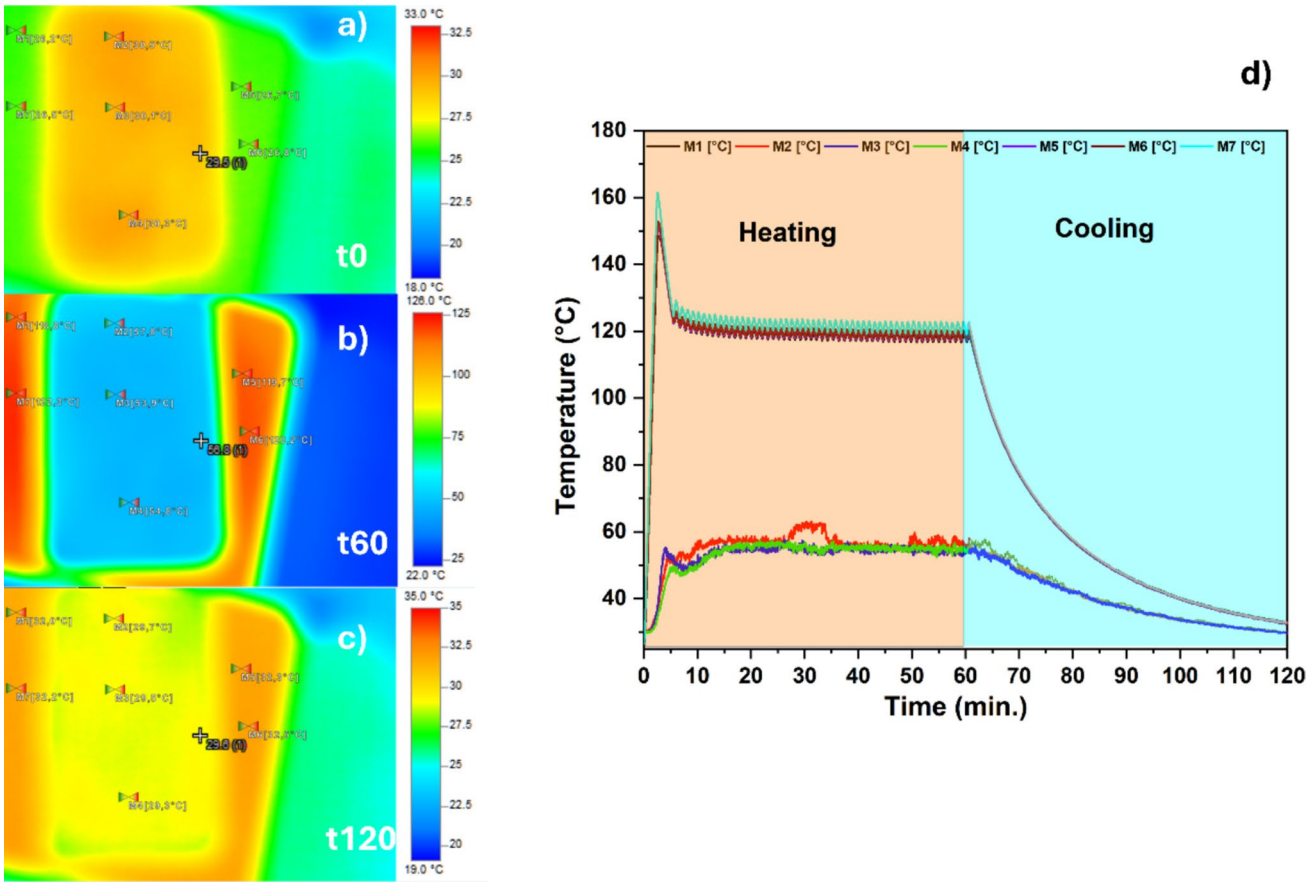

Fig. 5 Thermal camera images at t0 (**a**), t60 (**b**) and t120 (**c**) of diatomite doped lightweight aerogel composite and heating and cooling graphs (**d**)

Table 2 Temperature changes of diatomite doped lightweight aerogel composite at t0 and t60

Lightweight aerogel with diatomite	Warming moment		Cooling moment	
	t0	t60	t0	t60
Plate surface temperature	26 °C	108 °C	112 °C	29 °C
Sample temperature	32 °C	53 °C	50 °C	26 °C

images show that the light aerogel exhibits a cellular pore structure. The homogeneous distribution of the pore structure improves in relation to the homogenization time of the sol solution. It is known that materials with high porosity provide high efficiency in heat and sound insulation. In the synthesized lightweight aerogel, relatively regular, homogeneous and cellular pore structure and interconnected pore network increase the amount of air trapped in the pores (Do et al. 2020; Duong et al. 2021b; That Buu et al. 2023). The amount of air trapped in the pores increases, the amount of heat and sound transmission decreases and insulation is provided. The material with high porosity will also be very light. This lightness obtained is certain to reduce the building load of composites used as building material. In the study, freeze drying was preferred as the drying method of aerogels. In the drying phase, the liquid phase in the hydrogel structure rapidly turns into solid phase and both the skeletal structure is preserved and the regular internal structure is obtained. This will improve the insulation performance of the material (Do et al. 2020). Examination of the EDS spectrum showed that Si, C and O are the dominant components in the light aerogel structure in high mass ratio (Fig. 3). In addition to the mentioned component, negligible Na and Cl impurities are due to the composition of the raw diatomite used. It is possible to say that the light aerogel sample exhibits a homogeneously distributed elemental structure.

The crystal structure of the obtained LWA was elucidated using XRD. As seen in Fig. 4a, a broad peak of SiO_2 in amorphous structure is observed at 2θ 23° in Raw

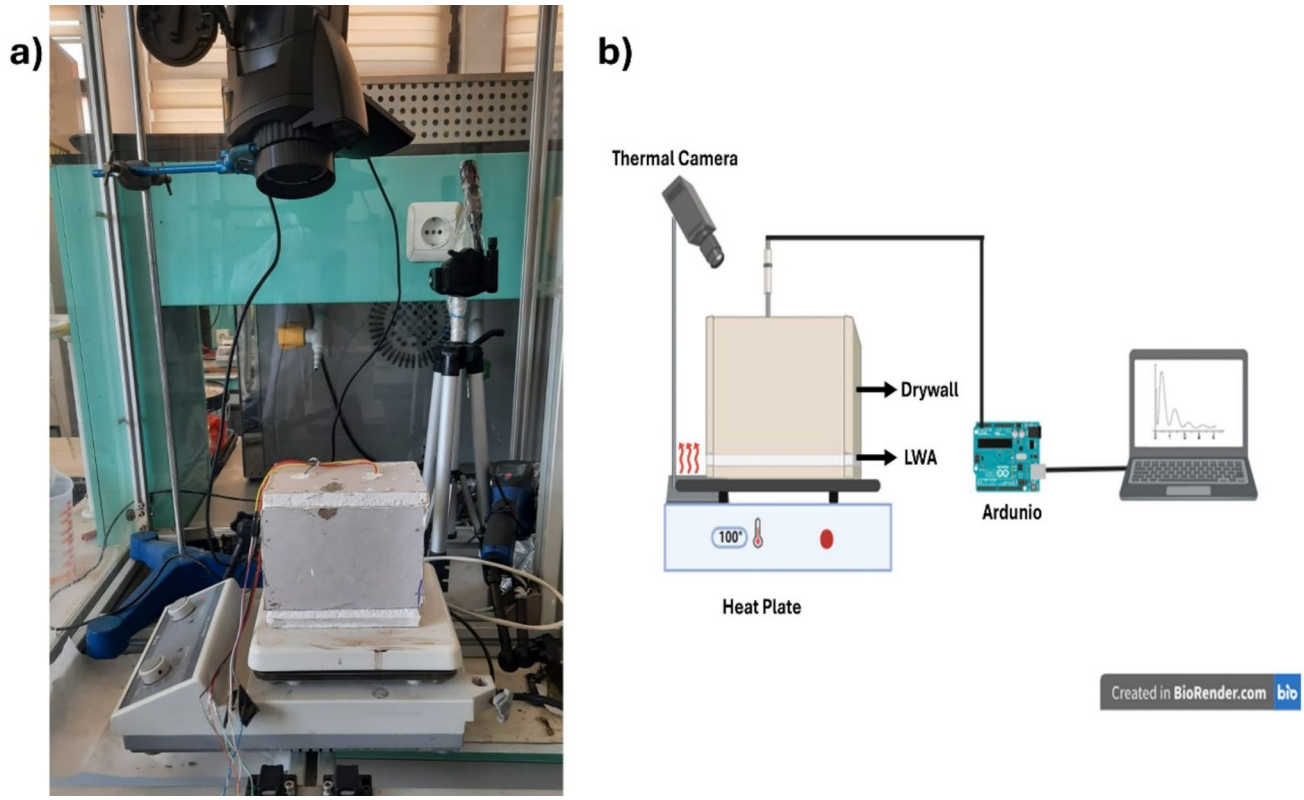

Fig. 6 Thermal insulation application (**a**) and schematic representation (**b**) of the LWA structure

Diatomite. Polymers with crystalline region have high and sharp diffraction peaks, while polymers with amorphous structure have broad diffraction peaks (Xie et al. 2023). According to the XRD graph of LWA, the peaks at 2θ 13.87°, 16.68° and 25.39° are due to the PVA in the LWA structure (Yi et al. 2024).

After the elucidation of the crystal structure of the LWA structure, the FT-IR spectra of the diatomite-based and polymer doped synthesized lightweight aerogels are given in Fig. 4b. FT-IR spectra of light aerogels synthesized using diatomite are given in Fig. 4b. The broad and strong peak at 3315 cm^{-1} wavelengths, which represents the typical bands of PVA, is the stretching peak of the -OH bond. In aerogel matrix, the -OH bond is known to hold solid particles together (Le et al. 2024). The band at 2909 cm^{-1} wavelengths refers to the C–H functional group arising from the presence of PVA and CMC. The characteristic peak observed at 1085 cm-1 wavelength shows Si–O-Si group, O-Si–O functional group at 423 cm^{-1} wavelengths (Ilia et al. 2009; Duong et al. 2021b; Liu et al. 2023).

The thermal conductivity of LWA was carried out with FOX-50 heat flow meter apparatus according to EN 12664 standard. The system consists of top and bottom plates, two heat flow meters and a protector to prevent heat losses. The LWA was placed between the top and bottom plates and the test was performed with an increase of 10 °C(Ruuska et al. 2017; Davraz et al. 2025). As a result of thermal conductivity measurement, LWA was found to have 0.041 W/(m.K).

In order to perform the mechanical testing of the LWA, a compression test was performed. In this context, different loads were applied to samples (n = 5) of 2*2 cm^2 size and 7.00 mm height. As can be seen in Figure S3, the amount of shrinkage increased proportionally with the increase in compression force. The load applied for 10% unit deformation was approximately 100 kPa, while for 30% deformation it was measured as approximately 735 kPa. (Do et al. 2021; Xu et al. 2023). Compared to conventional aerogels, LWA showed relatively high strength despite its low density and high porosity.

Although lightweight and highly porous aerogels are known as excellent insulation materials, their fire resistance is limited (Li et al. 2025). By improving the fire resistance of aerogels to be used as building materials, material safety will increase and it will be possible to obtain fire resistant structures. Fire resistance of aerogels can be increased by coating with ceramic-based materials, doping with boron-containing compounds and adding Al_2O_3 to the aerogel composition or surface coating (Shao et al. 2024). In addition, fireproof polymer coatings applied to the aerogel surface

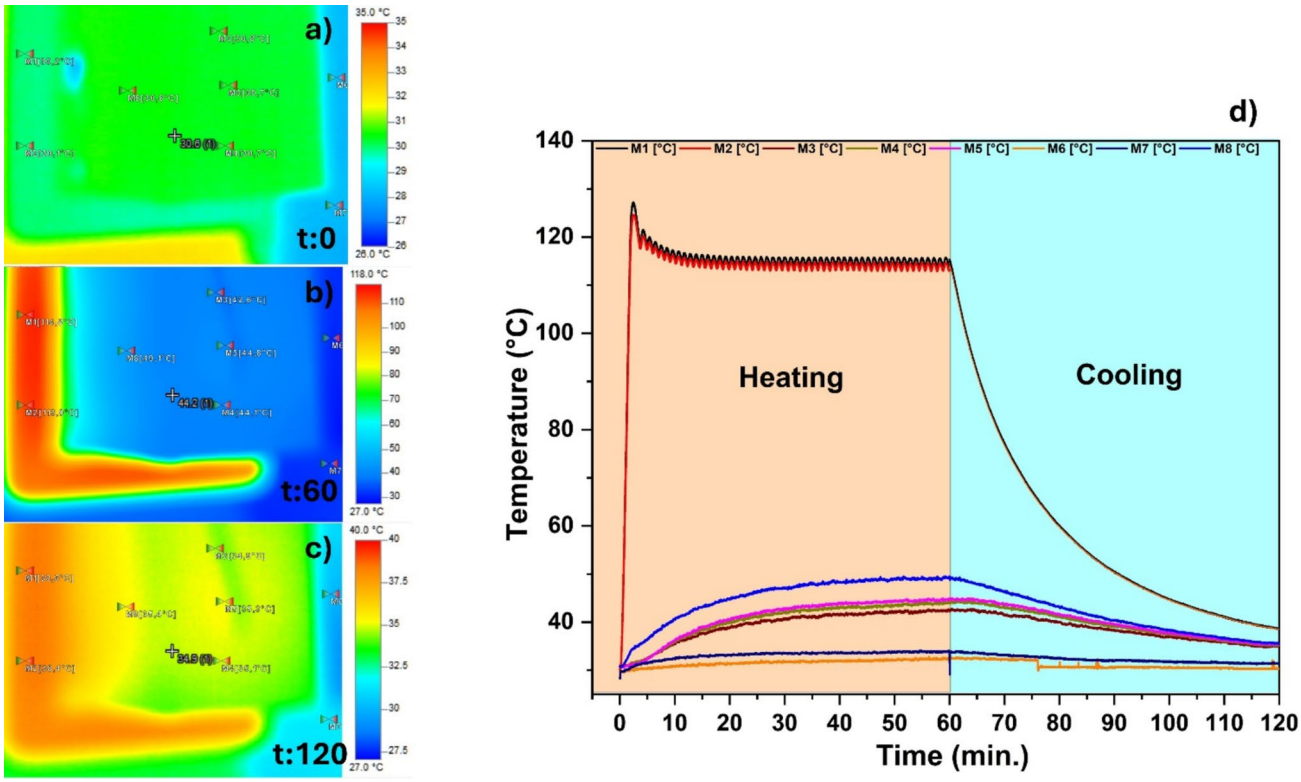

Fig. 7 Graph of thermal camera measurements and surface temperatures of test box t0 (**a**), t60 (**b**) and t120 (**c**) with plasterboard substrate and **d** time-dependent temperature variations of the measurement points (The color change from blue to red in the images indicates an increase in temperature)

show resistance to fire while maintaining low thermal conductivity. By increasing the safety of use of aerogels and providing resistance to fire, the use of this material as a building material will become widespread (Liu et al. 2021; Zhou et al. 2025). In order to determine the resistance of LWA aerogel to combustion, the samples cut in 20*20 mm dimensions were directly ignited with a lighter for 1 s. In the combustion test on 5 identical samples, each sample was completely carbonised by complete combustion at approximately 48 s (Figure S4). Since polymer doped samples are not exposed to any flame retardant modification during synthesis, it is expected that their flammability will be high. Various studies have reported that the use of flame retardant agents to prevent the flammability of polymeric aerogels will produce successful results. (Xu et al. 2023; Liu et al. 2025; Sui et al. 2025).

Examining the heating graph Fig. 5a for the lightweight aerogel composite synthesized with diatomite, it was observed that the temperature started at about 26 °C at the M4-M5 plate surface measurement points and reached 150 °C in about two minutes. During the same period, the in-sample temperatures (M1-M2-M3) were measured as 32 °C. Within the first 10 min, the internal temperature of the specimen stabilized at around 50 °C and reached around 53 °C by t60. It was observed that the heater surface temperature increased to approximately 108 °C at t60. When Fig. 5, the cooling graph for the same sample is analyzed, it is observed that the heater surface temperature is approximately 112 °C at t0 and the sample internal temperature is approximately 50 °C at the beginning. It was reported that the heater surface temperature decreased to approximately 42 °C within the first half hour, while the internal temperature of the sample was measured as 32.5 °C. At t60, it was observed that the internal temperature of the sample decreased to approximately 26 °C and the heater surface temperature ended at 29 °C.

Time-dependent temperature changes of diatomite doped lightweight aerogel and aerogel composite were observed by thermal camera. The in-sample temperatures of the samples were measured during heating at 100 °C for 1 h and cooling at 100 °C for 1 h, respectively. Hot plate was used for heating both light aerogel and light aerogel composite. Thermal changes were recorded by selecting three different measurement points inside the sample and four different measurement points on the plate surface (Table 2). In the obtained time-dependent temperature change graph, the temperature changes and equilibrium points of the sample during heating and cooling at the beginning (t0) and end (t60) are analyzed.

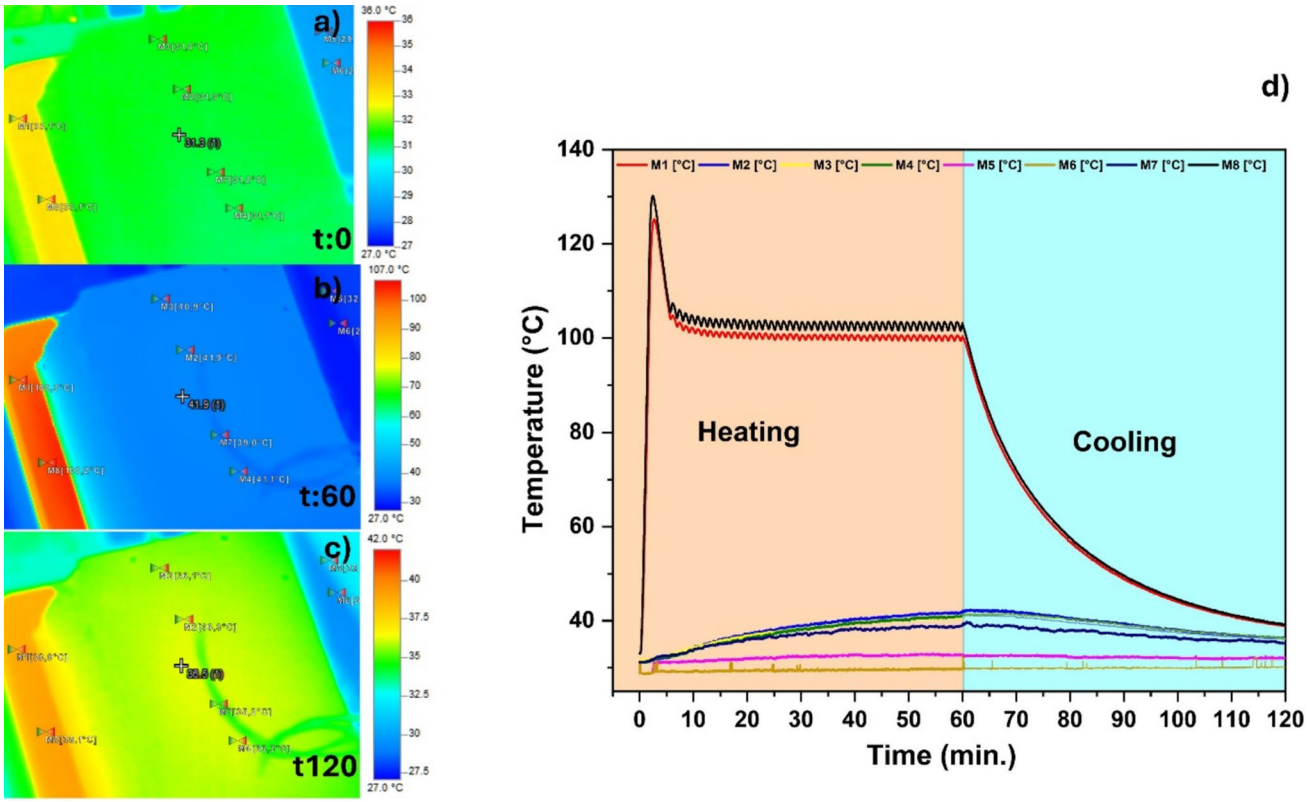

Fig. 8 Graph of thermal camera measurements and surface temperatures of test box t0 (**a**), t60 (**b**) and t120 (**c**) with LWA composite substrate and **d** time-dependent temperature variations of the measurement points (The color change from blue to red in the images indicates an increase in temperature)

In addition, the temperature measured on the plate surface and the temperature difference inside the sample are measured simultaneously.

In order to understand the effect of the LWA composite structure on thermal insulation, a test box with plasterboard walls shown in Fig. 6 was constructed. The test box measurements were carried out in a Plexiglas cabinet with no air flow. The bottom wall of the box heated from the bottom was combined with LWA composite structure and plasterboard and the internal temperature was measured with Ardunio DHT11 sensor and the surface temperatures were measured using a thermal camera (Testo 885–2).

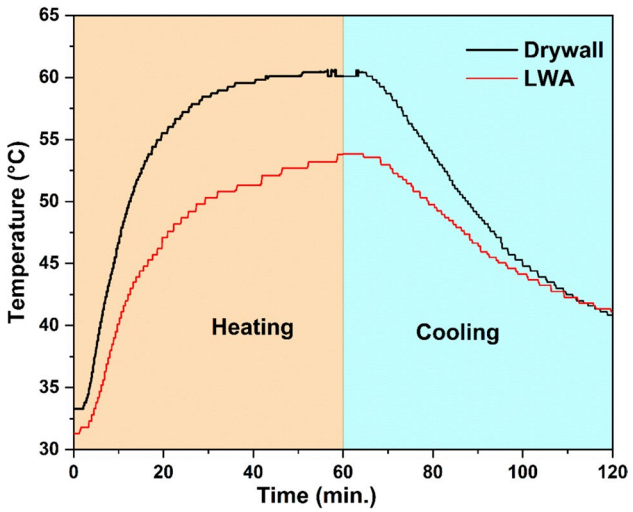

Fig. 9 Internal temperatures of plasterboard and LWA test boxes

After the test boxes with plasterboard and LWA composite substrate were prepared, their external and internal temperatures were measured separately. The temperature was increased in the first 60 min and switched off in the last 60 min. Firstly, measurements were started with the test box with plasterboard base. Figure 7a–c shows the thermal temperature images of the drywall box at t0, t60 and t120, respectively. Figure 7d shows the temperature change graphs of the thermal camera images of different points on the test box. The temperature on the side surface indicated by M8 reached 49 °C, while the surface temperatures of M3-M5 reached an average of 44.83 °C. The ambient temperature is indicated by points M6 and M7. In general, it was observed

Table 3 Comparison of LWA with insulation materials

Material	Thermal conductivity W/ (m.K)	Density (kg/m^3)	Compressive strength (kPa)	Fire resistance	Cost
XPS	0.030–0.040	≥ 25	150–700	Poor	Medium
EPS	0.035–0.040	≥ 15	60–200	Poor	Medium
PUR	0.030–0.040	≥ 30	20–100	Poor	Medium
ECB	0.045–0.055	90–490	100–200	Poor	Medium
Rock wool	0.030–0.050	20–200	20–200	Good	Low
Fiberglass	0.030–0.044	10–100	–	Good	Medium
LWA aerogel	0.041	114	100–735	Poor	Low

XPS extruded rigid polystyrene foam, *EPS* expanded polystyrene rigid foam, *PUR* polyurethane foam, *ECB* expanded cork board

that the box surface temperature increased in the first 60 min and the surface temperature decreased after the heat plate was switched off.

The data of the test box with LWA composite substrate are shown in Fig. 8 *a-d*. Figure 8 a–c, g shows the thermal temperature images of the LWA composite box at t0, t60 and t120, respectively. Figure 6d shows the temperature change graphs of thermal camera images of different points on the LWA composite-based test box. Points M3, M3, M4 and M7 in Fig. 7e–g shows the box floor temperature measurement points. As a result of the temperature application, the ceiling temperature increased to an average of 40.72 °C at the end of the 60th minute. Compared to the drywall-based test box, the LWA composite-based exhibited similar temperature profiles, although the presence of LWA resulted in lower surface temperatures. The internal temperature changes of the test boxes with plasterboard and LWA composite substrate are shown in Fig. 9. It is seen that the internal temperatures of the test boxes with plasterboard and LWA composite substrate reached 60 °C and 53 °C at 60 min, respectively. Examination of both test box models showed a temperature difference of approximately 7 °C.

Traditional thermal insulation materials are categorized in terms of thermal conductivity, density, specific heat capacity, thermal transmittance, mechanical strength and resistance to fire (Table 3) (Balaji et al. 2022; Kalkan and Gündüz 2023; Sayadi et al. 2024; Zhang et al. 2024).

The measurements showed that the LWA composite structure provided higher insulation performance than the plasterboard structure and prevented the internal temperature increase. The low density of silica aerogels, 0.1–0.3 g/cm^3, also complies with ISO 8302. The mechanical properties and durability of aerogels can be described according to ASTM E1952 standard. The mechanical strength of silica aerogels is met by forming them into composites. This improves the flexibility and durability of the material, making it a strong alternative to industrial thermal insulation solutions. Freeze drying method used in LWA production is a widely used drying method in aerogel synthesis. Freeze drying method can be used to obtain high quality aerogels for large scale production. In order to maintain the homogeneous structure in large volume production and to ensure consistency in quality, each stage of the method should be monitored. The prolongation of the production process will lead to an increase in energy consumption. Future research will aim to optimise the process with new techniques to improve the freeze drying process, shorten the production process and increase energy efficiency (Tchessalov et al. 2023; Pan et al. 2024). Aerogels exhibit poor durability against external factors due to their extremely light and porous structure. Although the structural integrity is preserved by freeze-drying, under extreme conditions such as high humidity, high temperature or UV exposure, structural integrity may deteriorate and material performance may decrease. With future research, aerogel performance can be increased in the medium and long term by strengthening the composition by including protective coatings to increase the durability of aerogel, and various additives containing durable polymers that will not disrupt the aerogel structure (Guo et al. 2025). The results obtained show that aerogel composite structures offer superior insulation performance in the presence of heat sources, providing innovative and sustainable applications in thermal insulation.

Conclusion

In this study, the synthesis of lightweight aerogels using diatomite as silica source and the potential application area of the obtained composite were investigated. In

the study, diatomite as silica source, PVA and CMC as binder, water as solvent, sol–gel as synthesis method and freeze drying as drying method were preferred. The drying method imparted high porosity and light weight to the obtained aerogel. The synthesized lightweight aerogel samples exhibit a very low density (0.114 g/cm^3) and a high porosity (91.50%). These properties increase the potential usability of the material in applications such as thermal insulation in buildings. The thermal conductivity of the obtained LWA aerogel was measured as 0.041 W/(m.K). The lightweight aerogel composite obtained can be used as a building material by pouring on ready-made plasterboard. Thus, the composite provides advantages in application areas such as heat and sound insulation in buildings. In order to determine the insulation effect provided by the prepared LWA composite, a plasterboard test box with LWA composite base was prepared. In order to make comparative measurements, a box with a plasterboard base was prepared and internal temperatures were measured with Ardunio DHT11 sensor and surface temperature changes were recorded with a thermal camera. Examination of both test box models showed a temperature difference of approximately 7 °C. The diatomite used as silica source during synthesis was not subjected to any pretreatment. Thus, the synthesized material becomes environmentally friendly and cost efficient. It is thought that such innovative materials will contribute to sustainability in industrial applications. In conclusion, this study provides a new and innovative opportunity for the use of lightweight aerogel synthesized using diatomite as a building material. It is thought that the researches to be carried out using diatomite will enable innovative materials to be obtained in other industrial areas.

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Data availability The data and materials used in this research are available on request.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval This research did not involve human or animal samples.

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