

Aerogel-Based Materials for Improving the Building Envelope's Thermal Behavior: A Brief Review with a Focus on a New Aerogel-Based Rendering

Mohamad Ibrahim, Pascal Henry Biwole, Patrick Achard and Etienne Wurtz

Abstract Most developed countries have set an objective to reduce their energy consumption and green house gas emissions. In most countries, the building sector is the largest energy consumer. This sector offers a significant potential for improved energy efficiency through the use of high-performance insulation and energy-efficient systems. For existing buildings, renovation has a high priority in many countries, because these buildings represent a high proportion of energy consumption and they will be present for decades to come. Several studies have shown that the best way to reduce the energy consumption in buildings remains the reduction of heat losses through the envelope. Nowadays, there is a growing interest in the highly insulating materials such as aerogels. Due to their highly insulating characteristics, aerogels are becoming one of the most promising materials for building insulation. Although the cost of aerogel-based materials remains high for cost-sensitive industries such as building industry, this cost is expected to decrease in the following years as a result of the advancement in the aerogel production technologies as well as the large-scale material production leading to lower unit costs. In this study, a brief review on aerogel applications in buildings is presented.

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Some examples of opaque aerogel-based materials and translucent aerogel-based systems are illustrated. Then, a new insulating rendering based on silica aerogels is presented. Its impact on energy performance for different houses is examined.

Keywords Energy efficient envelopes · Aerogel-based renderings · Thermal insulation · Building rehabilitation · Green building

1 Introduction

According to experts from intergovernmental panel on climate change (IPCC), it is almost certain that global warming observed over the past century is linked to greenhouse gas emissions produced by the human activities. To limit the aggravation of this phenomenon, the countries must reduce their greenhouse gas emissions. All business sectors are concerned, but the building sector requires a special attention because, according to a report on energy trends in buildings (Enerdata 2012), the building sector consumed about 41 % of total final energy requirements in Europe in 2010. It is the largest end-use sector, followed by transport (32 %), industry (24 %), and agriculture (2 %). The final energy consumption of buildings has increased by around 1 % per year since 1990 (Enerdata 2012).

The building sector offers significant potential for improved energy efficiency through the use of high-performance insulation and energy-efficient systems. For existing buildings, renovation has a high priority in many countries, including France, because these buildings represent a high proportion of energy consumption and they will be present for decades to come. Several studies (Verbeeck and Hens 2005; Enkvist 2007; EEW 2013) showed that the most efficient way to curb the energy consumption in the building sector (new and existing) remains the reduction of the heat losses by improving the insulation of the building envelope. For retrofitting and even for new buildings in cities, the thickness of internal or external insulation layers becomes a major issue of concern. Nowadays, there is a growing interest in the so-called super-insulating materials, such as aerogels. The unique properties of aerogels offer many new applications in buildings. Their extraordinary low thermal conductivity as well as their optical transparency allows their use for insulating building facades and insulating window panes.

Since their first discovery in the 1930s (Kistler 1931), aerogels have shown a great progress in the last decades. Due to their superior characteristic, they are used in different sectors including buildings, electronics, clothing, space applications, etc. However, lowering their production is still the most challenging issue for manufacturers, especially, when being used in the building sector. The cost of the aerogel-based insulation materials remain high compared to conventional insulation which hinders their entry to the market. Research is still continuing to develop more advanced technologies to lower the aerogel's production costs and enhance their performance.

2 Aerogel-Based Insulating Materials: Building Applications

Silica aerogels are silica-based dried gels having very low weight and excellent thermal insulation performance. Specifically, they have high porosity (80–99.8 %), low density (3 kg/m^3), and low thermal conductivity ($0.014 \text{ W/m}^{-1} \text{ K}^{-1}$) (Dorcheh 2008). Silica aerogels are an innovative alternative to traditional insulation due to their high thermal performance, although the costs of the material remain high for cost-sensitive industries such as the building industry. Research is continuing to improve the insulation performance and to decrease the production costs of aerogels. The unique properties of aerogels offer many new applications in buildings (TAASIS 2011). The extraordinary low thermal conductivity of aerogels as well as its optical transparency allows its use for insulating building facades and insulating window panes. Two different types of silica aerogel-based insulating materials are being used in the building sector. The first type is the opaque silica aerogel-based materials, and the second one is the translucent materials.

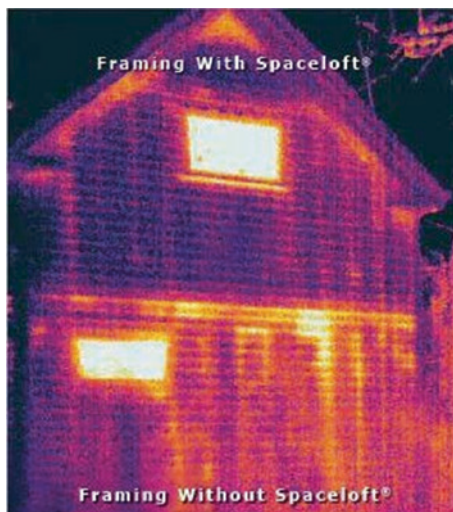
2.1 Opaque Silica Aerogel-Based Materials

Aerogel blankets/panels are used to insulate building walls, grounds, attics, etc. Aspen Aerogels Inc. (Northborough, MA, US) has developed an insulation blanket based on silica aerogels, Spaceloft® (Aspen Aerogels, Spaceloft® www.aerogel.com/products/pdf/Spaceloft_MSDS.pdf). It has a thermal conductivity of 0.0131 W/(m K) . Spaceloft® was used to convert an old mill house in Switzerland into an energy-saving passive house (Fig. 1). A 9 mm thickness layer was used externally and internally on the walls and also internally on the floors. The U -value of the walls improved from 1 to $0.2 \text{ W/(m}^2 \text{ K)}$ (Aspen Aerogels, Case study, www.aerogel.com/markets/Case_Study_House_Renovation_web.pdf).

Fig. 1 Aerogel blanket for retrofitting an old building



Fig. 2 A thermographic image of a timber wall where the studs of the *top floor* are insulated with a thin layer of aerogel insulation whereas the *ground floor* is not



Due to its small thickness, Spaceloft[®] can be installed on interior walls of buildings preserving the area of the occupied spaces. A case study was done in the United Kingdom where a number of governmental housing units were retrofitted by adding Spaceloft[®] insulation layer at the interior wall surfaces (Aspen Aerogels, Case study, www.aerogel.com/markets/Case_Study_Interior_Wall_web.pdf). A 44 % reduction in the U -value, a 900 kWh/year energy reduction, and a 400 kg/year reduction in carbon emissions were obtained.

In a typical building, the framing is not insulated, resulting in heat losses through the studs. Spaceloft[®] insulation decreases heat loss through thermal bridges and improves thermal performance up to 40 % in steel studs and up to 15 % in wood studs. Figure 2 shows the reduction in the thermal bridges heat losses between the ground floor un-insulated frames and the top floor insulated frames (Aspen Aerogels, Case study, www.aerogel.com/markets/Case_Study_Framing_web.pdf). From this thermographic figure, it is illustrated that the aerogel blanket allows an almost uniform temperature distribution throughout the wall area (upper floor); however, we can see the variation in the ground floor's wall due to the increased heat losses through thermal bridges as a result of the absence of the aerogel blanket.

In another study, thermal performances and experimental tests were performed on walls and roofs using aerogel insulation (Kosny et al. 2007). Hot box measurements on wall assemblies containing aerogels showed that the R -value of wood-framed walls is improved by 9 % and that of a steel-framed wall by 29 %. Finite difference simulations performed on steel-framed wall assemblies using 0.6-cm-thick aerogel strips showed that aerogel can help in reducing the internal surface temperature differences between the center of the cavity and the stud location from 3.2 °C to only 0.4 °C. For roof structures, hot box measurements performed on the fastened metal roof insulated with aerogel strips showed an increase in the overall roof R -value by about 14 %.



Fig. 3 Test bedroom and internal wall insulation of aerogel (*blue colored*) (Cuce et al. 2014b)

At the University of Nottingham, an experimental test house was built where a 2-cm layer of aerogel blanket was added at the internal surface of one of the bedroom's exterior walls. Co-heating test procedure was performed to the test bedroom before and after retrofitting, and thermal characteristics were determined both theoretically and experimentally. Also, heat losses through thermal bridges were analyzed with thermographic images. Figure 3 shows the test house, test bedroom, and the places insulated with aerogel. Initially, the wall had a U -value of 0.55 W/m^2 and was composed of a 1.3-cm layer of gypsum plaster (inner wall layer), a 10-cm layer of concrete block, a 5-cm cavity fill, and a 10-cm layer of brickwork. As a retrofit procedure, a 2-cm layer of aerogel blanket was applied. The U -value of the external wall after post-retrofit was determined to be $0.30 \text{ W/m}^2 \text{ K}$ resulting in heat losses reductions of around 46 %. In addition, a significant decrease in the thermal bridge heat losses was obtained in this study.

2.2 Translucent Silica Aerogel-Based Materials

Another type of silica aerogel-based materials which are used in buildings is the translucent insulation materials. These materials have the advantage to combine a low thermal conductivity along with high transmittance of solar energy and

Fig. 4 Cross-section through the granular aerogel-based glazing (Reim et al. 2002)

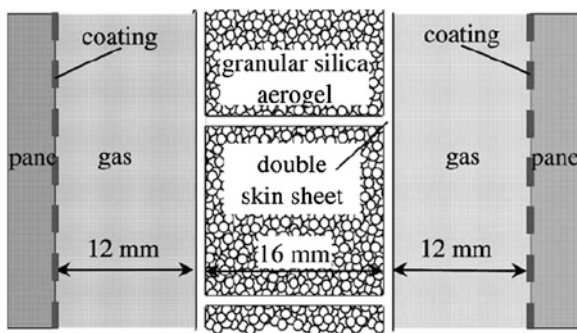
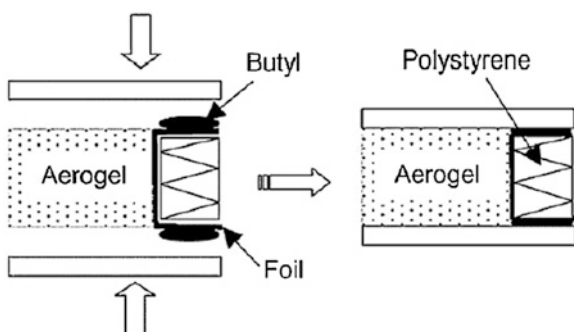


Fig. 5 Cross-section of the monolithic aerogel-based evacuated glazing (Jensen et al. 2004)



daylighting. Research has been conducted in the last decade on the development of highly insulating windows based on granular aerogels and monolithic aerogels (Pajonk 1998). A new glazing element based on granular silica aerogel was developed at ZAE Bayern, Germany (Reim et al. 2002, 2005). The glazing consists of 16-mm double skin sheet made of polymethylmethacrylate filled with granular silica aerogels separated by two gaps filled with krypton or argon and installing glass panes at the ends (Fig. 4). Two types of granular silica aerogels are used: semi-transparent spheres and highly translucent granulates. Three window systems were developed. The first is a daylighting system by applying a low-e coating (emissivity = 0.08) on the panes. A total solar transmittance between 0.33 and 0.45 and a U -value having a range of 0.44–0.56 W/(m² K) were obtained. The second system is a sun protecting system developed by applying a lower emissivity (0.03) to the glass panes. A U -value of 0.37–0.47 W/(m² K), a visible transmittance of the range of 0.19–0.38, and a solar transmittance between 0.17 and 0.23 were achieved. The third is a solar collector by placing a heat exchanger between a layer of aerogels and two glass panes. When compared to a traditional flat-plate solar collector, the collector using aerogel granules has a reduction in heat losses of about 40 % and has a 3 cm smaller system thickness.

In a project supported by the European Union, a monolithic aerogel-based window was developed (Fig. 5) (Jensen et al. 2004). They obtained a total heat transfer coefficient for the window (U -value) of 0.66 W/(m² K) and a solar transmittance of 0.85 using a 13.5-mm-thick monolithic aerogel. Vacuum glazing technology

Fig. 6 The two test rooms (Cotana et al. 2014)



was also used in developing this window. This U -value can be lowered when using more thickness of aerogel and at the same time keeping the solar transmittance more than 0.75. A case study was done for the Danish climate, where a triple-glazed window filled with argon was replaced by this aerogel-based window for a house built according to the passive house standards. Energy savings of about 19 and 34 % were achieved for 13.5 and 20 mm aerogel thickness, respectively.

In another study, the energy and lighting performance of a glazing system with silica aerogels is analyzed through in situ experiments (Cotana et al. 2014). Two identical test rooms (Fig. 6) were constructed in Perugia, Italy, one serves as the reference case and the other serves as the test case. Both test cells have a double-glazed south window; however, they differ in the filling layer between the window panes. The window of the reference case is filled with air while that of the test case is filled with aerogel granules. The obtained U -value is $1.5 \text{ W}/(\text{m}^2 \text{ K})$ for the reference window and $1 \text{ W}/(\text{m}^2 \text{ K})$ for the aerogel window. These test cells were highly instrumented, and continuous monitoring was performed during the heating season. Thermal energy monitoring showed the aerogel capability to keep the indoor thermal conditions more constant, i.e., total temperature decrease less than $3 \text{ }^\circ\text{C}$, even several days after the heating system switching off. On the other hand, the classic air-filled double-glazing system immediately tended to lower indoor air temperature up to the outdoor temperature values in winter conditions. The heating energy consumption could be decreased up to 50 %. Concerning the lighting characteristics, the aerogel glazing could reduce the daily average illuminance up to 10 % during sunny days. This study showed that such aerogel systems could be a good solution to enhance the building's energy efficiency and indoor thermal comfort.

Buratti and Moretti (2012) investigated experimentally that different glazing systems having granular or monolithic aerogel. Different glazing systems were constructed. The monolithic aerogel was supplied by Airglass AB, Sweden, and the granular ones were supplied by Cabot Corporation, USA (Nanogel[®]). Thermal and light performance of the different systems was measured. They showed that the monolithic aerogel glazing systems has the best performance providing higher light transmittance (0.62) and lower heat transfer coefficient ($0.6 \text{ W m}^{-2} \text{ K}^{-1}$) than the other systems. Also, the solar factor was 0.74. Furthermore, monolithic aerogel between two 4-mm glasses gave a 62 % reduction in heat losses, with a

Fig. 7 Solar thermal collector with aerogel glazing integrated to building facade (Dowson et al. 2012)



17 % reduction in light transmittance when compared to a conventional double glazing that is being used in buildings nowadays.

Another application of translucent silica aerogels is in solar thermal collectors. The idea is to replace the glass cover used in conventional solar collectors with a panel filled with aerogels. In situ performance of such collector integrated to a building's façade is investigated (Fig. 7) (Dowson et al. 2012). This study has shown higher performance than traditional single- or double-glazed solar thermal collectors. The useful energy gains were estimated to be in the range of 118–166 kWh/m²/year for collectors with different aerogel cover thickness. Comparing conventional collectors, the useful energy gains are 110 and 140 kWh/m²/year for a single-glazed collector and a double-glazed collector, respectively. The energy gains could be increased to 202 kWh/m²/year when using high-performance monolithic aerogel.

2.3 Life Cycle Assessment

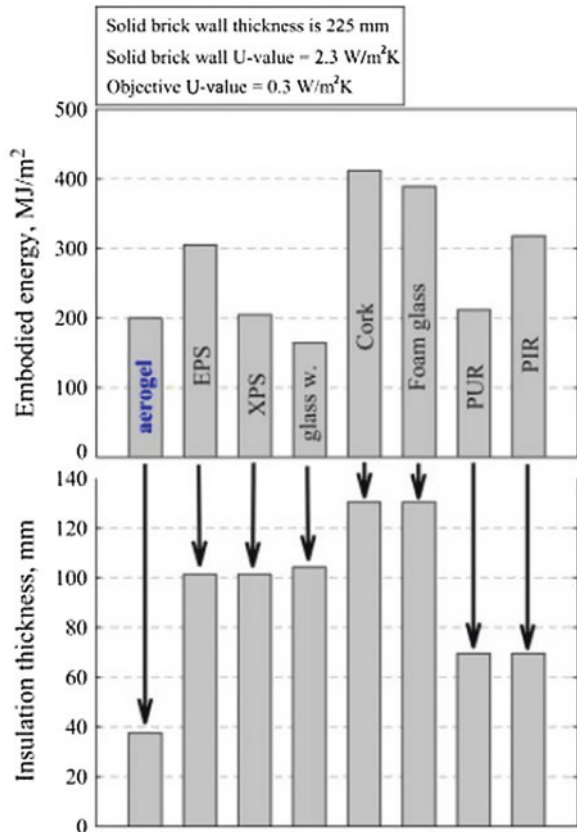
Dowson et al. (2012) investigated the life cycle assessment of silica aerogels. The mass of raw materials and electricity used for the production of 1 m³ of silica aerogel are determined to estimate the energy costs as well as the CO₂ burden during the manufacturing process. Then, this is compared to energy savings and CO₂ emission reduction when a single-glazed window is retrofitted by a translucent aerogel window over a 15 years product lifespan to see whether the resulting operational savings can payback the costs of aerogel production. Results showed that the payback period (PP) for the production cost and its CO₂ burden is within 0.3 and 1.9 years. However, the end of life processing impact, such as recycling, reusing, land filling, etc., and also transport costs were not taken into consideration

in this study. Also, this study is limited to the production of only 1 m³ of silica aerogel; thus, on a full scale (mass production), the results may not reflect accurately the energy cost and the CO₂ emission. Despite these factors, results have demonstrated that aerogel can provide a measurable benefit over its life cycle.

Huang (2012) has studied the feasibility of using silica aerogels in buildings. The energy-saving potential of silica aerogel used as building insulations is calculated by using the life cycle cost analysis. Results showed that silica aerogel can reduce the annual heat losses of a non-insulated building by around 51 %. Moreover, it can reduce about half of the annual heating costs when compared with other insulation materials. However, the cost of silica aerogel-based materials is higher than other traditional insulation materials. The payback time is estimated to be 3.54 years for aerogel materials which is longer than the other competitive solutions (0.22 years for expanded polystyrene, 0.07 years for extruded polystyrene).

Cuce et al. (2014a, b) compared the embodied energy of aerogel insulation with other conventional insulation materials for a simple case of retrofitting an exterior brick wall. Initially, the *U*-value of the wall is 2.3 W/(m² K), and the target *U*-value is 0.3 W/(m² K). Figure 8 shows the embodied energy and the insulation thickness needed to reach the objective using different insulating materials. It can be

Fig. 8 The embodied energy and insulation thickness for different materials used (Cuce et al. 2014a)



seen that aerogel in this regard performs favorably against the other conventional materials, with only glass wool having a lower value. However, the thickness of aerogel insulation is considerably lower meaning that more space savings could be achieved. Space savings is becoming an important factor especially in cities.

In another study, Cuce et al. (2014b) estimated the optimum thickness of aerogel blanket in exterior insulated and un-insulated cavity walls for the climate conditions of Nottingham, UK. They showed that the optimum thickness varies between 2 and 5 cm for already insulated walls and between 3.4 and 6 cm for un-insulated walls depending on the type of fuel being used. Aerogel insulation was found to be very appropriate for the non-insulated cavity walls (PP is around 2–3 years), whereas it is not a reasonable investment for the insulated cavity walls (PP is more than 10 years). Also, the impact of aerogel insulation on lowering the greenhouse concentrations is analyzed. Particularly, the annual reduction of SO₂ emissions for the UK's building stock is determined to be 326,000 and 512,400 tons for coal and fuel oil, respectively.

3 Aerogel-Based Rendering

A very limited number of studies exist on aerogel-based thermal insulating plasters. Barbero et al. (2014) provided an overall analysis of thermal insulating plasters in the European market. They concluded that innovative solutions for thermal insulating plasters based on materials with pore size in nanometer range, such as aerogel, could make a significant contribution to this field, reaching higher level of thermal performance and reducing the needed thickness. Additionally, successful approaches will have the ability to be used on both new and existing buildings, using techniques that are familiar to today's construction industry. According to the authors, thermal insulating plasters have the advantage of being applied on non-aligned, out of square, or, even, curved areas. They are flexible and can be suitable for any architectural and design solutions. Their easy application on the facades facilitates the rehabilitation of existing buildings. Researchers at EMPA building technologies laboratory (EMPA www.empa.ch) compared several insulating plasters found in the market today with the aerogel plaster (see Fig. 9) and concluded that the thermal conductivity of the aerogel plaster is significantly lower than that of the other plasters.

An innovative insulating coating or rendering (note that, in all what follows, the word “coating” is used to refer to an aerogel rendering or mortar having a certain thickness) based on the (super)-insulating materials silica aerogels has been developed (Fig. 10) possessing a low thermal conductivity (Achar et al. 2011 WIPO Patent WO/083174). The invention is a foam of mortar that can be applied to the external wall surfaces of a building to produce a thermally insulating rendering. It consists of water, a mineral and/or organic hydraulic binder, insulating filler comprising a powder or granules of hydrophobic silica xerogel, structuralizing filler (option), and additives (option).

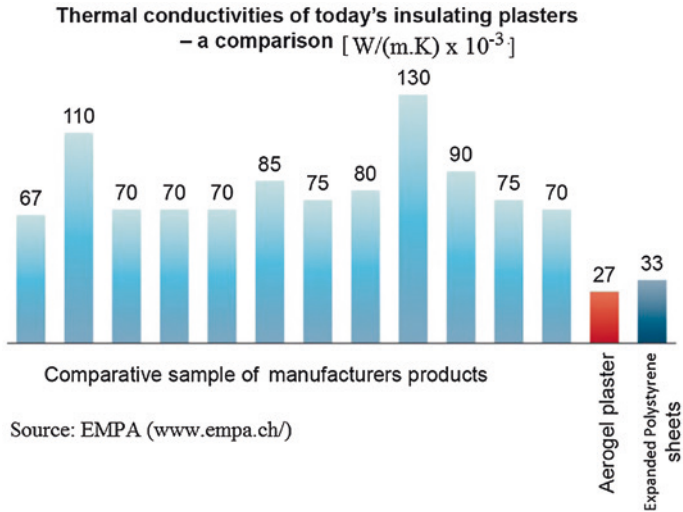


Fig. 9 Thermal conductivity of today's insulating plasters and the aerogel plaster



Fig. 10 The new aerogel-based insulating coating (*rendering*)

The aerogel granules are an industrial product manufactured separately in a specialized plant. Thus, the mortar is made from these aerogel grains that somehow replace the sand used in conventional mortar. The latter is prepared industrially as a dry composition by mixing all the above-mentioned components, and then, the mix is stored in bags and transported to the site for use. Then, on site, the product is mixed with water in order to obtain a paste with a viscosity suitable for the application, for example, by spraying, on the building's exterior surface.

This coating/rendering has been developed mainly for exterior wall surface applications. The coating thermo-physical characteristics are presented in Table 1. They are measured at the French scientific and technical center of buildings (CSTB). Its thermal conductivity is measured by means of guarded hot plate and heat flow meter according to the NF EN standard 12667. Its specific heat is measured by means of differential scanning calorimeter (DSC) according to NF EN 1159-3 standard. Its density is measured according to the NF EN 1602 standard. Its vapor diffusion resistance factor is measured using the Cup method according to the NF EN ISO 12572 standard.

Table 1 Thermo-physical properties of the new aerogel-based insulating coating

Thermal conductivity (W/m K)	0.0268
Specific heat (J/kg K)	990
Density (kg/m ³)	156 (dry)
Vapor diffusion resistance factor (–)	4.25 (average)
Water absorption coefficient (kg/m ² s ^{1/2})	0.184

The thermal conductivity of this new aerogel-based coating (ABC) is 0.0268 W/(m K) which is better compared to that of traditional insulation (See Table 2). Moreover, the volumetric heat capacitance ($\rho * cp$) is much higher than that of traditional insulation.

The rendering's application on the building facades is rather easy. It is done through direct spraying onto the facade manually (using the ordinary techniques well known by builders, such as traditional plastering) or using a plastering machine. This has an advantage over traditional insulations especially for building retrofit cases. Traditional insulation needs a plane surface to be applied on. Furthermore, adjustment, gluing, and even fastening by means of dowels are also needed. Insulation materials are often manufactured in precise dimensions; this can lead to discontinuity in thermal insulation. In this sense, the new rendering takes advantage over traditional insulation: its application is simple, allows a continuous thermal insulation, and adheres directly to the masonry without leaving hollow gaps where moisture could form. This type of rendering can also be used to limit heat losses through thermal bridges. It can be easily applied to places where existing solutions of external insulation are technically difficult to apply especially for buildings. The new ABC can be used in new and existing buildings. For old buildings, it provides not only a better thermal performance but also a decoration for exterior deteriorated facades. Thanks to its mineral basis, the new rendering is very similar to the traditional building materials (e.g., masonry facades), and this makes it ideal for use on old buildings.

In contrary, since this rendering is based on silica aerogels, its production cost remains high relative to other existing insulation materials which will increase the PP as illustrated previously (Huang 2012). Furthermore, its mechanical properties are still not sufficient enough, so there is a need to add a reinforcing mesh.

In a recent research (Stahl et al. 2012), a new kind of rendering based on silica aerogels granulates, very similar to the one we are presenting, has been developed

Table 2 Thermal conductivity of some traditional insulation products (Kobel et al. 2011 Aerogels for superinsulation: a synoptic view)

Insulation product	Chemical composition	Thermal conductivity (W m ⁻¹ K ⁻¹)
Mineral wool	Inorganic oxides	0.034–0.045
Glass wool	Silicon dioxide	0.031–0.043
Foam glass	Silicon dioxide	0.038–0.050
Expanded polystyrene	Polymer foam	0.029–0.055
Extruded polystyrene	Polymer foam	0.029–0.048

possessing a thermal conductivity of 0.025 W/(m K) and a density of around 200 kg/m^3 . It contains a purely mineral- and cement-free binder. It can be applied to walls both manually or by the aid of a plastering machine.

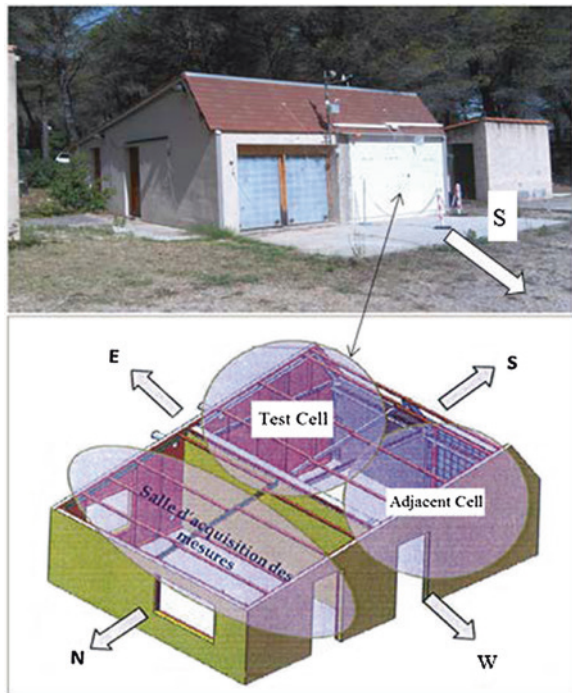
3.1 Hygrothermal Performance

3.1.1 Introduction

An experimental test unit was constructed in 1984 (Krauss 1985) at PERSEE research center in Sophia Antipolis (latitude 43.616 N , longitude 7.055 E) in the southeast Mediterranean region of France (See Fig. 11). It is composed of two adjacent cells orientated to the south which are identical in dimensions but differ in the composition of the south wall. The first one, we will call it hereafter the test cell, has the south wall initially composed of heavy weight concrete with a layer of glass wool interior insulation. The second cell, the adjacent cell, has its south wall composed of a semi-transparent glazing system consisting of a composition of silica aerogel granules and phase change material (Berthou 2011; Johannes et al. 2011). A third cell (acquisition cell), adjacent to the other two, is also present and is oriented to the north

Initially, the south wall of the test cell was composed of a 25-cm layer of concrete (exterior layer), a 16-cm layer of glass wool, and a 1.3 cm of plaster board.

Fig. 11 PERSEE experimental test cell



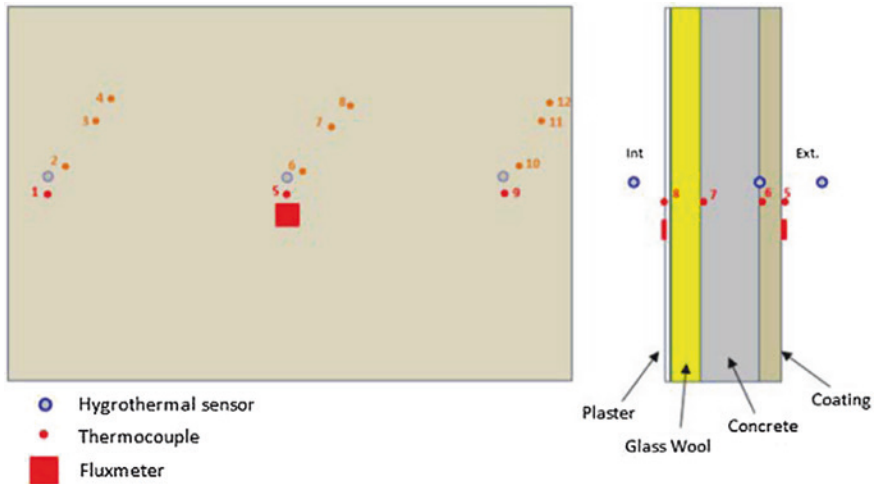


Fig. 12 Measurement sensors within the south wall

A 4-cm layer of ABC was then added at the exterior surface of this wall. Trying to isolate the south wall from the thermal effects of the other walls enclosing the test cell, these elements—i.e., the east wall of the test cell, all the partition walls, the roof, and the ground—are very well insulated. Also, to avoid the effect of the direct solar gains, the test cell has no windows. For the south wall, temperature sensors are placed at the exterior surface of the coating, at the interface between the coating and the concrete, at the interface between concrete and internal insulation (glass wool), and at the interior surface of the plaster layer. For each of these positions, three sensors are present: near the east edge, near the west edge, and at the middle of the wall. The hygrothermal sensors are placed at the interface between the coating and the concrete (see Fig. 12). Also, outdoor weather conditions are monitored through temperature, humidity, wind, and solar irradiation sensors. The objective of this experiment was to validate a numerical model developed in the commercial software WUFI (Kunzel 1995). The latter is a specialized software in assessing the thermal and moisture performance of exterior walls. After that, we will use this model to carry out different simulations.

3.1.2 Model Validation

The measured and simulated temperatures and relative humidity at the interface between the ABC and concrete are plotted in Fig. 13 for a 2-week period. It can be seen from this figure that the numerical model is capable of generating temperatures and relative humidity close to those of measurements. The maximums and minimums of the simulated data are in phase with the measured ones. The temperatures are in good agreement between the two curves where the maximum

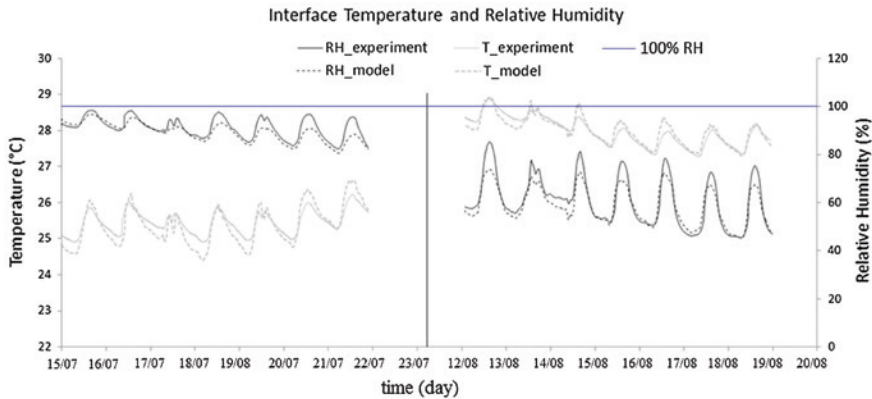


Fig. 13 Measured and simulated temperature and relative humidity at the interface coating/concrete

discrepancy does not exceed 0.6 °C. Concerning relative humidity, a satisfactory agreement is observed between the measurements and the simulation results; however, the maximums of the simulation results are lower than those measured where the discrepancy between the two varies between 4 and 14 %.

3.1.3 Simulation Results

The simulations are carried out for Grenoble climate representative of a semi-continental French climate. The city of Grenoble was chosen as a simulation case because of its very specific climate: rain is more abundant, winter is colder, and summer is generally warmer than most other cities in France. Due to the mountainous environment that slows the winds and decreases their thermal regulation effect, the daily temperature range is much higher than any other place in France. The nights are generally cooler (except during heat wave periods), and the afternoon is warmer than those in other main cities. While in winter, the temperature can drop relatively low; in summer, the city undergoes heat among the highest in the country (more than 35 °C each year, usually for several days as in 2003, 2006, 2009, 2010, 2011, 2012, 2013). The surrounding Alps Mountain forms a barrier preventing rain-filled clouds to move out, while rainy westerly winds are trapped. Thus, rainfalls reach almost a meter per year over the city.

Results show that interior thermal insulation systems can cause several moisture problems: no capability to dry out over the years, condensation risk, etc (Fig. 14). The un-insulated walls have, in addition to these moisture risks, very high heat losses compared to the other insulated ones. Adding the aerogel-based rendering on the exterior surface of the un-insulated or the already internally insulated walls reduces significantly or removes the moisture risks. It also reduces significantly the wall heat losses. Compared to the un-insulated wall, the wall having the rendering on its exterior façade has a more potential to dry out by about 20 %.

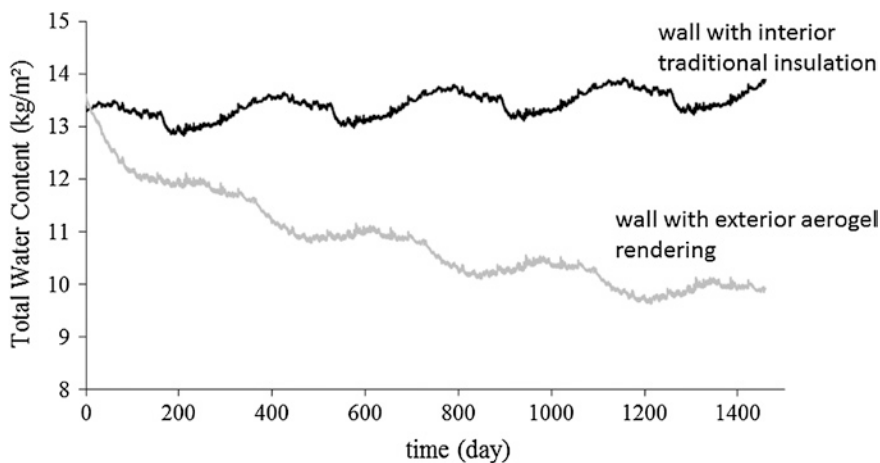


Fig. 14 Total water content for internal and external insulation configuration

Mold growth due to moisture formation is eliminated when the rendering is added. Also, heat losses reductions up to 70 % could be achieved.

3.2 Energy Performance

Figure 15 shows the house's energy load without the ABC and with 5-cm ABC on the exterior facades for the different construction periods and for the different climates. The construction materials for the different periods are shown in Table 3. For the period 1968–1974, we modeled two different houses: the first one “1968–1974(1)” has simple glazed windows with no insulation in the roof; the second one “1968–1974(2)” has double-glazed windows with 6-cm thermal insulation in the roof. Also, for the period after 1990, we distinguish two cases: the first one, >1990(1), has the exterior walls composed of concrete structure with 10-cm internal thermal insulation and the second one, >1990(2), has the exterior walls composed of 42 cm of brick monomur with no internal insulation.

From this figure, it is shown that for the old houses built before 1974, the percentages of energy reductions are between 40 and 53 % for the Mediterranean climate, 37–48 % for the oceanic climate, and 33–40 % for the semi-continental climate. For the houses built in the period 1975–1989, the reductions are about 32, 23, and 17 % for the Mediterranean, oceanic, and semi-continental climates. Lower reductions are achieved in the new houses, 23, 14, and 10 % for the three climates, respectively. Since the new houses have already thermal insulation in the exterior envelope, adding the ABC will not decrease a lot the annual load

The percentage of occupied time where heating is not needed for different coating (rendering) thicknesses for the old house is shown in Fig. 16. As the

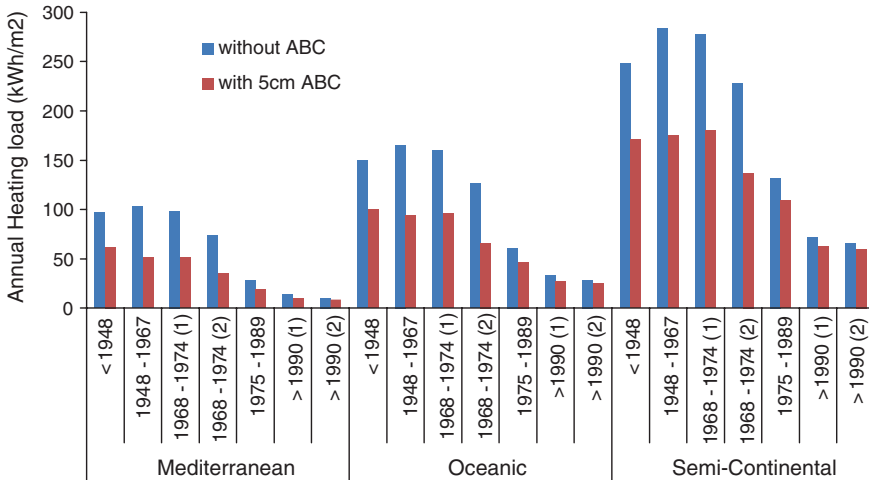


Fig. 15 Annual heating load for the different climates and the different construction periods with and without the coating [(1) and (2) represent different construction techniques within the same period]

coating thickness increases, the number of hours where heating is not needed increases. Taking the 5 cm as an illustration, the percentage increases by 10, 6, and 3 % for the Mediterranean, oceanic, and semi-continental climates, respectively, compared to the house with no coating.

Figure 17 shows the percentage of occupied time where heating is not needed for the new house for 0-, 5-, and 10-cm interior insulation. The black curves are for the Mediterranean climate, the blue ones are for the oceanic climate, and the red ones are for the semi-continental climate. For the cases with no interior insulation, applying 5 cm of the coating increases the percentage by 28, 17, and 10 % for the Mediterranean, oceanic, and semi-continental climates. For the houses with 5-cm interior insulation, adding 5 cm coating on the exterior facades increases the percentage by 12, 6, and 4 % for the three climates, respectively. For the houses with 10-cm interior insulation, the increase is about 6, 3.5, and 2.5 %, respectively.

3.3 Cost Analysis and Thickness Optimization

Selection and determination of the optimum thickness of insulation has been of prime interest for many researchers in recent years. The concept of optimum thermal insulation thickness considers both the initial cost of the insulation and the energy savings over the life cycle of the insulation material. The optimum insulation thickness corresponds to the value that provides minimum total life cycle cost. The optimum insulation thickness based on heating requirement depends mainly on the yearly heating load, the costs of electricity and insulation material, the building lifetime, and the interest and inflation rates.

Table 3 Houses' construction in France during the different periods

		Period					
		<1948	1948–1967	1968–1974	1975–1981	1982–1989	1990–2000
Space heating	Final energy use for space heating	214 (kWh/m ² /year)	226 (kWh/m ² /year)	177 (kWh/m ² /year)	142 (kWh/m ² /year)	106 (kWh/m ² /year)	95 (kWh/m ² /year)
Opaque wall	Construction	– Stone rubble: (such as sandstone, limestone, granite...) – Mud-brick	– Hollow concrete blocks	– Hollow concrete blocks	– Masonry blocks	– Concrete hollow blocks (67 % of houses)	– Concrete blocks
		– Solid bricks	– Hollow bricks	– Hollow bricks	– Cellular concrete	– Hollow bricks (15 %)	– More energy-efficient hollow bricks (such as brick monomur)
		– Timbered structure with soil, brick, or mixed filling	– Reinforced concrete	– Reinforced concrete	– Hollow brick		
	Thermal insulation	No	No	No	R = 2.3 (m ² K)/W	R = 2.4 (m ² K)/W	R = 3 (m ² K)/W
Roof/ceiling	Construction	Wood with a final finishing based on local materials	Wood with interlocked tiles or asphalt shingles	Wood with interlocked tiles or concrete shingles	Wood with cement finishing	Wood with cement finishing	Concrete insulated beam
	Thermal insulation	No	No	Some houses start to have insulation (4–10 cm glass wool)	R = 4.8 (m ² K)/W	R = 4.8 (m ² K)/W	R = 6 (m ² K)/W

(continued)

Table 3 (continued)

		Period					
		<1948	1948–1967	1968–1974	1975–1981	1982–1989	1990–2000
Space heating	Final energy use for space heating	214 (kWh/m ² /year)	226 (kWh/m ² /year)	177 (kWh/m ² /year)	142 (kWh/m ² /year)	106 (kWh/m ² /year)	95 (kWh/m ² /year)
Floor	Construction	Wood or slab on ground	Wood	concrete slab or terracotta	concrete slab or terracotta	concrete slab or terracotta	Concrete slab
	Thermal insulation	No	No	No	R = 1 (m ² K)/W	R = 0.8 (m ² K)/W for ground floor or R = 1.9 (m ² K)/W for crawl spaces	R = 3 (m ² K)/W
Window	Construction	Simple glazed	Simple glazed	Simple/double	Simple/double	Simple/double	Simple then double
	Window to wall ratio	10 %	20–27 %	37 %	25 %	25 %	20 %

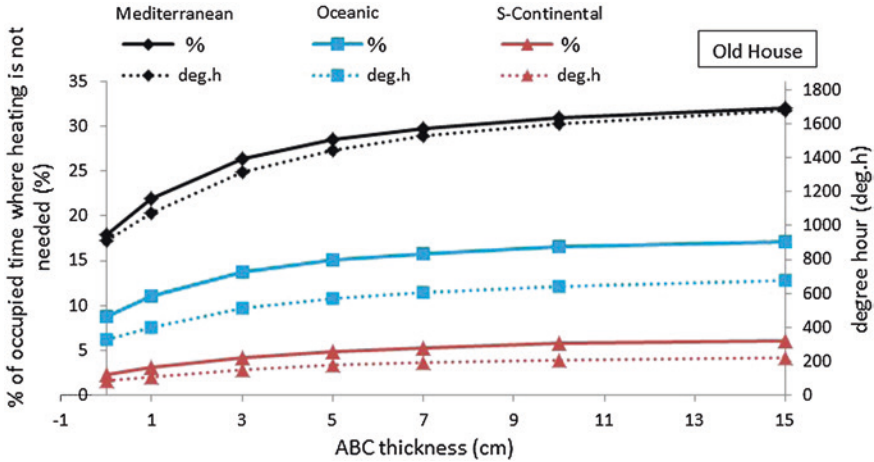


Fig. 16 Percentage of occupied time where heating is not needed and its degree hour for different coating thickness and different climates (*old house*)

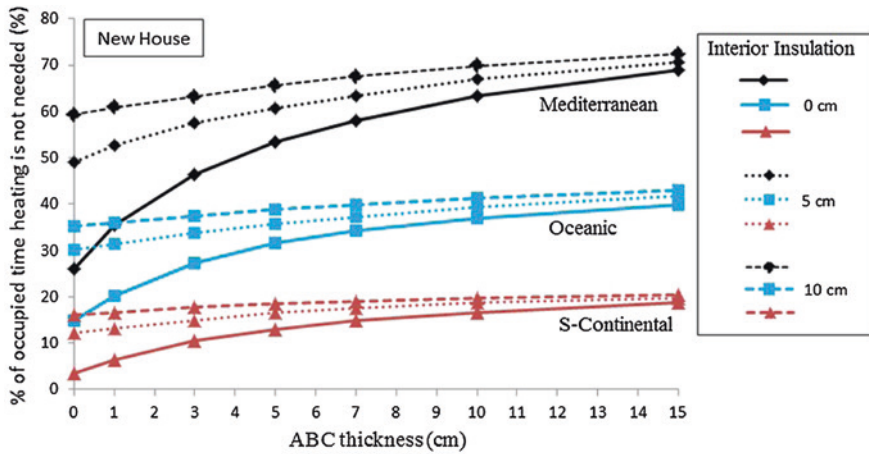


Fig. 17 Percentage of occupied time where heating is not needed its degree hour for different coating thicknesses and different climates (*new house*)

The coating's thickness optimization is carried out for different climates. Three cities of France are chosen representing different climates: Nice (Mediterranean climate; latitude 43.7°N, longitude 7.266°E), Bordeaux (oceanic climate; 44.84°N, 0.58°W), and Strasbourg (semi-continental; 48.58°N, 7.748°E). Other than France, we have also chosen three cold Nordic cities: Moscow (Russia; 55.75°N, 37.616°E), Stockholm (Sweden; 59.329°N, 18.068°E), and Montreal (Canada; 45.50°N, 73.566°W). The analyses are carried out for a typical house built before 1974. The

majority of these houses have no thermal insulation in their envelope. The heating system is electric with an efficiency of 0.9. The heating set point is taken as 19 °C. The cost of electricity is 0.13 €/kWh. The cost of aerogels is very erratic in the current market. However, it has a decreasing trend with time. According to Koebel et al. (2012), this cost could drop below 1500 US\$/m³ (≈1100 €/m³) by the year 2020. Cuce et al. (2014b) in their study assumed a value of 600 €/m³ for the cost of aerogel insulation based on future predictions. In our study here, 800 €/m³ (including labor cost) is considered as a base case; then, this value as well as the values of the other parameters are changed to examine the sensitivity of the optimum thickness to these inputs. Note that for the cities out of France, the simulations are carried out with the same electricity tariff just for comparison purposes.

Excessive insulation as well as low insulation is not desired from an economic perspective. Excessive insulation means high initial investments, while low insulation means high energy consumption costs. Here comes the necessity to find the optimum insulation levels that represents a compromise between the two. Figure 18 shows the coating’s cost, the heating consumption cost, and the total cost for the different climates. From these figures, we can deduce that the heating cost decreases exponentially as the coating’s thickness increases. The cost of

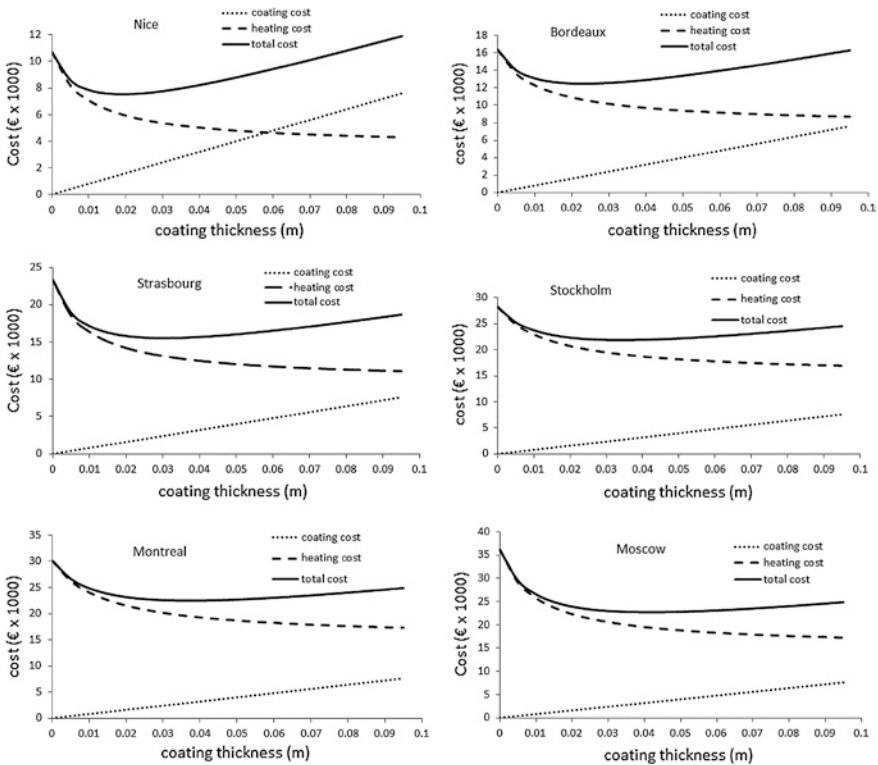


Fig. 18 Aerogel-based coating, heating, and total costs for the different climates

Table 4 optimum coating thickness for the different climates

City	Optimum thickness (cm)
Nice	1.71
Bordeaux	2.10
Strasbourg	2.93
Stockholm	3.26
Montreal	3.61
Moscow	4.37

Table 5 Payback period

City	Payback period (year)
Nice	2.7
Bordeaux	2.21
Strasbourg	1.64
Stockholm	2.1
Montreal	1.96
Moscow	1.47

insulation always varies linearly with the thickness. The total cost decreases to a certain minimum then starts to increase. The optimum coating's thickness is the one that ensures this minimum of the total cost. For each climate, the optimum thickness is presented in Table 4. We can conclude that as the climate gets colder, the optimum thickness increases. This is due to the increasing heating loads and, as a result, the increasing electricity costs. So, in the cold climates, there is larger potential to reduce energy consumption through applying the insulating rendering. As illustration, applying 2-cm layer of the coating saves around 4000 € for Nice while 9000 € for Strasbourg; however, the initial investment cost remains the same.

After determining the optimum coating thickness, the PP is calculated. It is defined as the time required to recover the initial investment cost. Long PPs are not desired especially in the building sector. Table 5 presents the PP for the different cities when the optimum coating thickness is applied.

From this table, it is understood that the PP ranges between 1.4 and 2.7 years. Due to the relatively low PPs, it is concluded that applying the coating could be seen as a good investment from economical point of view. Several parameters affect the optimum thickness. Among these are the cost of aerogels and the heating set point. Starting with coating cost, Fig. 19 shows the optimum coating thickness for different aerogel's costs: 600, 800, 1000, 1500, and 2000 €/m³. It is expected that as the cost increases, the optimum value decreases. This is due to the higher initial cost associated with the application of the coating making it difficult to recover this cost from the energy savings.

Concerning the heating set point, the variation of the optimum thickness as a function of the heating set point is shown in Fig. 20. It is illustrated that the optimum thickness varies linearly with the heating set point. As the heating set point increases, meaning that the annual heating consumption increases, the optimum thickness increases.

Fig. 19 Effect of the coating cost on the optimum thickness

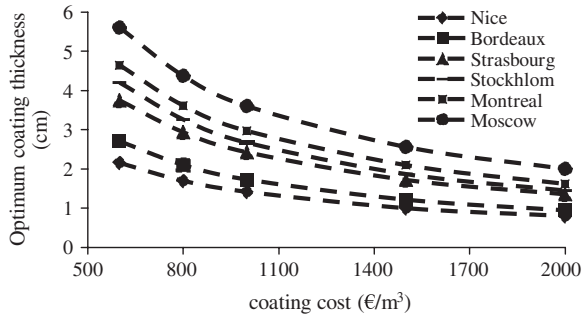
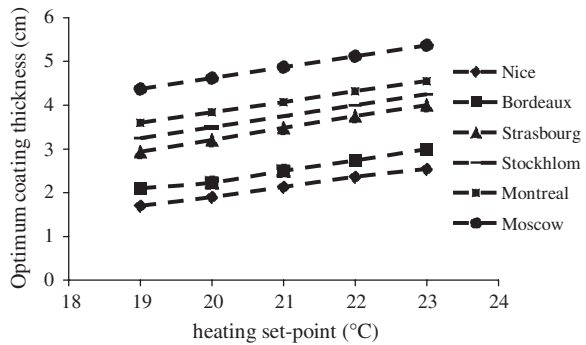


Fig. 20 Effect of the heating set point on the optimum coating thickness



4 Conclusion

In this study, a brief review on aerogels applications in buildings has been presented. They have shown a high potential for energy savings and improving the envelope’s thermal performance. Aerogels can reduce significantly the building’s energy consumption and enhance the indoor thermal comfort. In addition, aerogels are also very promising in terms of embodied energy data and provide slimmer construction when compared to other conventional insulation materials. The extraordinary low thermal insulation and optical transparency of aerogels allow its applications in window panes and solar collector covers.

Concerning the aerogel-based rendering, it is concluded that it has a maximum impact on the old houses which are poorly insulated. The heating load can be reduced up to 50 %. Also, it increases the thermal comfort during the winter season by decreasing the cold wall effects. For moderately insulated buildings, such as those built in the 80s and 90s with their exterior walls made of brick monomur (20 cm) or made of concrete with a 5–7 cm layer of interior thermal insulation, the reductions in the heating load can reach up to 25 % when adding the aerogel-based rendering. This is important for these houses to pass the newly imposed strict thermal regulations for buildings and be classified as energy efficient. For new buildings, lower reductions

are achieved (7–12 %) when adding the rendering. This is due to the fact that the exterior envelope is already highly insulated. Thus, we can conclude that the rendering has a significant effect when considering existing building rehabilitation. For new buildings, the rendering has a lower effect on the energy consumption; however, these buildings will be considered as highly energy-efficient ones.

A potential limitation on the use of aerogels as thermal insulation materials in the building sector is the risk of overheating, and thus thermal discomfort, in the warm climates and/or in summers with high heat waves. Moreover, higher thermal inertia at the building envelope might cause an increment in the cooling demand in summer.

Finally, aerogels are upcoming materials in the near future. As energy demand and cost increase, aerogel products are expected to increase in the future, especially in the building sector due to possessing high thermal insulation characteristics. Although the cost of aerogels materials remain high for cost-sensitive industries such as buildings and are much higher than conventional insulation, this cost is expected to decrease in the following years as a result of the advancement in the aerogel production technologies as well as the large-scale material production leading to lower unit costs. This will increase the competitiveness of aerogel insulating products compared to conventional materials.

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References

- Achard P, Rigacci A, Echantillac T, Bellet A, Aulagnier M, Daubresse A (2011) Enduit isolant à base de xerogel de silice. WIPO Patent WO/083174
- Aspen Aerogels (2012a) Aerogel insulation converts old mill house into modern energy-saving passive house. http://www.aerogel.com/markets/Case_Study_House_Renovation_web.pdf. Accessed 10 May 2012
- Aspen Aerogels (2012b) Case study: aerogel insulation converts old mill house into modern energy-saving passive house. Retrieved from http://www.aerogel.com/markets/Case_Study_House_Renovation_web.pdf. Accessed June 2012
- Aspen Aerogels (2012c) Case study: aerogel interior wall insulation reduces U-Values by 44 %, lowers energy use and carbon emissions. Retrieved from http://www.aerogel.com/markets/Case_Study_Interior_Wall_web.pdf. Accessed June 2012
- Aspen Aerogels (2012d) Case study: wood framing insulated with aerogel improves energy efficiency by 15 %. Retrieved from http://www.aerogel.com/markets/Case_Study_Framing_web.pdf. Accessed June 2012
- Barbero S, Marco D, Ferrua C, Pereno A (2014) Analysis on existent thermal insulating plasters towards innovative applications: evaluation methodology for a real cost-performance comparison. *Energy Build* 77:40–47
- Berthou Y (2011) Etude de parois de batiments passifs associant un materiau à changement de phase et une super isolation transparents. PhD thesis, Mines Paris Tech, Sophia Antipolis
- Buratti C, Moretti E (2012) Experimental performance evaluation of aerogel glazing systems. *Appl Energy* 97:430–437

- Cotana F, Pisello AL, Moretti E, Buratti C (2014) Multipurpose characterization of glazing systems with silica aerogel: in-field experimental analysis of thermal-energy, lighting and acoustic performance. *Build Environ* 81:92–102
- Cuce E, Cuce PM, Wood CJ, Riffat SB (2014a) Toward aerogel based thermal superinsulation in buildings: a comprehensive review. *Renew Sustain Energy Rev* 34:273–299
- Cuce E, Cuce PM, Wood CJ, Riffat SB (2014b) Optimizing insulation thickness and analysing environmental impacts of aerogel-based thermal superinsulation in buildings. *Energy Build* 77:28–39
- Dorcheh SA (2008) Silica aerogel: synthesis, properties and characterization. *J Mater Process Technol* 199(1):10–26
- Dowson M, Pegg I, Harrison D, Dehouche Z (2012) Predicted and in situ performance of a solar air collector incorporating a translucent granular aerogel cover. *Energy Build* 49:173–187
- EMPA material science and technology. www.empa.ch/
- Enderdata (2012) Energy efficiency trends in buildings in the EU: lessons from the ODYSSEE MURE project
- Energy efficiency watch, final report (2013) Improving and implementing national energy efficiency strategies in the EU framework
- Enkvist PA, Naucler T, Rosander J (2007) A cost curve for greenhouse gas reduction. *The McKinsey Quarterly*
- Huang L (2012) Feasibility study of using silica aerogel as insulation for buildings. Master of science thesis. KTH School of Industrial Engineering and Management, Stockholm, Sweden
- Jensen KI, Schultz JM, Kristiansen FH (2004) Development of windows based on highly insulating aerogel glazings. *J Non-Cryst Solids* 350:351–357
- Johannes K, Kuznik F, Jay F, Roquette P, Achard P, Berthou Y (2011) Université Claude Bernard and ARMINES. Elément d'enveloppe d'un bâtiment et ensemble comprenant un tel élément. French Patent application, no 11 581 9414, submitted on 14 Sept 2011
- Kistler SS (1931) Coherent expanded aerogels. *J Phys Chem* 36:52–64
- Koebel M, Rigacci A, Achard P (2011) Aerogels for superinsulation: a synoptic view, Chap. 26, p. 611. In: Aegerter M, Leventis N, Koebel M (eds) *Aerogels handbook*. Springer, New York
- Koebel M, Rigacci A, Achard P (2012) Aerogel-based thermal superinsulation: an overview. *J Sol-Gel Sci Technol* 63:315–339
- Kosny J, Petrie T, Yarbrough D, Childs P, Syed AM, Blair C (2007) Nano-scale insulation at work: thermal performance of thermally bridged wood and steel structures insulated with local aerogel insulation
- Krauss G (1985) Etude expérimentale des transferts de chaleur entre un bâtiment et son environnement: conception, réalisation, instrumentation d'une cellule test. PhD thesis, University P. & M. Curie, Paris
- Kunzel HM (1995) Simultaneous heat and moisture transport in building components. PhD Thesis, Fraunhofer Institute of Building Physics
- NF EN 1159-3, Advanced technical ceramics—ceramic composites, thermophysical properties—Part 3: determination of specific heat capacity
- NF EN 12667, Thermal performance of building materials and products—Determination of thermal resistance by means of guarded hot plate and heat flow meter methods—Products of high and medium thermal resistance
- NF EN 1602 standard, Thermal insulating products for building applications—Determination of the apparent density
- NF EN ISO 8130-2, Poudres pour revêtement—Partie 2 : détermination de la masse volumique à l'aide d'un pycnomètre à gaz (méthode de référence)
- NF EN ISO 12571, Performance hygrothermique des matériaux et produits pour le bâtiment—Détermination des propriétés de sorption hygroscopique
- NF EN ISO 12572, Performance hygrothermique des matériaux et produits pour le bâtiment—Détermination des propriétés de transmission de la vapeur d'eau
- Pajonk G, Elalouie E, Begag R, Durant M, Chevalier B, Chevalier JL, Achard P (1998) Inventors (Université Claude Bernard - Villeurbanne, Produits Chimiques Auxiliaires- Longjumeau,

- Armines, Centre Scientifique et Technique du Bâtiment). Process for the preparation of monolithic silica aerogels. United States Patent no 5-795-557, 18 Aug 1998
- Reim M, Beck A, Korner W, Petricevic R, Glora M, Weth M, Schliermann T, Fricke J, Schmidt CH, Potter FJ (2002) Highly insulation aerogel glazing for solar energy use. *Sol Energy* 72(1):21–29
- Reim M, Korner W, Manara J, Korder S, Arduini-Schuster M, Ebert HP, Fricke J (2005) Silica aerogel granulate material for thermal insulation and daylighting. *Sol Energy* 79:131–139
- Stahl Th, Brunner S, Zimmermann M, Ghazi-Wakili K (2012) Thermo-hygric properties of a newly developed aerogel based insulation rendering for both exterior and interior applications. *Energy Build* 44:114–117
- TAASI (2011) www.taasi.com/apps.htm
- Verbeeck G, Hens H (2005) Energy savings in retrofitted dwellings: economically viable? *Energy Build* 37(7):747–754