

Chapter 2

Aerogel Plasters for Building Energy Efficiency

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Abstract Nowadays in many countries, the building sector is the largest energy consumer and one of the best ways to reduce energy demand of buildings is the reduction in heat losses through the envelope. In this scenario, insulating materials with aerogels have growing interest and new applications such as insulating aerogel-based renderings are in development. This chapter deals with the analysis of superinsulating applications for building envelope such as aerogel-incorporated concrete- and aerogel-based renders. After an overall analysis of the market trend for these innovative systems, the rendering compositions, the physics, thermal, acoustic, and hygrothermal properties of aerogel-based renders are discussed. In situ applications of the new developed render are analyzed and the potential of the investigated materials is highlighted, by considering experimental measurements in Sect. 2.4. Finally, a comparison with traditional solutions and the future trends are considered.

2.1 Introduction

Thermal insulation in buildings contributes to reduce the size of the heating and cooling systems and the annual energy consumptions. In particular, in Italy, at least 90 % of buildings were constructed before 1991, the year of the Frame Law on Energy Saving, and they are not in compliance with the current regulations for the

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most part (the most recent norms date from 2006). Therefore, all these buildings would need refurbishment in order to be compliant with normative targets.

The application of innovative solutions can be therefore a useful tool not only for new constructions, but also for the refurbishment of existing buildings, in order to reduce the heat losses of the envelope. Many transparent insulating systems have been proposed and their optical, thermal, and acoustic properties have been investigated at the University of Perugia since 2003, with both experimental campaigns and simulation codes (Buratti and Moretti 2013, 2014; Tabares-Velasco et al. 2012; Kalnæs and Jelle 2015; Buratti et al. 2012, 2016; Moretti et al. 2014; Cotana et al. 2014): Silica aerogel, in particular, is a highly porous nanostructured and light material, and it represents an innovative alternative to traditional solutions because of the high thermal performance (low thermal conductivity 0.014 W/m K) and low density (about 3 kg/m^3). Nevertheless, the costs of the material are high for cost-sensitive building industry and this is a limit for a wide spread of the material in the market. Research aims to improve the insulation performance and to decrease the aerogel production costs. The optical transparency property allows its use for insulating window facades and window panes, but this is only one of the possible applications in the building sector. Aerogel blankets/panels have been developed to as insulation panels for building walls and grounds (Aspen Aerogels 2012). Moreover, the increasing of the thermal performance of wood and steel with local aerogel insulation has been studied by means of experimental tests (Ibrahim et al. 2014b): R-value of wood-framed walls is improved by 9 % and the one of steel-framed walls by 29 %. Recently, other types of silica-aerogel-based materials used in buildings are the aerogel-incorporated mortars/plasters and aerogel-based concretes (Gao et al. 2014; Kim et al. 2013).

In this chapter, some examples of opaque aerogel-based materials are presented with a particular attention on new insulating rendering based on silica aerogel. After a general overview of these materials, the performance assessment of aerogel-based renders are analyzed. Finally, in situ applications of this new material for building refurbishment are described.

2.2 Aerogel-Incorporated Concrete and Plasters: A General Overview

In this section, the attention will be focused on superinsulating coatings such as render and concrete. These kinds of application are important when the thermal buildings insulation would be improved with a small thickness increase of the walls. Generally, lightweight concrete has many important applications in modern buildings, thanks to its strength/weight ratio and heat and sound insulation characteristics higher than the ones of traditional solutions (Kiliç et al. 2003). Lightweight aggregates such as pumice, diatomite, volcanic cinders, and perlite can be added in the mixture in place of normal aggregates (i.e., sand and rocks), but an

intelligent selection of them is necessary in order to avoid possible interactions with the binder phase. The advantage of these concretes is the better thermal insulation properties when compared to conventional solutions, due to the large amount of air void in the matrix. Aerogel is a perfect aggregate for lightweight and thermal insulating concrete, thanks to its extremely low density (3–100 kg/m³ depending on the porosity), its low thermal conductivity (0.003–0.02 W/m K), and its good fire and acoustic resistances. Nevertheless, the application of this innovative material in thermal insulating concrete has not been widely spread because of the still high manufacture cost of aerogel. Moreover, a limited number of studies are available for aerogel-based thermal insulating renders, due to the high cost. Nevertheless, innovative solutions for thermal insulating plasters based on the materials with pore size in nanometer range, such as aerogel, could reach good thermal performance with a small thickness (Barbero et al. 2014).

2.2.1 Literature Review

Ratke (2008) presented a new application of aerogel-incorporated concrete with interesting fire and sound resistance, and Kim et al. (2013) reported the insulation performance of aerogel cement prepared with aerogel powder and cement paste. Different percentages of aerogel with respect to the mixture mass were considered, ranging from 0.5 to 2 wt%. Also 20 % of pozzolan, composed by SiO₂ and Al₂O₃, was substituted for cement in order to prevent detrimental expansion of the samples. Results are reported in Table 2.1: The thermal conductivity of aerogel cement with an aerogel mass fraction of 2.0 wt% decreased of about 75 %; considering the aerogel cement with 2 % of aerogel and 20 % of pozzolan, the reduction is about 72 %.

Recently, insulating coatings based on silica aerogels have been developed. In particular, a lightweight aerogel-incorporated concrete (AIC) was prepared by replacing the normal aggregate of concrete with silica aerogel particles (Gao et al. 2014). AIC samples were prepared by adding cement, sand, silica fume, water, superplasticizer, and aerogel particles. The cement used has a density of about 3140 kg/m³; hydrophobic aerogel granules with a density of 100 kg/m³ was added (the percentages in volume vary in 0–60 % range) together with distilled water (the water–binder (w/b) ratio was set to 0.4). The thermal conductivity of AIC samples

Table 2.1 Percentages of decrease in thermal conductivity of aerogel cement (adapted from Kim et al. 2013)

	Aerogel cement				Aerogel cement and pozzolan			
Aerogel content (wt%)	0	0.5	1	2	0	0.5	1	2
Thermal conductivity (W/m K)	0.51	0.38	0.27	0.13	0.56	0.45	0.33	0.10
Percentage of decrease	–	26	47	75	–	9	29	72

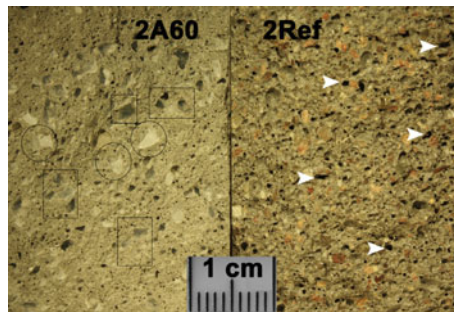


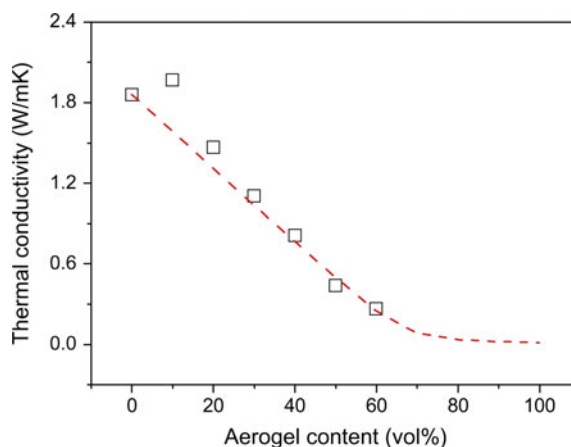
Fig. 2.1 Optical images of AIC samples (2A60) compared to the plain concrete sample (2Ref) (Gao et al. 2014)

was analyzed by using a Hot-disk Thermal Constants Analyzer (model TPS 2500S) and a disk-type Kapton Sensor 5465, which acts both as heat source and temperature record. Figure 2.1 shows the image of a AIC sample with 60 % of aerogel in volume (2A60) compared to a reference concrete sample: The cement paste in the AIC samples has less air voids than those of the reference sample because the aerogel particles affect the air entrainment by gas diffusion due to the porous nature and the large surface area of aerogel particles.

Moreover, the absorbed CO_2 in aerogel particles would react with $\text{Ca}(\text{OH})_2$ from the binder phase to form CaCO_3 during the curing process, which changes also the microstructure (see the area marked with circles). Generally, the aerogel content increasing corresponds to a density decreasing: Considering a percentage of aerogel in volume equal to 60 %, the density is about 1000 kg/m^3 , compared to 1980 kg/m^3 of the reference plain concrete sample (reduction of about 50 %). Also in this case, the thermal conductivity of AIC decreases [the same behavior is as shown in Kim et al. (2013)]: The reference plain concrete has a thermal conductivity of about 1.86 W/m K , whereas the AIC sample with the aerogel content of 60 vol.% shows a thermal conductivity of only 0.26 W/m K (decreasing of about 86 %) (Fig. 2.2). Also the compressive strength was measured and a value of about 8.3 MPa was obtained considering an aerogel content of 60 %, while the compressive strength of the reference concrete is about 55 MPa, showing a decrease of about 85 %. At an aerogel content of 40 vol.% where a minimum compressive strength of 20 MPa was maintained, the AIC samples registered a thermal conductivity of 0.8 W/m K , rendering this system unfitting for specific insulating purposes (Gao et al. 2014).

Also Serina et al. (2015) shows an experimental investigation of aerogel-incorporated mortar (AIM) with up to 80 vol.% aerogel, prepared by using a reduced ultrahigh-performance concrete (UHPC) mixture. Mechanical strength properties of cured AIM samples were measured according to DIN EN 196-1 standard, while the thermal conductivity was measured with the same Hot-disk Thermal Constants Analyzer of the type TPS 2500S. Both flexural and compressive strength decreased with aerogel loading: When only 20 vol. % aerogel was presented, a difference of 42 % (from 120 to 70 MPa) in compressive strength was

Fig. 2.2 Thermal conductivity of AIC versus aerogel content variations (Gao et al. 2014)

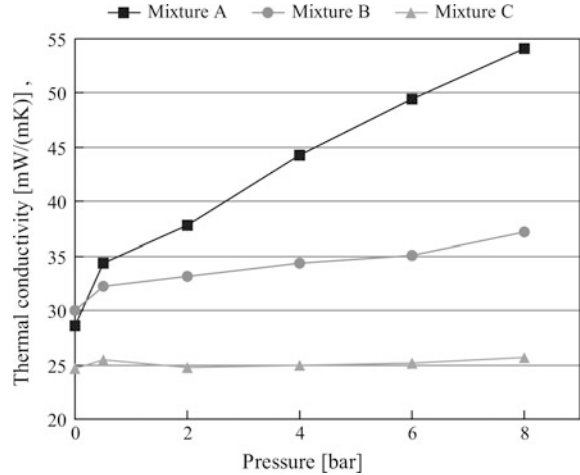


observed. The AIM sample with 50 vol.% aerogel content has a thermal conductivity of about 0.55 W/m K and a compressive strength of 20 MPa; it decreases by almost 4–6 MPa, while only a 20 % reduction in thermal conductivity is obtained, when aerogel content increases to 70 vol.%. By an aerogel loading of 80 %, the compressive strengths were very low (about 4 MPa).

Finally, Fickler et al. (2015) developed a high-performance aerogel concrete by embedding silica aerogel granules in high-strength cement matrix: In this work, a new aerogel-based construction material with extraordinary heat-insulating and load-carrying properties was examined. Various mixtures were examined in terms of their compressive strength and thermal conductivity: Considering 70 % in volume of silica aerogel, the bulk density and the compressive strength decreased in comparison with conventional concrete. The compressive strength could be increased by reducing the percentage of aerogel granules to a minimum of 60 % of volume. The thermal conductivity was determined with the transient hot bridge (THB) measurement principle: Good heat-insulating properties were observed, values variable in the range 0.16–0.37 W/m K were measured, considering a compressive strength variable between 6 and 23 MPa.

A new kind of insulating plasters based on silica aerogel granules has been developed (Stahl et al. 2012); it consists of hydrophobized granular silica aerogel (60–90 vol.%) and contains a purely mineral- and cement-free binder and some additives which enhance the workability of the rendering. It can be applied to walls both manually or by plastering machines. The thermal conductivity has been measured by a special hot plate device (sample dimensions 65 mm × 65 mm and 12–13 mm in thickness). The samples were made manually and dried in a climatic chamber (23 °C, 50 % r.H.) for 28 days. Measurements were carried out for at least 20 samples. Also water vapor transmission resistance was determined by the dry cup method, according to the European standard EN 12086. Conventional insulation renders were also tested in order to compare the results with traditional solutions. For all the plasters, the thermal conductivity increases when samples were

Fig. 2.3 Thermal conductivity of different rendering mixtures as functions of the pressure in the steel pressure vessel (Stahl et al. 2012)



produced by the plastering machine compared to manually produced ones: it was due to the higher water inserting into the render by using plastering machines. The measured thermal conductivity of the aerogel render is 0.025 W/m K and the density is 200 kg/m³: the λ value is very low in comparison with traditional coatings (0.065–0.103 W/m K). This thermal conductivity generally increases when production pressures increase (Fig. 2.3—Mixture A, with cement binders) because liquid water enters the nanopores of the aerogel granule due to the high pressure, it remains trapped and will take a very long time to dry. The dependence from pressure can be reduced avoiding cement binders in the mixture (see mixture B and C, without cement binders with two different procedures).

Achard et al. (2011) (WIPO Patent WO/083174) developed another innovative insulating rendering based on silica aerogel. It consists of water, a mineral and/or organic hydraulic binder, insulating filler comprising a powder or granules of hydrophobic silica aerogel, and other filler and additives (option). The rendering has been developed mainly for exterior wall surface applications. The coating thermophysical characteristics are presented in Table 2.2. The measured thermal conductivity is only 0.0268 W/m K, very low in comparison with traditional renders (0.2–0.05 W/m K). Unfortunately, the production costs are still high in comparison with other traditional insulation materials and it will be illustrated below (Huang 2012). Moreover, the mechanical properties are still not sufficient enough and reinforcing mesh should be added.

Table 2.2 Thermophysical properties of new aerogel insulating coatings (adapted from Ibrahim et al. 2014c)

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
Water absorption coefficient (kg/m ² s ^{1/2})	0.184

2.2.2 Market Survey

Innovative solutions for thermal insulating plasters could make a significant contribution to energy savings. Aerogel-based renders have high thermal resistances, and high thermal performance can be reached by applying them also in small thicknesses. But new plaster solutions have to respond to specific economical and technical features, in order to be spread in the market. An overall analysis of the thermal insulating plasters in European market was carried out by Barbero et al. (2014). Different characteristics were evaluated for each plaster: the volume mass powder, the dry bulk density of the hardened mortar, the thermal conductivity, and the costs. Currently, the nanomaterials and all the products made with them are more expensive than other commercial solutions.

A market survey was carried out considering all the European countries and in particular the western ones that represent the colder part of the Europe. Technical, chemical, and physical data and the price information of these plasters were directly supplied by each producer and manufacturer. The names of the manufacturers and the commercial products were not published for privacy reasons. The examined plasters were divided into two families: cement-based insulating plasters and natural hydraulic lime-based plasters. The incidence of the cost was evaluated considering both the cost per square meter of each plaster necessary to obtain the same final thermal resistance R_x equal to $1 \text{ m}^2 \text{ K/W}$ and the cost per functional unit (the reference unit is the money required to make 10 mm of thickness). Table 2.3 shows the prices of the analyzed plasters: the average cost of the cement-based products with the same thermal performance is €43/sqm, while the average cost of the natural hydraulic lime-based plasters is €82/sqm. In comparison with these plasters, it is possible to consider the aerogel-based plaster developed and studied by Buratti et al. (2014): the costs of the natural lime plaster with 80 % of granular aerogel is expected to be about 8 €/sqm, considering a thickness of 1 mm of the coat. In this case, the commercial solution of the Agosti Nanotherm aerogel-including render was considered ($\lambda = 0.045 \text{ W/m K}$ and 80–90 % in volume of aerogel granules): Higher percentage of aerogel in the mixture can be added to obtain a final render with a thermal conductivity less than 0.02 W/m K . In this context, the large-scale production of aerogel-based plasters can improve the spread of new render solutions, by modifying the final costs of the product and the production system.

In the European market, an aerogel-incorporated render solution is Fixit 222 (Fixit, Fixit 222 Aerogel Hochleistungsdämmputz, 2015), by EMPA (Filate 2014, EMPA 2015). This is another very good product with a density of hardened mortar of 220 kg/m^3 and a thermal conductivity of only 0.028 W/m K . The product has very good performances, and it can be applied in the same way of standard renders (about 2 kg/m^2 for a thickness of 10 mm are necessary). The cost of this material is about 80–90 €/m² considering a thickness of 10 mm of the coat (8 €/m² for $s = 1 \text{ mm}$). It can be compared with conventional plasters shown in Table 2.3: the cost is higher than the ones of traditional plasters, but the thermal conductivity of Fixit 222 is very low in comparison with the others. However, these aerogel-based

Table 2.3 Pricing table of conventional plasters (adapted from Barbero et al. 2014 and Röfix, Fixit Group 2014)

Product	Type	Thermal conductivity (W/m K)	Price [€/sqm R_x for $s = 10$ mm]	Thickness R_x (mm/sqm)	Price [€/sqm R_x]
1	Cement-based plaster	0.055	3.590	55	19.75
2	Cement-based plaster	0.090	5.437	90	48.94
3	Cement-based plaster	0.074	3.700	74	27.38
4	Cement-based plaster	0.056	4.440	56	24.64
5	Cement-based plaster	0.090	5.200	90	46.80
6	Cement-based plaster	0.062	3.520	62	21.82
7	Cement-based plaster	0.075	4.587	75	34.40
8	Cement-based plaster	0.111	10.840	111	120.32
9	Lime-based plaster	0.200	11.500	200	230.00
10	Lime-based plaster	0.075	8.550	75	64.13
11	Lime-based plaster	0.060	4.800	60	28.80
12	Lime-based plaster	0.091	5.840	91	53.14
13	Lime-based plaster	0.066	11.080	66	73.13
14	Lime-based plaster	0.088	5.360	88	47.17
15	<i>Aerogel-based plaster Fixit 222</i>	0.028	80.000	28	224.00

solutions are applied as finished paintings and their application thicknesses are very low (about 3–5 mm).

For further information, it can be useful to analyze the influence of the aerogel costs on the optimum thickness of the coating. Figure 2.4 shows the optimum coating thickness for different aerogel costs (from 600 to 2000 €/m³): As the cost increases the optimum, thickness value decreases (Ibrahim et al. 2015). The higher initial costs due to the application of the coating make difficult their recovery by means of energy savings.

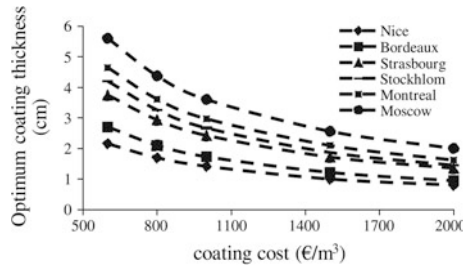


Fig. 2.4 Effect of the aerogel cost on the optimum thickness (Ibrahim et al. 2015)

2.3 Performance Assessment of Aerogel-Based Renders

In this section, the performance assessment of aerogel-incorporated renders is examined considering different points of view. Firstly, different experiences of aerogel-based render manufacturing techniques and their in situ applications will be described. As shown below, the most important characteristics of the innovative renders are the thermal insulation, the acoustic performance, and the hygrothermal properties. The innovative renders have a thermal conductivity very low with respect to traditional solutions (reduction up to 90–96 %) and a better acoustic absorption coefficient when compared to the same plaster without aerogel. Considering the hygrothermal properties, it will be shown that the new renders are able to efficiently reduce the moisture formation.

2.3.1 Rendering Mixing and Setup

Insulation plasters can be applied to external and internal walls. Thanks to its mineral basis, the new plaster is very similar to the original historical building materials, and it is ideal for use on old buildings, on internal as well as external surfaces, offering a noninvasive method for renovating historic buildings and for saving energy without altering their aspect.

The production and in situ setup of the aerogel-based renders are very important. The manufacturing step and the installation of the aerogel-incorporated plaster are described in Buratti et al. (2014). The aerogel in the renders has nanometer-sized pores and consists of 90–98 % of air.

The coating was manufactured by manually mixing natural lime with granular aerogel in different percentages, allowing the absorption of air in the mix. In this way, the density of the plaster decreases of about 90 %. Different kinds of calcium hydroxide were considered, and different percentages of aerogel were mixed in the first mixing phases. Firstly, only a 50 % of aerogel in volume was considered (the thermal conductivity varied in 0.08–0.06 W/m K range). The good properties of the natural lime maturing are important in order to obtain a good quality of the final



Fig. 2.5 Various steps of the mixing: (a) original components; (b) mixing phase; (c) final composition of the plaster (Buratti et al. 2014)

composition. Water was added slowly, in order to obtain a uniform mixture with all aerogel particles having uniform coating of cement floating. The preparation of the product is made by mixing the two components in a bucket: This phase should be slow, accurate, in order to avoid the pulverizing of the granules. The original size of the aerogel granules is usually about 3–4 mm and they are irregular in shape: after the mixing phase, the granules are partially broken, but they are not completely pulverized. In the final mix, the particle dimensions are included in the 0.1–2 mm range. Aerogel granule dimensions have not to be very small because the plaster becomes hydrophobic and its binder properties decrease, even if the thermal conductivity is the same.

Figure 2.5 shows the mixing steps of the different components of the plaster (granular aerogel, calcium hydroxide, and water). The new coating has also the advantage to be simultaneously water repellent and permeable to water vapor. It is much more breathable than conventional plasters, and its surface does not become wet. The hydrophobic nature of aerogel is important because the aerogel particles incorporated into renders avoid the water absorption that could change the volumetric composition of the final mix and the thermal performance.

The direct spray in situ application of the new plaster on to brickwork is represented in Fig. 2.6. The installation is very easy also in complex wall geometries. Moreover, it is possible to eliminate gaps where moisture could form, reducing condensation inside walls that can cause mold.

Also Achard et al. (2011) describe the composition of an innovative insulating coating based on silica aerogel: It consists of water, a mineral hydraulic binder, insulating filler and, in particular, a powder of silica aerogel in granules, and other possible additives and structuralizing fillers. The render is made of aerogel granules used in place of sand and inert, that are usually inserted in conventional coatings. Aerogel granules are industrially manufactured in a specialized plant; then, the mortar/render is prepared industrially as a dry mixing of all the mentioned components; the mix is then stored in bags and transported to the site for use. Finally, the product is mixed with water in order to obtain a viscosity suitable for the application on-site, for example, by spraying on the wall surface.



Fig. 2.6 In situ application of the aerogel-based plaster (courtesy of Agosti Fabrizio, Agosti Nanotherm s.r.l., Naturalcalk-Tillica 2015)

2.3.2 Thermal Properties

Thermal conductivities were evaluated in some research works (Stahl et al. 2012; Achard et al. 2011) already described in Sect. 2.2.1. In these cases, aerogel-based renders with thermal conductivities of 0.025 and 0.027 W/m K were performed.

Stahl et al. measured a thermal conductivity of 0.025 W/m K at a density of about 200 kg/m³. The sample was produced by means of a plastering machine to real-use condition, and a number of commercially available insulating renders was also realized in order to compare the results. All the thermal conductivity measurements were carried out by a guarded hot plate apparatus. The comparison is shown in Table 2.4.

Achard et al. measured the thermal conductivity by means of guarded hot plate and heat flow meter, according to the EN ISO standard 12667. The heat is measured

Table 2.4 Thermal conductivity of insulation renderings in comparison (adapted from Stahl et al. 2012)

	Thermal conductivity (W/m K)	Insulating additives	Density [kg/m ³]
Render 1	0.103	Perlite, cork	432
Render 2	0.099	Mineral	478
Render 3	0.067	Expand polystyrene (EPS)	297
Render 4	0.072	Expand polystyrene (EPS)	318
Render 5	0.072	Expand polystyrene (EPS)	250
Aerogel render	0.025	Aerogel	200

Table 2.5 Thermal measurement results for the examined samples (Buratti et al. 2014)

Specimens	Description	Percentage of granular aerogel in volume (%)	Density ρ (kg/m ³)	Thermal conductivity λ (W/m K)
T0	Natural plaster without aerogel	–	2200	0.50
T1	Natural plaster with granular aerogel	80–90	300–275	0.050–0.045
T2	Natural plaster with granular aerogel	91–95	136–126	0.021–0.019
T3	Natural plaster with granular aerogel	96–99	125–115	0.016–0.014

by means of differential scanning calorimeter (DSC) according to NF EN 1159-3 standard. The density is measured in compliance to the NF EN 1602 standard, and the vapor diffusion resistance factor is measured according the NF EN ISO 12572 standard by means of the cup method. The thermal conductivity obtained is only 0.027 W/m K (with a density of about 156 kg/m³), better than the ones measured for traditional insulating materials (0.034–0.050 W/m K is obtained, for example, for mineral wool, glass wool, and foam glass), and it can be very useful in order to limit heat losses through thermal bridges both in new and existing buildings.

Considering the thermal characterization of the material, also the research activities of Buratti et al. (2014) are reported. Four kinds of insulating aerogel-based plasters were tested by means of a heat flow meter apparatus and the thermal conductivity of the specimens was calculated in compliance with EN ISO 12667 standard. Natural lime plasters with granular aerogel in different percentages were tested.

Table 2.5 shows the properties of the samples (density, percentage of granular aerogel in the mix) and the thermal conductivity measured. The density of the plaster decreases when aerogel is added in the mix and also the thermal conductivity decreases by about 90–97 %, due to the highly porous light aerogel nature. In fact, granular silica aerogel has a density of about 50–200 kg/m³ and a thermal conductivity variable in the 0.013–0.018 W/m K range. Nevertheless, for aerogel types T2 and T3, the mechanical resistance of the plasters decreases a little bit because of the high porosity of the aerogel added in the final mix. A good solution that can be launched on the market also characterized by good mechanical resistance properties is the innovative plaster type T1, with an 80 % aerogel (0.050 W/m K). Finally, the compressive strength of this innovative plaster is only 0.36 MPa, very low considering the values obtained for standard mortars (2–12 MPa).

2.3.3 Acoustic Performance

Sound absorption properties of aerogel-based renders were investigated by Buratti et al. (2014). The tests were carried out by means Kundt's tube in order to estimate the acoustic absorption coefficient of the material.

The normal incidence absorption coefficient was measured by means of two-microphone impedance tube (Brüel & Kjær, Nærum, Denmark, model 4206) using the transfer function method and cylindrical samples with diameters of 29 and 100 mm (combined frequency from 50 to 6400 Hz), according to ISO 10534-2 standard (ISO 10534-2 1998 and UNI 10351 1994). Plasters of natural lime with a percentage of granular aerogel of about 80 % was applied to a plasterboard support (thickness 12.5 mm); a preliminary test was carried out considering the only plasterboard support (type A0), in order to establish a reference value for the comparison.

Two kinds of plaster were tested (the thickness of the only plaster is 10 and 30 mm, respectively); in both the samples, a final coat of 2 mm was applied, for a total thickness of 24.5 mm (type A1) and 44.5 mm (type A2), respectively; three specimens were tested for each type and an average trend was analyzed. Figure 2.7 shows the average normal incidence absorption coefficient trends for the samples (large tube measurements); the absorption coefficient of A0 is lower than the others (smaller than 0.05 in 100–1600 Hz range). By increasing thickness, the greatest shift is toward lower frequencies; two picks of the absorption coefficient are observed: for A1 at frequencies 700–800 Hz, for A2 at 400–500 Hz.

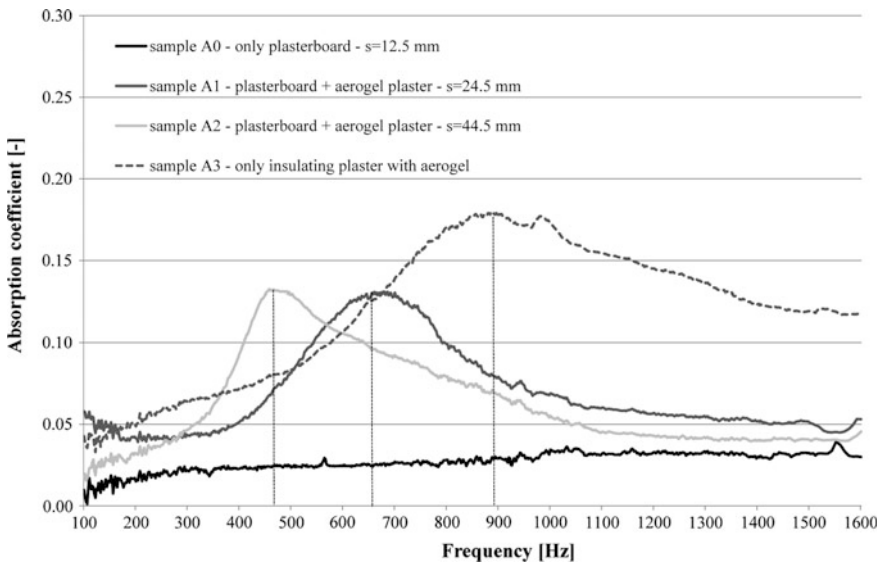


Fig. 2.7 Absorption coefficient at normal incidence (large tube measurements, 100–1600 Hz): comparison with insulating plaster (without final coat) (Buratti et al. 2014)

The acoustic properties of the only insulation plaster with aerogel were measured by removing the final coat layer of the specimens. The absorption coefficient trend of A3 was higher than the others: The final coat of the sample makes the acoustic behavior worse (Fig. 2.7).

It can be observed that the absorption coefficient strongly depends on the final coat, so the aerogel-based plaster layer moderately influences the final value; in any case, the normal incidence absorption coefficient values of the aerogel-incorporated plasters are not very high at all (always small than 0.2). Finally, the evaluation of the noise abatement properties of the render was not considered till now, but this property is not so incisive because of the small thickness of the aerogel-based render applied to a wall.

2.3.4 Hygrothermal Performance

The hydric performance is very important in building envelope design. Moistures problem can cause wood decay, mold growth, poor indoor air quality, corrosion of metals, damage to materials, and loss of structural strength. For these reasons, the installation of external or internal water vapor barriers is often required.

In order to examine the hygrothermal behavior of a patented insulating render based on silica aerogel, a numerical model was developed and an experimental campaign was carried out by Ibrahim et al. (2014c). The aim of the work was the analysis of the hygrothermal performance of walls with new renderings and the comparison with different thermal insulation configurations. The hygrothermal behavior was modeled by using the software WUFI: The numerical model was validated by means of an experimental setup on a test cell having the aerogel-based renders on its south wall. The experimental test unit was built in 1984 (Krauss 1985) at PERSEE in University of Nice Sophia Antipolis, in the southeast of France. It is composed of three cells (current test cell, adjacent cell, and acquisition cell): the test cell (total volume 30 m³) has two external walls (southeast exposure) and two internal walls (partitions with the other cells). No windows are present in order to avoid the effect of the solar gains. The south wall was considered as test wall. The original stratigraphy of the walls is as follows: concrete (external layer, $s = 0.25$ m), glass wool ($s = 0.16$ m), and plaster (internal side, $s = 0.013$ m). A layer of aerogel-based render was applied at the exterior surface of this wall ($s = 0.04$ m). The hygrothermal sensor was positioned between the concrete and the external aerogel-based plaster. The experimental campaign was carried out during the two weeks in summer: The validation of the model was carried out considering the measured and simulated temperatures and relative humidity at the interface between the concrete and the aerogel-based coating.

After the model validation, different simulations were examined considering the city of Grenoble (semi-continental French climate, with cold winter and warm summer and abundant rain). It is one of the warmer cities of French in summer (more than 35 °C); in winter, the temperatures are generally very low and the daily

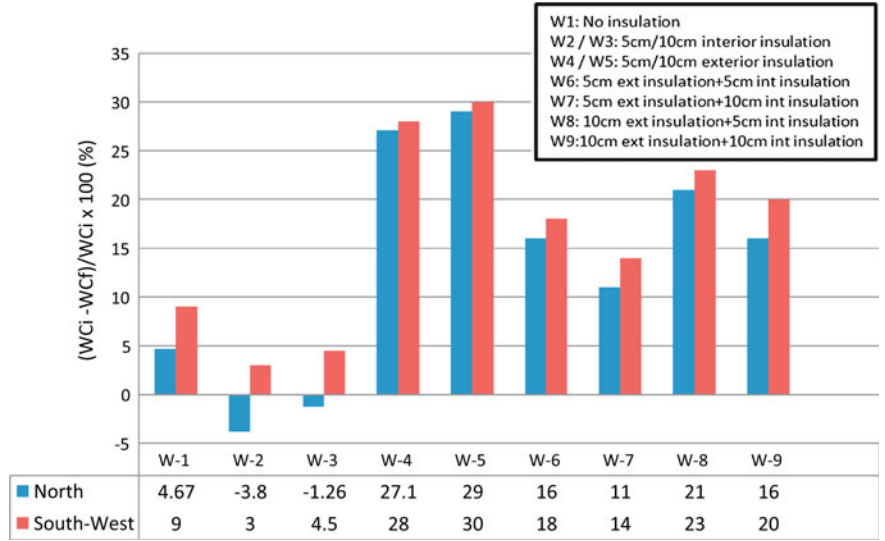


Fig. 2.8 Dryness rate (DR) for different walls (Ibrahim et al. 2014c)

Table 2.6 Wall assembly insulation configurations (adapted from Ibrahim et al. 2014c)

Case	Layer 1	Layer 2	Layer 3	Layer 4
W-1	Concrete 20 cm	Plaster	–	–
W-2	Concrete 20 cm	Polystyrene 5 cm	Plaster	–
W-3	Concrete 20 cm	Polystyrene 10 cm	Plaster	–
W-4	Aerogel render 5 cm	Concrete 20 cm	Plaster	–
W-5	Aerogel render 10 cm	Concrete 20 cm	Plaster	–
W-6	Aerogel render 5 cm	Concrete 20 cm	Polystyrene 5 cm	Plaster
W-7	Aerogel render 5 cm	Concrete 20 cm	Polystyrene 10 cm	Plaster
W-8	Aerogel render 10 cm	Concrete 20 cm	Polystyrene 5 cm	Plaster
W-9	Aerogel render 10 cm	Concrete 20 cm	Polystyrene 10 cm	Plaster

temperature range is high. The simulation results can be compared in terms of dryness percentage (DR) over a period of 4 years (it is the difference between the initial water content and the final one at the end of the simulation period, and it represents the drying power of the wall, see Fig. 2.8). Different insulated walls were considered (Table 2.6).

The best behavior in terms of drying potential of the wall assembly is obtained for walls types W-4 and W-5 [aerogel rendering layer with a thickness of 5 and 10 cm, respectively, and concrete (20 cm)]: DR is about 23 %. Moreover, the dryness rate for exterior insulation is the highest of all configurations. The external application of aerogel-based plaster improves the dryness rate also for walls with an internal insulation layer (W-6, W-7, W-8, and W-9): The effect is better when the

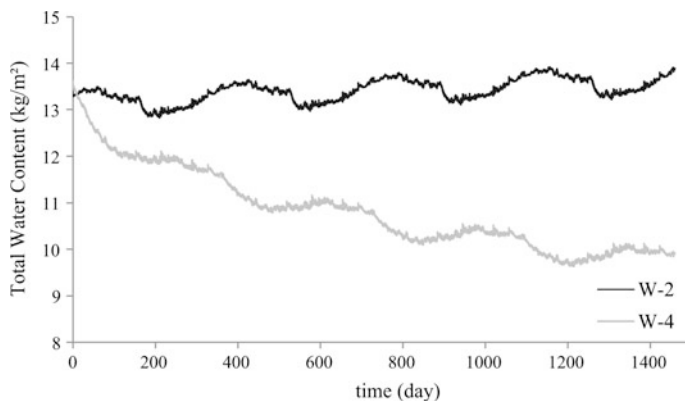


Fig. 2.9 Evolution of the total water content over 4 years for W-2 and W-4 (Ibrahim et al. 2014c)

internal insulation polystyrene has lower thicknesses (5 cm) (W-6 and W-8). Adding the aerogel-based render on the exterior surface of the walls reduces significantly the moisture risks. Figure 2.9 shows the assembly water content over time for a north orientation for two cases: 5-cm polystyrene interior insulation (W-2) and 5-cm aerogel-based rendering exterior insulation (W-4). The drying capacity of the wall decreases considering an interior insulation layer, and the moisture content increases: A vapor barrier is usually added in interior insulating wall. In W-4, the water content decreases and this effect is higher in southwest orientation, thanks to the solar radiation. A heat loss reduction up to 70 % could be achieved thanks to the aerogel-based rendering application and the mold can be easily eliminated.

2.4 Applications in Building Refurbishment

In order to evaluate the real effectiveness of the innovative insulating renders, it is important to examine their in situ applications by experimental monitoring tests. The building's outside envelope interacts with the external environment: External air temperature and solar radiation influence the outside surface temperatures of roofs and walls, and the heat flux through the envelope is affected by fluctuations during the day period. In this context, it is important to carry out deepen researches dealing with optimizing layers configuration in exterior walls. Considering old buildings, it can be useful to analyze their thermal behavior before and after refurbishment actions, such as using aerogel-incorporated renders.

In this section, some examples of in situ applications and a benefit analysis of the new renders are analyzed, considering also a comparison with traditional solutions.

2.4.1 In Situ Applications

The in situ performance of the proposed solutions in different kinds of existent buildings was analyzed considering the refurbishment by using the new plasters (Buratti et al. 2014). Table 2.7 shows the decreasing of the thermal transmittance of different walls, due to the aerogel-based plasters ($\lambda = 0.05 \text{ W/m K}$, 80 % of aerogel). As shown the innovative coating is very effective, above all for a stone wall with a thickness of about 60 cm (type 1) (U value equal to $2.14 \text{ W/m}^2 \text{ K}$). Applying 5 mm of aerogel-based plaster, the thermal transmittance of the wall becomes $1.73 \text{ W/m}^2 \text{ K}$ (reduction of about 20 %).

Table 2.7 Thermal transmittance values of different types of wall before and after the insulating plastes application (Buratti et al. 2014)

Wall type	Description	Before refurbishment		After refurbishment		
		Total thickness (m)	U value ($\text{W/m}^2 \text{ K}$)	U value ($\text{W/m}^2 \text{ K}$)	Total thickness (m)	U reduction (%)
1	Stone wall (s = 600 mm), internal and external lime plastered (s = 15 mm)	0.63	2.14	1.73	0.635	19
2	Brick wall (s = 300 mm), internal and external lime plastered (s = 15 mm)	0.33	1.61	1.37	0.335	15
3	Cavity wall (s = 250 mm) (air brick wall 120 mm + 50 mm air gap + air brick wall 80 mm), internal and external lime plastered (s = 15 mm)	0.28	1.10	0.98	0.285	11
4	Cavity wall (s = 250 mm) (air brick wall 120 mm + 50 mm polystyrene + air brick wall 80 mm), internal and external lime plastered (s = 15 mm)	0.28	0.50	0.47	0.285	6

The study of thermal performances can be carried out also by means of simulation model analysis (Cotana et al. 2013). A study of the thermal performance of exterior walls covered with an aerogel-based insulating coating is illustrated by Ibrahim et al. (2014a). A numerical model was developed in order to evaluate the effectiveness of the coating in terms of energy performance and thermal comfort. The reference experimental campaign was described in Sect. 2.3.4: The aerogel-based coating is applied on the exterior surface of the south wall of a test cell.

This experiment was carried out to validate a numerical model using the implicit finite difference scheme (one-dimensional heat conduction equation) under real weather conditions. The energy loads with and without 5 cm of the aerogel-based coating were analyzed considering different construction periods and different climates. Two house models in the period 1968–1974 were considered: the first one (1) with simple-glazed windows and no thermal insulation in the roof and the second one (2) with double-glazed windows and a 6 cm insulation layer in the roof. In the period after 1990, the first type of house (1) has an exterior wall with a 10-cm internal insulation layer and the second kind (2) has no thermal insulation. It can be observed that in old houses (<1974), the percentage of energy reductions are between 40 and 53 % (Mediterranean climate) and 33–40 % in semi-continental climate (Fig. 2.10). Obviously, in new houses the application of the ABC is not very effective and the annual load decreasing is not very high. In any case, the coating application is more interesting and efficient for old uninsulated buildings where a small thickness can reduce a lot the energy load.

In terms of thermal comfort, the number of hours where heating is not needed was analyzed for different coating thicknesses for an old house. It was observed

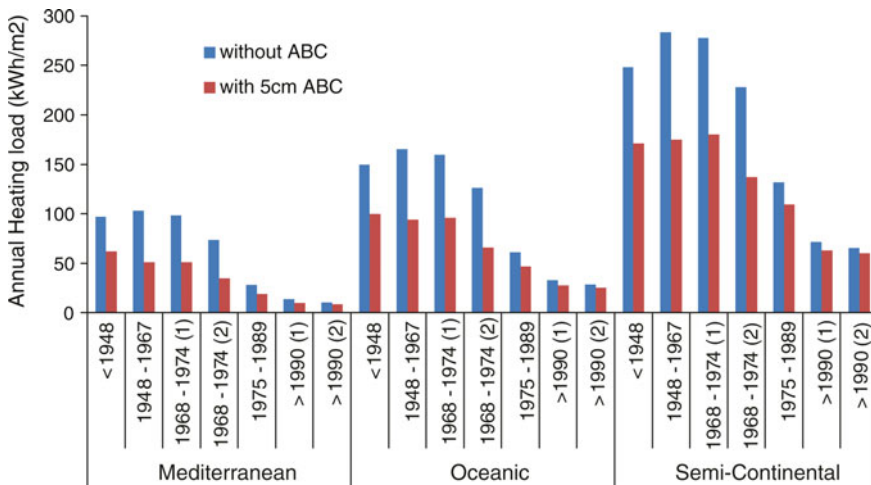


Fig. 2.10 Annual heating loads for different climates and different construction periods (Ibrahim et al. 2015)

that, by increasing the ABC thickness from 0 to 15 cm, the percentage of occupied time where hating is not necessary increases by 10, 6 and 3 %, respectively, for the Mediterranean, Oceanic, and semi-continental climates (Ibrahim et al. 2014a, 2015).

Another study concerning the examination of the long-term behavior of aerogel plaster surfaces (Ghazi Wakili et al. 2015) is described. In situ measurements of temperature, humidity, and heat flux within different layers of a wall were examined. F222 plaster is an aerogel-containing render, easily adaptable to structured façades and a promising solution for improving the thermal behavior of historic buildings. It was applied to the historical building of the Vienna University of Technology with different finishing layers, and a series of temperature and moisture sensors were applied and monitored for 5 months. Four different wall partitions were considered (F1-F4): aerogel plaster F222 was applied (40 mm thick, $\lambda = 0.029 \text{ W/m K}$) and then covered by the four final finishes (see Table 2.8).

The theoretical value of the thermal transmittance of the walls before the aerogel-based render application is $1.12 \text{ W/m}^2 \text{ K}$ (F0); the U reduction is about 60 % considering the one-dimensional steady-state calculation of U after the refurbishment ($0.44 \text{ W/m}^2 \text{ K}$).

The heat flux through the wall and the internal and external surface temperatures were used in order to find the evolution of the conductance before and after the retrofit. The average method of ISO standard 9869 was used. The thermal transmittance before the refurbishment varies in the $0.97\text{--}1.04 \text{ W/m}^2 \text{ K}$ range considering the four kinds of walls (F1-F4); the final values after the refurbishment vary in the $0.58\text{--}0.78 \text{ W/m}^2 \text{ K}$ range. The differences depend on the external final finish applied to the walls: Wall type F4 has a humidity value on the external side lower than the other three types, because it has a water-repelling final finish containing silicon resin paint. A similar behavior can be observed for F2 (application of a silicate-paint final finish). For these types of walls, the thermal transmittance is lower (about $0.58\text{--}0.60 \text{ W/m}^2 \text{ K}$).

Table 2.8 Wall type configurations (adapted from Ghazi Wakili et al. 2015)

Case	Layer 1 (15 mm)	Layer 2 (250 mm)	Layer 3 (20 mm)	Layer 4 (40 mm)	Layer 5 (1 mm)
F0	Internal plaster	Hollow bricks	External plaster	–	–
F1	Internal plaster	Hollow bricks	External plaster	F222	External finish R380 + PE819
F2	Internal plaster	Hollow bricks	External plaster	F222	External finish R750 + PE225
F3	Internal plaster	Hollow bricks	External plaster	F222	External finish R380 + PE819S
F4	Internal plaster	Hollow bricks	External plaster	F222	External finish R380 + PE419

Finally, another aspect of the retrofit procedures is the internal comfort condition improvement. In the present paper, Ghazi Wakili et al. (2015) measured the internal air temperatures and the inside surface temperatures: Before the refurbishment, a difference of about 4 °C was observed, reduced to less than 1–2 °C in the post-retrofit conditions.

2.4.2 Comparison with Traditional Solutions and Benefits Analysis

In order to evaluate the potential of aerogel-based plasters, a comparison with traditional solutions was carried out by Buratti et al. (2014). In Table 2.9, the thermal conductivities of different types of commercial plasters are compared with the innovative aerogel-based plasters. Traditional plaster values vary in 0.29–0.70 W/m K depending on the type and on the density of the coat.

The thermal benefit of the plaster application in building refurbishment was observed also by means of in situ infrared thermography analysis (Buratti et al. 2014). A three-story apartment was photographed, and a thickness of about 5 mm of aerogel-based plaster ($\lambda = 0.05$ W/m K) was applied on the internal walls of then third floor. On the first and on the second floor, the internal plaster was not applied. The investigated building was built in the 1960s in the north of Italy. The northern façade was considered in order to avoid the influence of the direct solar radiation and the infrared thermography was carried out in autumn (external emissivity

Table 2.9 Comparison with traditional solutions: thermal conductivity values (in Italic innovative plasters, Buratti et al. 2014)

Plasters	Density ρ (kg/m ³)	Thermal conductivity λ (W/m K)
Coating/mortar with different sizes of aggregate	600	0.29
Coating/mortar with different sizes of aggregate	1000	0.47
Coating/mortar with different sizes of aggregate	1200	0.58
Lime-based plaster	1400	0.70
Gypsum-based plaster	1200	0.35
<i>T0-Natural plasters without aerogel</i>	<i>2200</i>	<i>0.50</i>
<i>T1-Natural plasters with aerogel (80–90 %)</i>	<i>275–300</i>	<i>0.045–0.050</i>
<i>T2-Natural plasters with aerogel (91–95 %)</i>	<i>126–136</i>	<i>0.019–0.021</i>
<i>T3-Natural plasters with aerogel (96–99 %)</i>	<i>115–125</i>	<i>0.014–0.016</i>

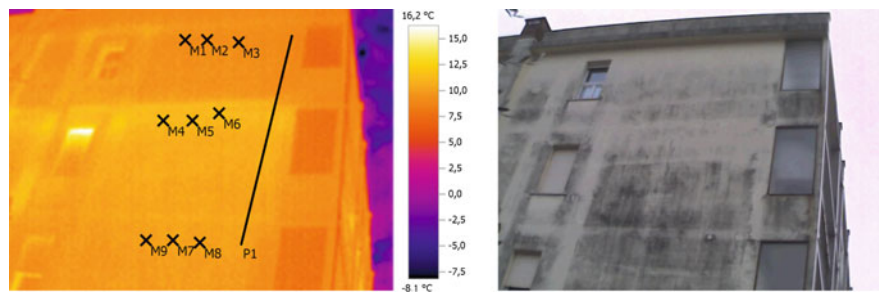


Fig. 2.11 View of the investigated building and corresponding infrared imagine (Buratti et al. 2014)

Table 2.10 Temperature values measured by means of the thermographic camera (Buratti et al. 2014)

Points	Emissivity (–)	Temperatures (°C)
M1	0.93	9.1
M2	0.93	9.2
M3	0.93	9.1
M4	0.93	11.5
M5	0.93	11.4
M6	0.93	11.7
M7	0.93	10.4
M8	0.93	10.4
M9	0.93	10.4

considered equal to 0.93). Figure 2.11 shows a thermogram of this building: it can be observed that the temperature values in M1, M2, and M3 are about 9 °C (third floor), whereas the values are 10.5–11.5 °C in M4–M9 (first and second floor): The decreasing of about 2 °C is due to the aerogel-based plaster application (Table 2.10).

2.4.3 Future Trends and Barriers

New aerogel-based plasters are the focus of the HIPIN Project (HIPIN, 2015, from European Union’s Seventh Framework Program). This project aims to test new formulations of aerogel in order to obtain a good mechanical strength and thermal conductivity, other characteristics being equal. Moreover, it aims to develop three nanostructured systems, in which aerogel should be incorporated (paint layers, plasters, and sandwich panels), in order to improve thermal efficiency in existing buildings and new constructions. As regards the incorporation of aerogel into paints, a replacement of a portion of the lime with hydrophobic and hydrophilic aerogel is considered. Three stages are considered for the aerogel plaster preparation: dry

mixing, mixing with water, and pumping in application stage. Generally, the thermal plaster layer has to be covered with a final render of about 2–5 mm, but in future a single aerogel-based plaster insulating layer as final finish of the wall will be developed according to this project. Finally, the developed high-performance aerogel would be included into panels to decrease the thickness of the insulating blanket: the ideal thickness is the lowest possible, but a good common solution could be 3 cm. This insulating layer should allow water transpiration and should be affordable considering the costs: Specific matrix materials with good mechanical and thermal properties should be selected for aerogel binding.

Until now, aerogel has been considered too much expensive and mechanical fragile for the diffusion in the construction sector. Furthermore, many technical changes recently enabled aerogel plasters to have higher mechanical resistance to be manufactured at lower costs. The thermal and mechanical properties of these new materials allow high efficient retrofit also in buildings in which the insulation with conventional solutions is difficult; so they can be considered very impacting in the construction sector also considering their complete integration in the building.

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