

Article

Development of Innovative Aerogel Based Plasters: Preliminary Thermal and Acoustic Performance Evaluation

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Abstract: The thermal and acoustic properties of innovative insulating systems used as building coatings were investigated: Granular silica aerogel was mixed with natural plaster in different percentages. This coating solution is transpiring and insulating, thanks to the use of a natural lime coat and aerogel, a highly porous light material with very low thermal conductivity. The thermal conductivity of the proposed solution was evaluated by means of a Heat Flow meter apparatus (EN ISO 12667), considering different percentages of aerogel. The natural plaster without aerogel has a thermal conductivity of about 0.50 W/m K; considering a percentage of granular aerogel of about 90% in volume, the thermal conductivity of the insulating natural coating falls to 0.050 W/m K. Increasing the percentage of granular aerogel, a value of about 0.018–0.020 W/m K can be reached. The acoustic properties were also evaluated in terms of the acoustic absorption coefficient, measured by means of a Kundt's Tube (ISO 10534-2). Two samples composed by a plasterboard support, an insulation plaster with aerogel (thicknesses 10 mm and 30 mm respectively) and a final coat were assembled. The results showed that the absorption coefficient strongly depends on the final coat, so the aerogel-based plaster layer moderately influences the final value. The application of this innovative solution can be a useful tool for new buildings, but also for the refurbishment of existing ones. This material is in development: until now, the best value of the thermal conductivity obtained from manufacturers is about 0.015 W/m K.

Keywords: aerogel based plasters; silica aerogel; thermal and acoustic performance; refurbishment of buildings

1. Introduction

Thermal insulation in buildings contributes not only to reducing the size of the heating and cooling system, but also the annual energy consumptions. Moreover, it can be useful to extend the periods of thermal comfort without dependence on heating and cooling systems, especially during inter-season periods [1]. The application of innovative solutions can be a useful tool for new constructions, but also for the refurbishment of existing buildings, reducing the heat losses of the envelope. In particular, in Italy, at least 90% of buildings were constructed before 1991 and they are not in compliance with the law for the most part (the most recent norms date from 2006). Therefore, all these buildings would need refurbishment in order to be compliant with normative targets. Many innovative insulating systems for building insulation 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 [2–4]. In particular, silica aerogels seem to have the largest potential in the market of building insulation materials. Aerogel is a highly porous nano-structured and light material: The porosity is higher than 90% and the density is in the 50–200 kg/m³ range; the thermal conductivity is very low (down to 0.010 W/m K) [5–7]. Different glazing systems with translucent granular aerogels in interspace (polycarbonate panels, structural panels for façades, insulated glasses) were developed, offering excellent thermal performance, a good solar heat gain, and a good sound insulation [8–12]. Opaque aerogels, such as flexible aerogel blankets, were proposed in order to reduce thermal bridges in the building envelope, offering a thermal conductivity of about 0.013 W/m K [13].

Recently, granular aerogels were employed as additives for high thermal performance materials in buildings: Coatings, plasters or concrete. The application of aerogel as aggregate for lightweight and thermal insulating concrete was recently investigated [14]: A thermal conductivity of 0.26 W/m K was found (60 vol % of aerogel), while the reference values for a conventional concrete are higher, at about 1.7–2.5 W/m K, without and with rebars; the measured density was about 1000 kg/m³, compared to 1980 kg/m³ of the reference plain concrete sample. Moreover, aerogel particles were found stable during the hydration of cementitious materials and the compressive strength was good, encouraging the research on aerogel employment in concrete for buildings. Another study [15] presents the development of new kind of rendering based on silica aerogel granulates: Hydrophobized granular silica aerogel (60–90 vol %) was mixed with purely mineral and cement free binder. A thermal conductivity of 0.025 W/m K was measured for the investigated aerogel based rendering at a density of about 200 kg/m³ and a water vapor transmission resistance of 4 was achieved. Nevertheless, the thermal conductivity depended on the production pressure and the optimal recipe is currently under development in cooperation with an industrial partner [15].

The application of thermal insulating plasters in façades can be a clever solution for decreasing the heat losses in existing buildings with reduced thickness. The present study is focused on thermal and acoustic characterization of innovative insulating coatings constituted by granular silica aerogel and

natural plaster; the high performance plaster was developed and manufactured by Agosti Nanotherm (Bolzano, Italy) and Arte & Mestieri (Pordenone, Italy) [16,17], two companies that have been performing different insulating products composed by natural calk and aerogel.

The aerogel based plaster is currently under development in order to improve thermal performance without altering the workability, but some products are already available on the market. Three solutions with different percentages of aerogel were considered so far. The thermal properties of the proposed plasters were evaluated by means of a heat flow meter apparatus (ASTM C518-10 and ISO 8301 [18,19]) at the Labs of the Agosti Nanotherm Company.

Moreover, in order to estimate the acoustic behavior of the innovative plaster, the acoustic absorption coefficient ranging from 50 to 6400 Hz were measured at the Labs of Building Physics of the Department of Industrial Engineering, University of Perugia.

The experimental results were compared with the thermal properties of traditional plaster systems generally adopted for buildings and the potential benefits in buildings refurbishment were discussed.

2. State of the Art of Innovative Aerogel Based Plasters

2.1. Materials and Applications

Insulation plasters can be used in many applications, including external and internal walls systems. In order to have new refurbishment methods, an aerogel-based high performance insulating plaster has been developed and soon thereafter, it became a commercial solution. Thanks to its mineral basis, the new plaster is very similar to the original historical building materials, and this makes it ideal for use on old buildings, on internal as well as external surfaces. The new material offers a non-invasive method for renovating historic buildings and for saving energy without altering their appearances. The selling point of the product is aerogel: This material has nanometer-sized pores and consists of 90% to 98% of air. Aerogel can be considered a very good insulating material because of the small dimensions of the pores.

The coating is manufactured by manually mixing natural calk with granular aerogel in different percentage, allowing the absorption of air in the mix. In this way the density of the plaster decreases of about 90%. Many attempts were considered in the first mixing phases: Different kinds of calcium hydroxide were considered and different percentages of aerogel were mixed. At the beginning only a 50% of aerogel in volume was considered (the thermal conductivity varied in 0.08–0.06 W/m K range). Furthermore, the good quality of the final composition is due to the good properties of the natural calk maturing. 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 can be made by mixing the two components in a bucket. This phase has to be slow and accurate, in order to avoid the pulverizing of the granules: In fact, aerogel granules 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. The original size of the aerogel granules is usually about 3–4 mm and they are irregular in shapes: After the mixing phase, the granules are partially broken but they are not completely pulverized. The particles dimensions in the final mix have to be included in the 0.1–2 mm range.

Figure 1 shows the three original components of the plaster (granular aerogel, calcium hydroxide, and water) and the different steps of the mix.

Figure 1. Various steps of the mixing: (a) original components; (b) mixing phase; (c) final composition of the plaster.



The new coating has also the advantage to be simultaneously water repellent and permeable to water vapor. The hydrophobic nature of aerogel is helpful for preventing water absorption: The aerogel particles incorporated into concrete allow to avoid the water absorption that could change the volumetric composition of the final mix. The product is significantly more breathable than conventional plasters, and its surface does not become wet.

The direct spray application on to brickwork is very easy also in complex wall geometries. In addition, it eliminates gaps where moisture could form, reducing condensation inside walls that can cause mold.

The *in situ* application of the new plaster is represented in Figure 2.

Figure 2. *In situ* application of the aerogel-based plaster.



2.2. Descriptions of the Samples

The importance of this plasters is due to their thermal insulation properties. In fact, for thermal measurements, different kinds of plasters were investigated, considering various percentages of aerogel in the mixture. Three interesting solutions were examined.

For thermal measurements, square samples were realized. All the samples were assembled with external dimensions 300×300 mm, for a total area of 0.09 m^2 , due to the dimensions of the experimental apparatus. At first a specimen composed by only natural plaster without aerogel was tested (specimen T0). Therefore three kinds of plasters with aerogel were analyzed; they had different percentages of aerogel in their compositions: The first sample had a percentage of aerogel of about 80%–90% in volume (type T1), the second one had 91%–95% of aerogel (T2), and the last one had 96%–99% in volume of aerogel (type T3) (Table 1).

Table 1. Description of the samples for thermal measurements.

Sample	Description	Percentage in Volume of Aerogel (%)
T0	Natural plaster without aerogel	-
T1	Natural plaster with granular aerogel	80–90
T2	Natural plaster with granular aerogel	91–95
T3	Natural plaster with granular aerogel	96–99

Figure 3 shows the samples tested by means of the hot plate for thermal measurements.

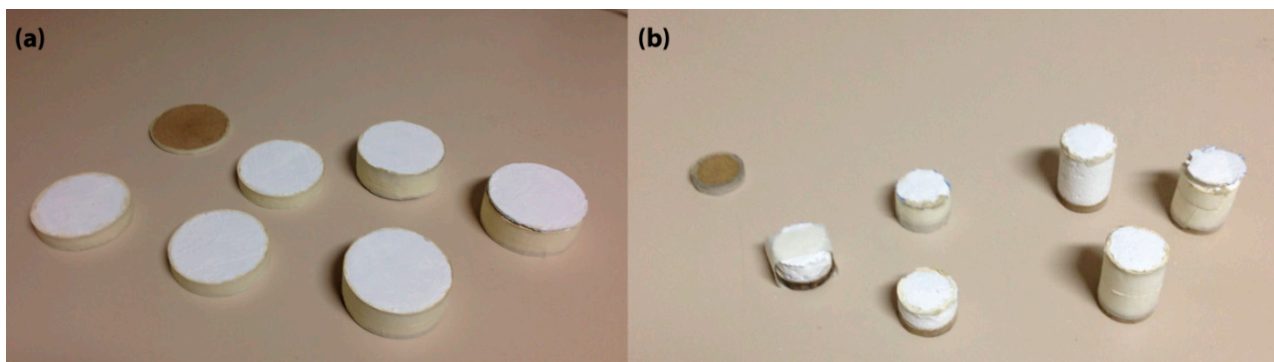
Figure 3. Plaster samples for the thermal experimental campaign.



For acoustic tests, cylindrical samples with diameters of 29 and 100 mm were manufactured. Two samples were assembled for acoustic measurements (Figure 4): They are composed by a plasterboard support, an insulation plaster with aerogel (thicknesses 10 mm (type A1) and 30 mm (type A2) respectively) and a final coat (see Table 2). The insulation plaster has a percentage of granular aerogel of about 80% in volume. Only this composition was considered in the acoustic experimental campaign because it is a good commercial solution. The thicknesses of the insulation plasters should not influence very much the acoustic absorption coefficient value because it is a property of the samples surface.

Table 2. Description of the samples for acoustic measurements.

Sample	First Layer	Second Layer	Third Layer	Total Thickness (mm)
A0	Plasterboard support (s = 12.5 mm)	-	-	12.5
A1	Plasterboard support (s = 12.5 mm)	Insulation plaster with aerogel (s = 10 mm)	Final coat (s = 2 mm)	24.5
A2	Plasterboard support (s = 12.5 mm)	Insulation plaster with aerogel (s = 30 mm)	Final coat (s = 2 mm)	44.5

Figure 4. General view of the samples for the Kundt's Tube measurements: Large tube (a) and small tube (b).

3. Methodology

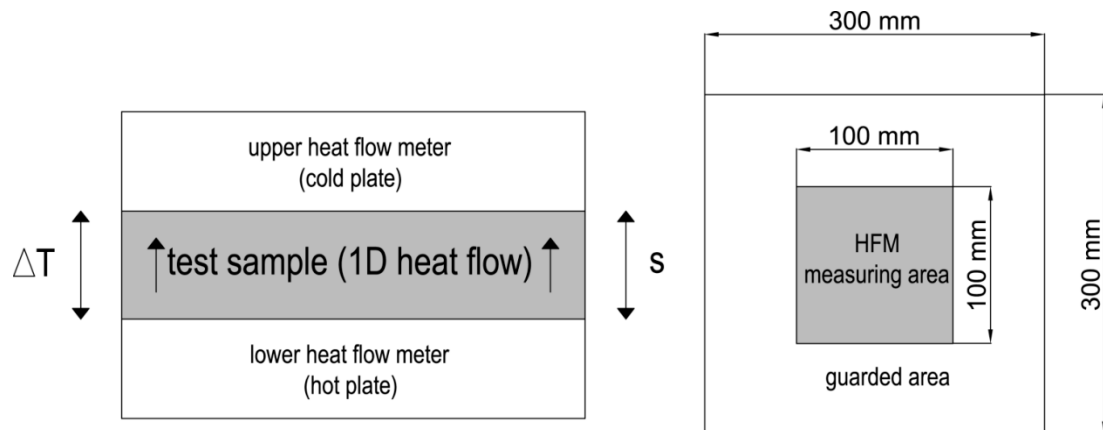
3.1. Thermal Measurements

The heat flow meter apparatus establishes a steady state one-dimensional heat flux through a test specimen between two parallel plates at constant but different temperatures. Fourier's law of heat conduction is used to calculate thermal conductivity and thermal resistivity, or thermal resistance and thermal conductance. The main equipment used in Nanotherm Laboratory is the Fox 314 HFM apparatus (Figure 3), which measures the steady-state heat transfer through flat materials according to ASTM Standard C518 (2003) [18] and EN ISO 12667 [20]. A 30 cm square sample with a thickness of up to 10 cm thick is placed between two flat plates controlled to a specified constant temperature. Thermocouples fixed in the plates measure the temperature drop across the specimen and wireless thermal flux meters (HFMs) embedded in each plate measure the heat flow through the specimen (Figure 5). Thermal flux meters are located in the center of the plates. The guarded area ensures a one-dimensional heat transfer through the measuring area when a homogeneous sample is tested [21,22]. The thermal conductivity of the specimen (λ in W/(m·K)) can be calculated by measuring the heat flux (q in W/m²), the temperature difference across the specimen (ΔT in K), and the thickness of the specimen (s in m), at steady state, as:

$$\lambda = \frac{s \cdot q}{\Delta T} \left[\frac{W}{mK} \right] \quad (1)$$

The thermal conductivity has to be measured in steady state conditions. Only when the average temperatures of the top and bottom plates are within ± 0.2 °C of the set temperatures and the average readings of the thermal flux meter are within 2% of the previous registered values, the steady state conditions should be considered attained.

Figure 5. Schematic diagram of the Fox 314 heat flow meter apparatus and plan view of the upper/lower plate showing the guarded area.



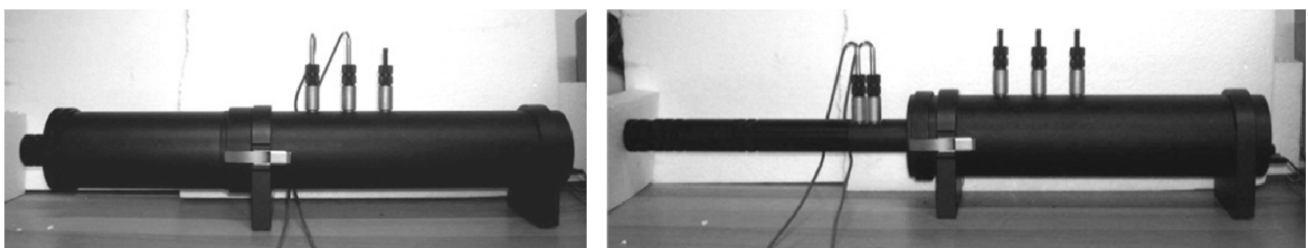
3.2. Acoustic Characterization

Sound absorption properties of the samples were investigated. The behavior of the material should be studied in a reverberation room, using the real thickness; however, the sample preparation for this test is complex and expensive. Therefore, preliminary tests on small samples were carried out with Kundt's Tube in order to estimate the acoustic behavior of the material and to evaluate the opportunity of preparing large samples for measurements in reverberation rooms.

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 [23,24].

The experimental apparatus in the two different configurations is showed in Figure 6.

Figure 6. Schematic view of the Kundt's Tube apparatus: Large tube (**left**) and small tube (**right**).



4. Results and Discussions

4.1. Thermal Performance

Considering the thermal characterization, four kinds of insulating aerogel based plasters were tested by means of the heat flow meter apparatus and the thermal conductivity of the specimens was calculated. Table 3 shows the properties of each sample (density, percentage of granular aerogel in the mix) and the thermal conductivity results.

Table 3. Thermal measurements results for the examined samples.

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

The density of the plaster falls when aerogel is added in the mix: The thermal conductivity decreases by about 90%–97%. In fact, aerogel is a highly porous light material (bulk density of about 50–200 kg/m³ because of the very high porosity) with the lowest thermal conductivity among solid materials: It ranges from 0.013 to 0.018 W/m K for granular silica aerogel to 0.004 W/m K for evacuated monolithic silica aerogels.

4.2. Acoustic Properties

A preliminary test was carried out considering the only plasterboard support (thickness 12.5 mm) (experimental proof A0), in order to evaluate the contributions of the plaster.

Therefore, three samples for the first type of plaster A1 were tested (total thickness of 24.5 mm) (three for the large tube and three for the small one) and an average trend was analyzed. In addition, for A2 (the sample with a total thickness equal to 44.5 mm) the average value of the measurements was considered. Several measurements were carried out also for the same disk, modifying the position of the sample inside the tube. Figure 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, it is no more than 0.05 in 100–1600 Hz range. It can be noticed that by increasing thickness the greatest shift is towards lower frequencies; two picks of the absorption coefficient are observed: For A1 at frequencies 700–800 Hz, for A2 at 400–500 Hz.

The combination of the large and the small tube measurements was made in order to obtain a global trend from 100 to 6400 Hz (Figure 8). The trends of the combined results are irregular: Many peak values are visible at the medium–high frequencies because of the non-uniformity of the edges of the small samples.

Finally, the acoustic properties of the only insulation plaster with aerogel were measured by removing the final coat layer of the specimens (measurement A3). Only the Large Tube measurements were considered because it was not possible to carry out the measurements for the small disk. The absorption coefficient trend of A3 is higher than the others: The final coat of the sample makes the acoustic behavior worse (Figure 9). The peak value is shifted and it is about 0.18 (900 Hz), while the maximum value is 0.13 both for A1 and A2.

Effectively, the absorption coefficient strongly depends on the final coat, so the aerogel-based plaster layer moderately influences the final value; moreover the acoustic absorption coefficients are not very high for the examined plasters, therefore a further acoustic characterization is worthless.

Figure 7. Absorption coefficient at normal incidence (Large tube measurements, 100–1600 Hz).

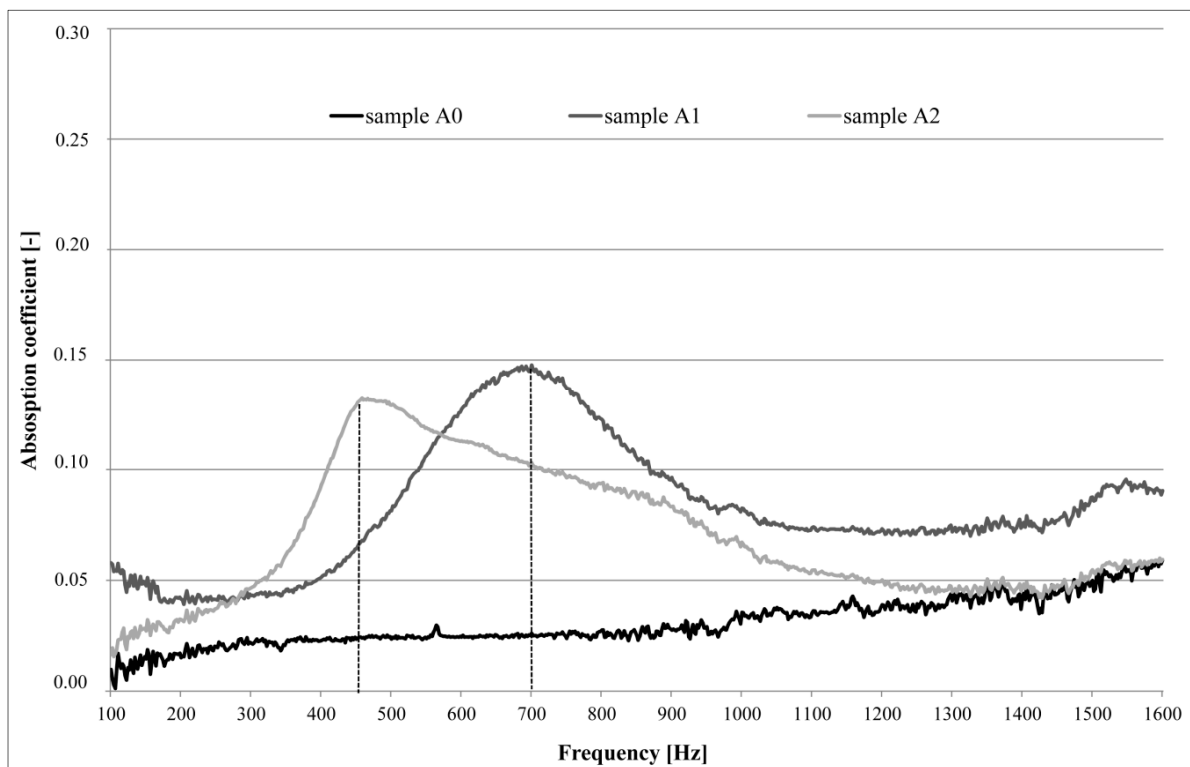


Figure 8. Absorption coefficient at normal incidence (combination Large and Small tube measurements, 100–6400 Hz).

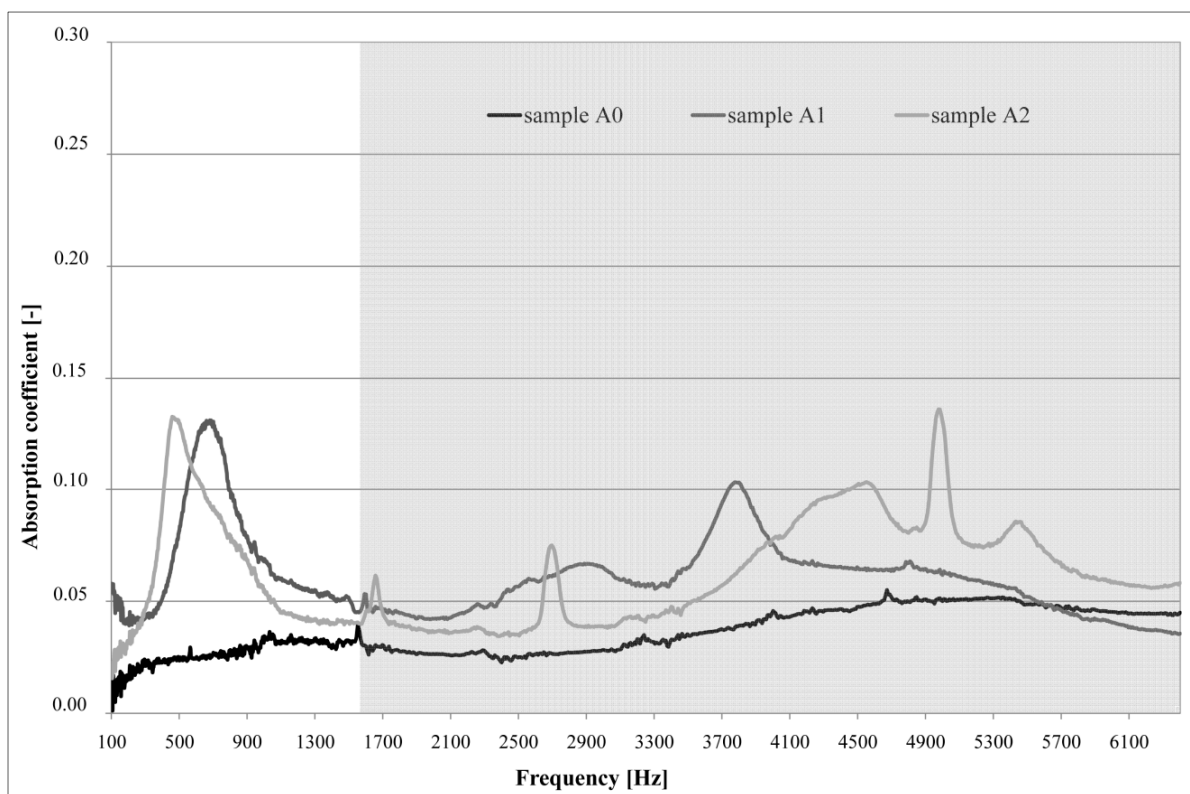
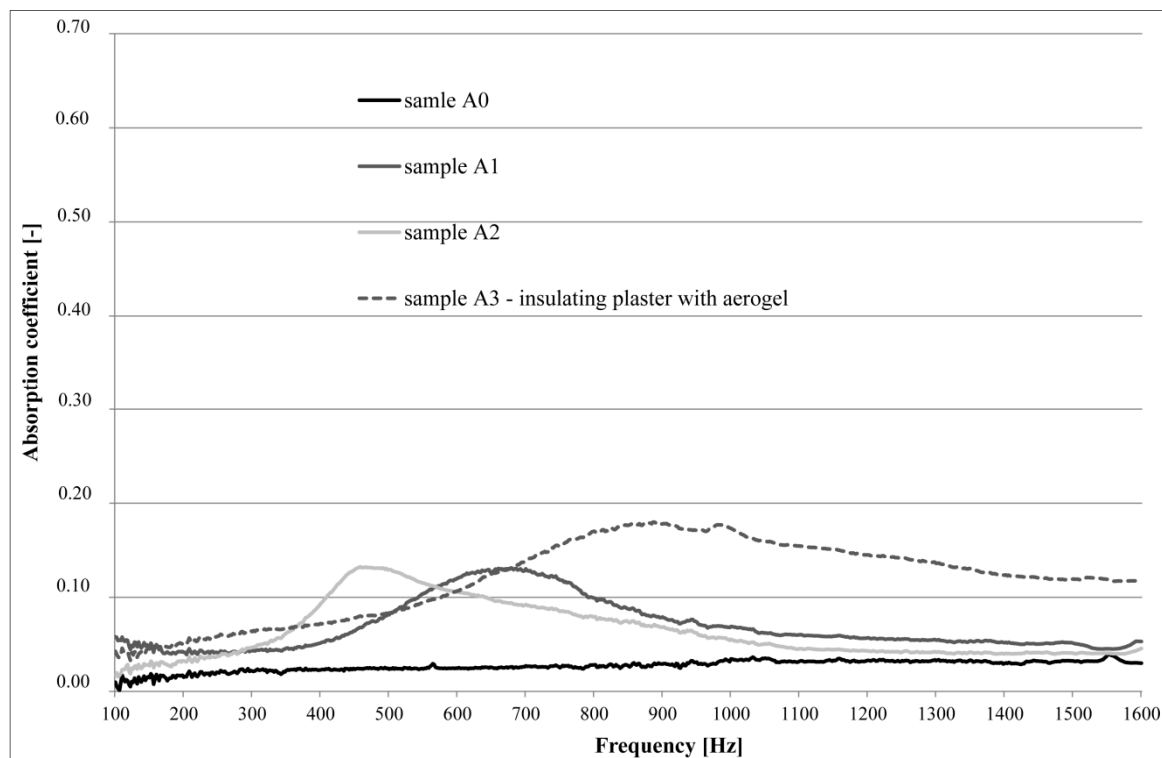


Figure 9. Absorption coefficient at normal incidence (Large tube measurements, 100–1600 Hz): Comparison with insulating plaster (without final coat).



5. Aerogel-Based Plasters for Building Refurbishment: 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. Table 4 shows the thermal conductivity values for different types of commercial plasters as compared with the innovative aerogel based plasters [25]. Traditional solutions usually have values that vary in 0.29–0.70 W/m K depending on the type and on the density of the coat. In order to evaluate the *in situ* performance of the proposed material, different existent buildings were refurbished by using the new plasters: Table 5 shows the decreasing of the thermal transmittance of different kinds of wall, due to the aerogel-based plasters ($\lambda = 0.05$ W/m K, 80% of aerogel). It can be observed that the innovative coating is very effective for a stone wall with a thickness of about 60 cm (Type 1), internal and external plastered with natural lime coating (U value equal to 2.14 W/m² K). Applying 5 mm of aerogel-based plaster, the thermal transmittance of the wall becomes 1.73 W/m² K (reduction of about 20%).

The thermal benefit of the plasters application in building refurbishment can be observed also by means of *in situ* infrared thermography analysis. A thickness of about 5 mm of aerogel-based plaster ($\lambda = 0.05$ W/m K) was applied on the internal walls of a three-story apartment. The investigated building (Figure 10) was built in the sixties and it is a multi-family house located in Pordenone, in the north of Italy. The northern façade was considered in order to avoid the influence of the direct solar radiation. On the first and on the second floor the internal plaster was not applied. Infrared thermography of the building was carried out in autumn; the external emissivity of the wall was considered equal to 0.93. Figure 10 shows a thermogram of this building: It can be observed that the

temperatures values in M1, M2 and M3 are about 9 °C (third floor), whereas the values vary in 10.5–11.5 °C range in M4-M9 (first and second floor) (Table 6). A decrease of about 2 °C is due to the application of the aerogel-based plaster.

Table 4. Comparison with traditional solutions: Thermal conductivity values.

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
T0–Natural plasters without aerogel	2200	0.50
T1–Natural plasters with aerogel (80%–90%)	275–300	0.045–0.050
T2–Natural plasters with aerogel (91%–95%)	126–136	0.019–0.021
T3–Natural plasters with aerogel (96%–99%)	115–125	0.014–0.016

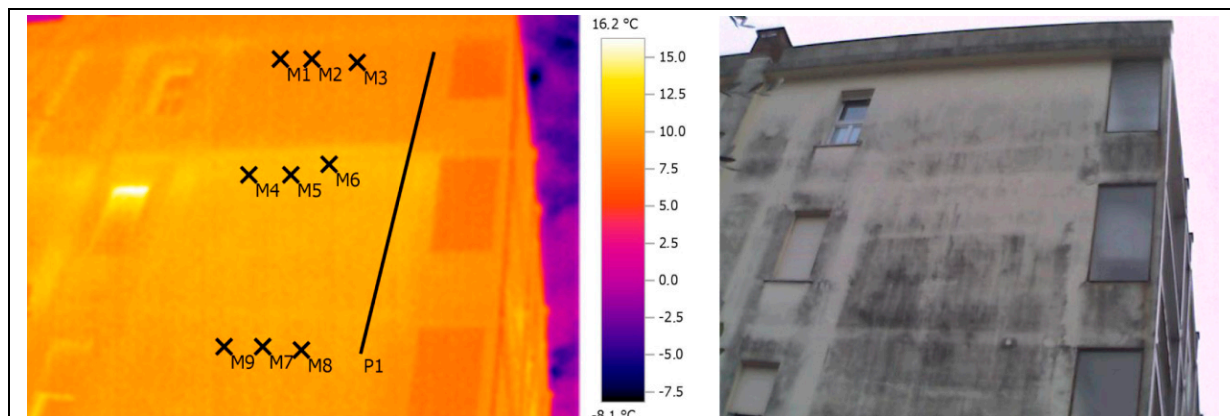
Table 5. Thermal transmittance values of different types of wall before and after the insulating plasters application (layer thickness 0.005 m).

Wall Type	Description	Before Refurbishment		After Refurbishment		
		Total Thickness (m)	U Value (W/m ² K)	U Value (W/m ² 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

Table 6. Temperature values measured by means of the thermographic camera.

Plasters	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

Figure 10. View of the investigated building and the correspondent infrared image: The aerogel-based plaster was applied in the internal wall of the third floor.



The cost of the lime based natural plaster without aerogel is about 2 €/m² (thickness of 1 mm). The innovative plaster with a percentage of silica aerogel equal to 80% has a cost of about 10 €/m² (s = 1 mm). The additional cost of the innovative plaster, compared to conventional materials, is expected to be about 8–10 € per square meter, considering a thickness of 1 mm of the coat. The maximum thickness of the innovative coating is 5 mm because a higher value is not economically affordable and a thickness of 2–3 mm is usually enough to significantly decrease the heat losses of the envelope.

6. Conclusions

The employment of efficient insulating materials reduces the heat losses from buildings and allows energy and costs savings for air conditioning and heating during the building lifetime. Many innovative insulation products have recently emerged on the market. In the present paper, a granular aerogel based plaster is presented. This coating solution is transpiring and insulating, thanks to the use of a natural lime coat and silica aerogel, with a very low thermal conductivity (0.013–0.018 W/m K for granular silica aerogel, 0.004 W/m K for evacuated monolithic silica aerogels). It can be applied in the walls of existent buildings that need refurbishments, in order to improve their thermal insulation properties.

Both thermal and acoustic properties were measured, in order to characterize the innovative plaster. The thermal experimental tests were carried out by means of a heat flow meter apparatus (ASTM C518–10 and ISO 8301) at the Labs of the Agosti Nanotherm Company, in order to measure the thermal conductivities of the materials. The thermal properties of the aerogel based plasters are very good in comparison with traditional solutions. Considering a percentage of aerogel in the mix of about 96%–99%, the thermal conductivity decreases of about 97% (0.014–0.016 W/m K values were obtained as compared to 0.50 W/m K of the natural plaster without aerogel). Nevertheless, for these solutions, the mechanical resistance of the plasters decreases a little bit because of the high porosity of the aerogel added in the coating manufacture. Actually, a good commercial solution can be considered the innovative plaster with a 80% of aerogel (0.050 W/m K). Thanks to the application of this new plaster, the thermal transmittance of different walls can be considerably reduced (a decreasing of U of about 6%–20% depending on the kind of the stratigraphy). These results will be monitored by means

of *in situ* experimental measurements, after the aerogel based plaster application (thickness of about 5 mm on the internal side).

Finally, considering the proposed commercial solution (80% of aerogel), the acoustic absorption coefficient at normal incidence was measured by means of a Kundt's Tube (ISO 10534-2). Two specimens composed by three layers were considered: A plasterboard support, an insulation plaster with aerogel and a final coat; they have different thicknesses (24.5 mm and 44.5 mm). The acoustic absorption coefficients are not very high for the proposed plasters: Effectively, the absorption coefficient strongly depends on the final coat, so the aerogel-based plaster layer moderately influences the final value.

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Author Contributions

All the authors contributed equally to the conception and to the design of this study. In particular, Elisa Belloni, Cinzia Buratti and Elisa Moretti especially contributed to the acoustic and thermal measurements analysis, Fabrizio Agosti contributed to the thermal measurements collection.

Conflicts of Interest

The authors declare no conflict of interest.

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