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Development of an aerogel-based thermal coating for the energy retrofit and the prevention of condensation risk in existing buildings

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The energy retrofit of existing buildings, particularly historic and/or listed buildings, presents several issues; that is, the compatibility between the identified solutions and the heritage value or the internal space reduction (if internal interventions have to be adopted).

For this reason, an emerging method to address the target of the energy retrofit of historic buildings is the use of advanced materials characterized by high thermal insulation performance.

In the framework of an European research project (Horizon 2020), a novel aerogel-based insulating coating, particularly suitable for the mitigation of thermal bridges and for the prevention of the condensation risk, is under development.

In this paper, both the laboratory and the in-fields research activities are described. The first was aimed at optimising the thermo-hygrometric properties of the coating; the latter dealt with the results of a monitoring activity carried out on a full-scale application.

Results highlight that the internal application of 12 mm of the developed material can lead to a significant increase of the indoor surface temperature (about 1.4°C) with a decrease of the wall $U$-value of about 37%. Moreover, a mitigation of the thermal bridges was also observed with an increase of the minimum surface temperature up to 1.6°C.
Introduction

The building sector is responsible for nearly 40% of the total energy consumption in Europe (Directive 2010/31/EU). About 50% of the European stock was built before the first thermal regulations in the 1970s (EU Buildings Factsheets). Italy is not an exception, in fact, more than 60% of residential buildings were built before 1976, the year of the first law on energy savings, and 30% of buildings (12.5 million) is dated before 1945 (ISTAT 2011). Therefore, a large part of the building stock is characterized by traditional non-insulated construction systems. Moreover, about 1.8% of these buildings are classified as cultural heritage, according to the definition of the Italian Legislative Decree no. 42 of 22/01/2004 pertaining to the Cultural Heritage and Landscape Code.

In the last decade, the importance of energy efficiency and thermal comfort in historical buildings has widely increased as it is also testified by a number of recent researches.

While energy retrofit was previously seen as a potential threat to the character and fabric of historic and traditional buildings, it is now seen largely as an opportunity to protect these buildings and respond to global environmental concerns (Webb A.L. - 2017).

There is a growing research activity facing the challenge of matching energy efficiency measures and internal thermal comfort with the requirement of maintaining the cultural and historic significance of buildings (De Bouw M. et al. - 2016). Among the various technical solutions to reduce thermal losses, technologies for indoor insulation are particularly suitable for this purpose (Walker R. and Pavía S. - 2018). Innovative materials and products, like vacuum insulation panels and aerogel-based materials, shall be explored because of their high insulation potential that allows guaranteeing significant indoor space saving compared to traditional insulating materials (Fantucci et al. – 2019).

In the framework of the on-going European H2020 research project Wall-ACE a novel aerogel-based thermal coating (to be applied together with an additional abrasive resistant top layer) has been developed, with the main aim of mitigating thermal bridges in the existing buildings.

In this paper results related to the thermal characterisation in the lab and the performance in-field are presented. The study was aimed at:
• the optimisation of the thermal coating
• demonstrating (through a full-scale application) the effectiveness of the technology to prevent the risk of surface condensation and the improvement of the whole wall thermal performance.

State of the art on aerogel-based wall plasters

The use of aerogel granules as lightweight aggregate in a plaster mixture allows the final density and the thermal conductivity to be drastically reduced, reaching values of 150-200 kg/m$^3$ and 0.025–0.027 W/mK, respectively (Stahl et al. 2012, Ibrahim et al. 2015, Berardi and Nosrati 2018). Further, Buratti et al. (2014) demonstrated that by pushing the aerogel content up to 96-99% (by volume) allows reaching a density of about 115-125 kg/m$^3$ with a thermal conductivity of 0.014-0.016 W/mK. However, in the same study, for the in-situ application a more mechanically performant formulation with a lower aerogel content (80%) and a thermal conductivity of 0.05 W/mK was used.

The effective thermal insulation capability together with the plaster features (i.e easy application on irregular substrates, relatively high compressive strength) make the aerogel-based plaster a suitable candidate for the energy retrofit of historic constructions, in which the old and damaged plaster can be easily replaced with up to 4-6 cm aerogel plaster layers, if the existing layer has no heritage value (Ghazi Wakili et al. 2015, Schuss et al. 2017, Stahl et al. 2017, Lisitano et al. 2018)

For these reasons, in the last years, several aerogel-based plasters were developed and are nowadays available at least in the EU market, that are FIXIT 222 (2018), FIXIT 244 (2018), Heck-Aero iP (2017) and Interbran Premium 028 (2019). They typically have a declared thermal conductivity in the range 0.028-0.048 W/mK.

Despite the fact that several studies demonstrated the high compatibility with historic buildings and the high energy retrofit capability, this technology is not, so far, largely diffused, because of its high cost, which remains one of the major market limitations. In fact, it was demonstrated that for a thermal insulating plaster improved with 80% of aerogel in the mixture, the cost reached a value between 80-90 €/m$^2$ for 1 cm
of thickness (Buratti et al. 2016, Ibrahim et al. 2017). However, more recent market research highlight that for larger amount of aerogel plaster/render the cost updated at 2019 is in the range 30 €/m²·cm (material cost only) up to 60 €/m² per 1 cm thick layer if the cost of application is considered (Aerogel applications, 2016; FIXIT, 2019 and personal communication from Fixit).

A possible solution to reduce the final cost is based on minimising the aerogel content by partially replacing it with other lightweight aggregates (de Fátima Júlio et al. 2016, Fantucci et al. 2018). Nevertheless, in most of the studies done so far, the final thermal conductivity of such products revealed to be quite comparable with that of traditional thermal insulating plasters that are available on the market since a long time. Therefore, this solution is not optimal, and no significant benefits can be achieved compared to the state of the art.

Other possible solutions aimed at reducing the final cost are based on the minimisation of the thickness. In a previous study of the authors (Fantucci et al. 2018), the development of an aerogel coating with a thickness between 3 and 12 mm has been proposed for thermal bridges mitigation and for slightly improving the wall performance in terms of surface temperature of the non-insulated wall.

Methods

Five different aerogel-based thermal coatings (called R0 to R4 in the paper) were developed adopting a different ratio of mineral and organic binders. Kwark® granular aerogel, produced by Enersens (2018), perlite, glass and ceramic spheres were used, in various percentage, as lightweight aggregates (LWA).

A first series of preliminary tests aimed at determining the thermal and mechanical properties were carried out in the laboratory. The aim was to check the compliance of the plaster with the market needs and its potentials in mitigating thermal bridges and avoiding mould growth risk.

Moreover, in order to test the plaster behaviour under actual operating conditions, a monitoring campaign was set-up and carried out on an actual building (full-scale case study) provided by ATC (Regional Agency for the Central Piedmont House).

Laboratory characterization
The laboratory measurements were aimed at determining: the dry bulk density, the mechanical resistance and the thermal conductivity of the developed aerogel-based plaster (Figure 1a).

The dry-bulk density was measured by weighing a specimen with a known volume (0.4 x 0.4 x 0.05 m), previously dried in a climatic chamber (ACS DM 340, figure 1c) as long as any weight variation of more than 0.2% in 24 h occurred.

Flexural and compression strength tests were carried out by Vimark S.r.l. (2019) adopting prismatic samples of 16 x 4 x 4 cm according to UNI EN 1015-11:2007 (figure 1b).

**Thermal conductivity measurement**

The thermal conductivity was measured on the dried specimen according to UNI EN 12667:2002, by means of a heat flux meter apparatus (Lasercomp FOX 600, figure 1d).

Thermal conductivity measurements were performed at an average temperature of 10°C on the dry specimen. The samples were enveloped in a polyethylene sheet in order to avoid any water vapour adsorption during the test. Moreover, the specimens were sandwiched between two natural rubber mats (2 mm thick), having a well-known thermal resistance. This was done in order to reduce the influence of the surface resistance (between the sample and the hot/cold plates) on the measured equivalent thermal conductivity of the plaster.

![Figure 1: a) Coating sample - surface aspect; b) Flexural strength measurement; c) Climatic chamber (ACS DM 340); d) Heat flux meter apparatus (Lasercomp FOX 600).](image)

**Specific heat capacity tests**

The specific heat capacity measurements were performed according to the methodology proposed by Tleoubaev and Brzezinski 2017, through the adoption of the Heat Flow Meter apparatus. The instrument can measure the heat required to increase the temperature of the samples for a set of temperature difference.
It is necessary to fix the initial temperature set point (T1) and the final temperature (T2), the HFM thus measures the heat absorbed by the sample to increase the temperature from T1 to T2 (Figure 2). The total specific absorbed heat is determined as the integration of the net specific heat flux from the two plates over the time-period, \( \tau \), that is:

\[
H = \sum_{i=1}^{N} [Q_{\text{upper}} + Q_{\text{lower}}] \tau \left[ \frac{1}{m^2} \right]
\]  

(1)

Figure 2: Specific heat required by the sample to increase the temperature from T1 to T2.

Finally, the specific heat capacity \( c_p \) [J/kgK] can be determined as:

\[
c_p = \frac{H}{\Delta T \cdot s \cdot \rho} \left[ \frac{1}{kg \cdot K} \right]
\]  

(2)

Where: \( \Delta T \) is the difference between the first and the second set-point temperatures [°C]; \( s \) is the sample thickness [m]; \( \rho \) is the sample density [kg/m³].

The specific heat capacity tests were performed on all the aerogel-based thermal coating formulations (that is R0 to R4). The \( \Delta T \) was set at 10°C, with a temperature variation of the plates from 15 °C (T1) to 25 °C (T2). The standard deviation (SD) of the specific heat capacity measurement was also calculated and reported within the results.

**Case study building**

The in-field application was aimed at investigating practical aspects related to the innovative plaster, like, e.g. installation techniques, technical feasibility and appearance, as well as its energy effectiveness. For this sake, a monitoring campaign on a 1920s building (Figure 3) located in Turin (Italy, Lat. 45°N, Long. 7.65°E) was undertaken. From the point of view of the thermal properties, the aim of the in-situ measurements was to evaluate the capacity of the optimised coating (R4) to reduce, on one hand, heat
losses through the wall and, on the other hand, to mitigate thermal bridging effect and to increase the wall indoor surface temperatures (during the winter time). An east-oriented room was chosen for the tests. Two identical walls, named CW (coated wall) and RW (reference wall), were analysed. One of the two was used as a reference (RW, figure 4a) and was left unchanged (as-built). The other (CW wall, figure 4b) was coated with the aerogel coating (R4 formulation).

Figure 3: The 1920’ test-building in Torino.

Figure 4: a) Reference wall (RW); b) Coated wall (CW).
The coating was prepared and applied on CW wall and the adjacent thermal bridge (vertical intersection between wall and window). In order to improve the adhesion of the thermal coating on the existent wall, a mono-component primer in thin layer was firstly applied (figure 5a). The thermal coating, mechanically mixed with ~1:1 water ratio, was manually applied to reach a thickness of ~12 mm (figure 5b, c, d). The measurements were directly performed on the aerogel-based coating layer without applying an abrasive resistant top-layer.

**In-field monitoring**

The monitoring campaign was carried out for about two months in the winter period. Temperature and specific heat flux sensors were placed both on CW and RW walls and on the thermal bridges. To avoid the sensors being placed in a non-homogeneous area of the wall, a preliminary set of thermography were performed, by analogy to thermal insulating plasters analyses carried out by Ghazi Wakili et al. (2014) and Fenoglio et al. (2018). As shown in figure 6, two heat flux sensors (HFP01) were located in the centre of walls. T-type thermocouples were adopted for measuring air and surface temperatures, both on the walls and in the thermal bridges zones.

Thermocouples were also placed at the interface between the thermal coating and the pre-existing wall (CW) (figure 6).

A pyranometer sensor was used to measure the incident solar radiation. The indoor temperature was kept at 23 ± 1°C for all the monitoring period, in order to achieve a temperature difference, between the indoor and the outdoor, high enough to measure with sufficient accuracy the specific heat fluxes. To avoid the
influence of the solar radiation on the monitored surfaces, the window shutters were kept closed during the measurements.

Figure 6: Sensors type and position.

The continuous average method (ISO 9869-1:2014) was used to assess the centre of wall thermal transmittance $U$ (eq.3) and the thermal conductance $C$ (eq.4):

\[ U = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n} (T_{aj} - T_{aej})} \quad (3) \]

\[ C = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n} (T_{si} - T_{sej})} \quad (4) \]

where: $q_j$ is the measured specific heat flux; $T_{si}$ and $T_{sej}$ are the internal and external surface temperatures, respectively; $T_{aj}$ and $T_{aej}$ are the internal and external air temperatures, respectively.

**Results and discussion**

**Laboratory results**

Laboratory tests showed that the aerogel coatings are characterised, in general, by good thermophysical properties (table 1). The density of the dry specimens is ~50% lower than that of traditional thermal insulating coating without aerogel (R0 table 1).

As it is possible to observe from the table 1, the so far optimized formulation with the Kwark aerogel (R4), has an equivalent thermal conductivity of 0.051 W/mK. This corresponds to a reduction of the equivalent thermal conductivity of about 62% compared to the reference R0 formulation.
As far as mechanical properties are concerned, the flexural strength of R4 is equal to 0.8 MPa, with a negligible reduction of performance with respect to the R0 formulation.

The intermediate optimisation steps that were implemented for switching from the reference formulation, R0, to the optimized one, R4, were represented by:

- the replacement of part of the LWA with the aerogel (from R0 to R1). This action provided a slight improvement of the thermal performance (~13%) with a reduction of the dry bulk density from 617 to 577 kg/m³;
- the replacement of part of the mineral binders with organic ones. This action led to a reduction of the thermal conductivity of about a 44% (from R2 to R3) and allowed to reduce the density significantly. Moreover, the differences in binders also determined an increase of the specific heat capacity of about 30%.

| Binders       | LWA (type)       | \( \rho \) (kg/m³) | \( \lambda \) (W/mK) | \( c_p \) (J/kgK)* | Flexural strength (MPa) |
|---------------|------------------|--------------------|----------------------|------------------|-------------------------|
| R0            | mineral          | 617                | 0.131               | 1000             | 0.8                     |
| R1            | mineral+aerogel  | 577                | 0.120               | 740              | 1                       |
| R2            | mineral          | 495                | 0.102               | 810              | -                       |
| R3            | mineral+aerogel  | 369                | 0.057               | 1050             | 1                       |
| R4            | mineral+aerogel  | 326                | 0.051               | 1070             | 0.8                     |

*The relative standard deviation on the \( c_p \) measurement is ~ 0.2%.

**In-field monitoring results**

The centre of wall temperature and the specific heat fluxes were analysed considering the entire monitoring period from December 21st to March 3rd (Figure 7). Moreover, additional analyses were carried out focusing on the potential thermal bridge mitigation attainable with the thermal coating finish.
Centre of wall thermal performance

In figure 8, the boxplot analysis of the center of wall temperatures and the specific heat fluxes of the CW and RW, respectively, are shown.

The monitored data highlight that the application of the thermal coating finish allows to:

- increase of about 1.4 °C and of about 0.9°C the median and the minimum indoor surface temperatures, respectively (improvement of the indoor thermal comfort and reduction of the surface condensation and mould risk) (Figure 8a);
- decrease of about 1 °C and of about 1.4 °C the median and the minimum outdoor surface temperature, respectively (this aspects mainly concern the durability of the outer plaster layer that might be exposed to freezing-thaw cycles in cold climate) (Figure 8b);
- reduce of about 30% the median value of the centre of wall heat losses during the winter time which can provide heating energy demand reduction (Figure 8c).

Figure 9 shows the time evolution of the U-values and of the conductance of the walls determined at each time step by means of equations (3) and (4). As it is possible to see, the measured U-values of CW and RW are 0.90 and 1.22 W/(m²K), respectively. From a practical point of view, the addition of about 12 mm of aerogel coating finish, determined a reduction of ~37% and of ~27% in the wall thermal transmittance and thermal conductance respectively. Particular care has to be taken in relation to the maturation time of the
layer. As it has been observed during the field tests, about 2 months are needed for the water in the mixture to be removed. During this time the moisture content is higher than in normal operating conditions, and this fact affects the thermal performance of the layer negatively. All the data presented in this paper have been measured after two months that is near the final condition of the wall.

Figure 8: Box-plot analysis of the monitored a) indoor surface temperature; b) external surface temperature; c) indoor surface specific heat fluxes.

Figure 9: Measured thermal conductance $C$ and thermal transmittance $U$ of the reference wall RW and of the coated wall CW.

**Thermal bridges mitigation**

The intersection between the wall and the window frame has been identified as the area mostly affected by the presence of the thermal bridge. For this reason, the surface temperatures of the wall side were analysed in detail (Figure 10a). Firstly, the infra-red images of the coated (CW) and uncoated (RW)
thermal bridges were compared. Results are shown in figures 10b and 10c; the temperature increases significantly thanks to the presence of the R4 thermal coating.

Figure 11 shows the boxplot analysis of the surface temperatures of the CW and RW configurations.

The monitored results confirm that the application of the aerogel-based thermal coating allows the temperature in the proximity of the thermal bridge to be appreciably increased. In particular, an effective increase of the minimum surface temperature at 5 cm distance from the construction node (sensor $T_{s\_tb\_c}$), from 15.3°C to 16.9°C, can be observed; while the difference is negligible at 15 cm (sensor $T_{s\_tb\_b}$). Conversely, at 25 cm from the construction node (sensor $T_{s\_tb\_a}$) the application of the thermal coating finish determines slightly lower surface temperature.

An additional analysis was also done as far as the potential mitigation of the surface condensation risk is concerned. This study was performed for a point at 5 cm distance from the node, and the results are resumed in Figure 12. The cumulative frequency distribution of the difference between the monitored surface temperature and the dew-point temperature for different indoor relative humidity classes (from 60 to 70%) are plotted. The analysis highlighted that:

- no surface condensation occurs at 60% of indoor relative humidity for both the wall configurations (RW and CW);
- condensation occurs for about 30% of the time in the reference wall (RW) at 70% indoor relative humidity, while the surface condensation risk can be considered neutralised in the coated wall (CW).
Figure 10: a) Thermocouples installed on thermal bridges area; b) Infrared image of CW thermal bridge; c) Infrared image of RW thermal bridge.

Figure 11: Box plot analysis of the surface temperatures of the thermal bridge.
Figure 12: Cumulative frequency distributions of the difference between the node temperature ($T_{\text{node}} - T_{\text{dew-point}}$) and the dew-point temperature, for different indoor relative humidity conditions.

Conclusions

In the framework of the Horizon-2020 project ‘Wall ACE’, a novel aerogel-based thermal coating was developed.

As a first research step, the main physical properties of a set of four mixtures were assessed through laboratory analyses. The results allowed to optimise the material properties and to finally select a mixture that presents a thermal conductivity of about 0.05 W/mK. Furthermore, the best performant material was applied for an external wall energy retrofit in a 1920’ demonstration building in Turin. The thermal behaviour of the retrofitted wall was monitored during the winter season, and its performance was compared with an uncoated reference wall. The obtained results highlight that the application of a thin thermal coating finishing layer can lead to a significant increase of the median indoor surface temperature (about 1.4°C), with a decrease of the wall thermal transmittance of about 37%. Moreover, a mitigation of the effect of the thermal bridge was also observed with an increment of the minimum node surface
temperature (wall-window frame) of up to 1.6°C. The obtained results highlighted that the developed thermal coating can provide a non-negligible reduction of heat losses through the wall.

Moreover, the aerogel-based coating represents a promising solution to mitigate the adverse effects of the thermal bridges on the condensation risks, even when the indoor environment is characterised by high relative humidity. These results are a good argument for the suitability of the developed product for the application in all the buildings in which usual thick internal insulating solutions cannot be addressed for space, historical and technical constraints.

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