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Durability of insulating materials: a comparison between traditional and nanocomposite mortar thermal insulating, basing on the thermal conductance measured by means of the heat flow meter approach

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Abstract. Every insulating material has to meet the double requirement of thermal performance and durability. While the conductivity grants a proper thermal resistance, durability represents a crucial planning aspect to assess the long-term building performance from the point of view of costs and environmental impact. Differently from traditional insulators, the recent nanotechnological mortars claim to provide dramatic insulating performances and there is no consolidated evidence about both reliable thermal performance (e.g. CE marking, ETA, third party laboratory tests) and durability. The present paper compares the durability and thermal performance of two different scenarios by means of the heat flow meter approach: a stone wall covered with nanotechnological insulating mortar and a brick wall insulated with polystyrene. The thermal conductance of the former case shows a difference between measured and self-declared values of about +500% after the end of the installation cycle. Two years later, the conductance almost doubles, showing very poor thermal performance and durability, against the not representative, self-declared values. In the latter case, the wall thermal conductance after about 30 years is still aligned with the original design performed in 1995, showing very good durability of the performance declared in the original, standard compliant design dating back to the time.

1. Introduction

The European directives issued from 2002 to 2024, such as the latest called "Green Homes" [1], require a constantly increasing performance in terms of both energy saving and internal comfort of buildings. This target pushes towards the search for increasingly performant and innovative solutions for the thermal insulation of buildings. In fact, residential and non-residential buildings, excluding farm and industrial ones, are responsible for 40% of primary energy consumption and 36% of greenhouse gas emissions in the entire European Union [2]. Thermal insulation is the basis for achieving energy efficiency: only if the energy need of the building is reduced, most of the energy intensive services can be covered by means of renewable sources up to the point of reaching the Zero Emission Building (ZEmB). In this context, reliable values about the insulating properties of materials become essential for designers and energy certifiers to correctly reproduce and model the energy performance of the building envelope. Such values play a key role also to grant the access to substantial tax incentives.

According to the Italian standard [3,4], the reliability of the declared thermal conductivity λ_D, or thermal resistance R_D values, is guaranteed by either a mandatory CE marking (in presence of harmonised product standard) or a European Technical Assessment (ETA) issued by a Technical Assessment Body (TAB), whenever appliable.

In all the other cases, with no appliable CE or ETA, the manufacturer must declare the λ_D or R_D values according to the UNI EN ISO 10456 standard [5], basing on a sufficient number of tests to guarantee the statistical representativeness of the data, carried out by a certified, third-party laboratory.

Each time the reliability of the thermal performance is supported by neither CE/ETA nor standard-compliant laboratory tests, the thermal resistance in the technical sheet becomes just a producer’s self-declaration that can be adopted by the designers at their own risk. This is the case of mortars based on hollow nanoceramic microspheres for which miraculous thermal conductivity values of about 0.001-0.003 W/(m K) are often declared, claiming that a coating few millimetres thick provides the same effects as 10-12 cm of a traditional insulating material (EPS or rock wool). If the above-mentioned insulation properties were reliable, great advantages would be obtained by significantly reducing the energy needs of buildings and complying with the technical requirements set by national regulations. In addition, the facades would not be altered significantly, without the need to dismantle gutters, drainpipes and shutters, or the need to assemble scaffolding and therefore containing installation costs [6,7]. However, according to the researches available in literature, these values are not realistic, since the carried out tests indicate higher thermal conductivity values, ranging from 0.01 W/(m K) to 0.7 W/(m K), in line with those of normal thermal mortars. In addition, even the Italian standard UNI/TR 11936:2024 [4] does not recognize the performance of such mortars. Literally quoting “at the date of publication of the present standard, no marketed thermal mortar or paint can be associated to conductivities certified by tests in accredited laboratories lower than 0.025 W/(m K)”.

Bozsaky conducted four series of laboratory experiments, according to EN 12667 standard [8], to test the insulation properties of a liquid hollow nanoceramic microspheres paint available on the market. Tests were conducted both indirectly by spraying 1-2 mm thick layer on three different types of conventional thermal insulation materials, expanded polystyrene (EPS), extruded polystyrene (XPS) and fiberwood, and directly on samples of pure nanoceramic paint solidified [9,10]. He concluded that the extremely low thermal conductivity values reported in the manufacturers' data sheets were not supported by experimental measurements; in case of pure material the measured thermal conductivity is about 0.11 W/(m K) for wet samples and 0.069 W/(m K) for dry samples. Moreover, the indirect tests conducted on inhomogeneous multilayer structures with the nanoceramic coating layers applied in air gaps revealed a modest reduction in equivalent thermal conductivity (up to 12%, according to the considered backing material). The hypothesis that the insulation properties of nanotechnological paints are given by the low convective coefficients at the surfaces appears weak since the reduction in heat transmission occurs only with certain materials. Furthermore, the influence of the instrumentation accuracy should be accounted to carry out reliable conclusions from the results of the study.

Other laboratory tests indirectly estimate the thermal conductivity of paints based on hollow nanoceramic microspheres, obtaining very discordant values, but still order of magnitudes larger than the most common producer's self-declared value: in [11] a conductivity of 0.7 W/(m K) is estimated using the heat flow meter based on UNI ISO 9869-1 [12] on a 25 cm perforated brick plastered on both sides by a 8 mm thick layer of nanotechnological mortar. In [13] the estimated conductivity drops to 0.02 W/(m K) by hot box method and holometrix apparaturs applied on a brick wall coated by a 2 mm thick insulating paint. Even in this last case, the conductivity is still one order of magnitude greater than the values averagely self-declared by nanotechnological paints producers (e.g. 0.001-0.002 W/(m K)).

A comparative study concerning optical properties and thermodynamic performances of different coatings applied on the vertical, non-transparent, external building surfaces is presented in [14,15]. Three paints were considered for different measured samples: a standard coating of acrylic base, a widely used coating consisting of hollow ceramic microspheres and a low emissivity coating consisting in metal particles. No differences were found between the reflective properties of traditional materials and hollow ceramic microspheres paints both in the infrared and visible radiation ranges. Moreover, dynamic outdoor tests, based on guarded hot-box methodology, revealed that the reduction in the heating/cooling loads for hollow microspheres coating was as negligible as a standard coating. On the contrary, the low-emissivity coating can have a distinctive thermal performance, consisting mainly of a reduction up to 15% in the winter night-time heat load, depending on the type of sample and the climatic conditions. The same conclusion can be deduced from [16], where thermophysical properties of different thermal paints applied to skimmed 12 mm plasterboard samples are measured.

Kruzel et al. [17] discuss the potential advantages offered by insulating paints based on hollow ceramic microspheres in treating the facades of historic buildings compared to traditional insulation with expanded polystyrene or rock wool panels: preservation of the aesthetic appearance of the facades with no change in the decorative elements, speed of execution in the case of spray application without requiring the installation of scaffolding and the removal of gutters and downpipes. On the other hand, innovative paints are expensive, and, in any case, the measured conductivities do not allow the respect of the limit thermal transmittance imposed by national regulations. This aspect is in open contrast with the Producers' self-declaration for which only a thin paint coat seems sufficient to meet the same effect of traditional insulation. Anyway, in absence of CE marking, ETA or laboratory tests, the value is not considered reliable.

The application of liquid nano-ceramic paints in insulation of pipelines is carried out in [18,19]. A great uncertainty emerges on the reliability of the thermal conductivity referred to nanoceramic paints: in [18] the very low value provided by the manufacturer (λ = 0.003 W/(m K)) was assumed in order to calculate the annual consumption of equivalent fuel of a district heating system as a function of the paint thickness. According to the study, the apparent difference in temperatures between painted and not painted pipe by means of infrared camera is about 5-10 °C. Nevertheless, the same study admits that non-contact temperature measurements can have a divergence of 8-12 °C with respect to the usage of contact thermometers. This observation proves once again that the effective performance of such paintings is not aligned with the declared performance. In [19] a thermal conductivity of 0.014 W/(m K) was indirectly obtained from experimental measurements of a pipe coated with nano ceramic thermal insulation.

A significant contribution to test the real insulating properties of nanotechnological paints can be obtained from on-site measurements. In a previous paper [20], the authors measured the thermal conductance of a stone wall externally coated by a 1 cm thick layer of nanotechnological mortar, using the heat flow meter technique according to UNI ISO 9869-1 [12]. The comparison between the conductance of both bare and coated wall allowed an indirect estimation for thermal conductivity of around 0.015-0.02 W/(m K) against the manufacturer's self-declaration of 0.0019 W/(m K). Although the dramatic difference between measurements and expected results, a reduced insulating capacity was anyway detected, aligned with the range of other experimental works previously illustrated [10], [13], [19].

While the state-of-art presents some researches concerned with the measurement of the nanotechnological mortars, the literature review does not reveal any studies regarding their durability, especially in terms of thermal conductivity. This issue is worsened by the lack of experience of in situ and naturally aged nanotechnological coatings as most of them have been just developed. An interesting laboratory study is reported in [21], where the long-term thermal conductivity of thermal insulating mortars incorporating EPS, cork and silica gel is evaluated by means of accelerating ageing methods. The investigated mortars are characterized by measured thermal conductivities between 0.032 W/(m K) and 0.447 W/(m K) that can increase from 10% to 20% after accelerated ageing corresponding to 10 years of exposures to natural weather conditions. The main causes of degradation are represented by high temperatures, moisture content (water absorption and freeze-thaw cycles) and exposure to biological agents.

More in general, the issue of durability is of paramount importance, to correctly assess the payback time and long-term energy efficiency strategies. In addition, this feature becomes another critical aspect in the comparison with traditional insulators which on average still allow consolidated and durable performance after 20 years [22], [23], [24].

In [16] a study at a nanoscale level concerning the integrity of the insulating spheres has been carried out by means of a Scanning Electron Microscopy. The results clearly show that the added particles are not sufficiently robust and therefore, instead of void, they become filled with air. In addition, the disposition of the spheres is irregular and part of them is broken, already during the application stage. Such important results indirectly affect the material durability, as the illustrated issues occur shortly after the laying of the material.

The present work enquires the issue of durability of both a traditional insulating material and a nanotechnological mortar by means of in situ measurements using the heat flow meter approach. In both cases, the insulating materials are installed on existing buildings, and they have been subjected to natural ageing, solar radiation and atmospheric agents. More in detail the traditional insulator is polystyrene installed in a multilayer brick wall about 30 years old, while the nanotechnological mortar was installed on a stone wall in 2022. The durability shall be assessed by means of onsite conductance measurements basing on the heat flow meter technique. According to the present approach, naturally aged materials shall be tested, eluding the uncertainties derived from artificial laboratory approaches to reproduce the effects of weather and time on the material performance. Any change in the thermal behaviour of wall will result in a direct information about its durability over time.

2 The heat flow meter approach

The Heat Flow Meter (HFM) approach is referred to the average method described in UNI ISO 9869-1 [12] and previously illustrated in the Authors' work [20]. Briefly, the average method allows the estimation of conductance of walls under transient conditions, by measuring the heat flow rate and the surface temperature on both sides over a sufficiently large period.

In symbols:

$$\Lambda = \frac{\sum_{j=1}^{M} q_j}{\sum_{j=1}^{M} T_{si,j} - T_{se,j}} \tag{1}$$

where:

Λ is the wall thermal conductance [W/(m^{2}K)];

q_j is the density of heat flow rate referred to the j-th measurement [W/m^2];

$T_{si,j}$, $T_{se,j}$ are respectively the internal and external surface temperatures referred to the j-th measurement [K];

M represents the total number of measurements collected during the test.

The typical layout of the HFM instrumentation is shown in Figure 1: the measurement node 1 is installed on the inner side of the wall, to measure both the heat flux and the surface temperatures. The measurement node 2 is on the outside part of the wall, where only surface temperatures are collected. Two values of surface temperature are measured on each side, to check the uniformity of temperature distribution over the investigated region.

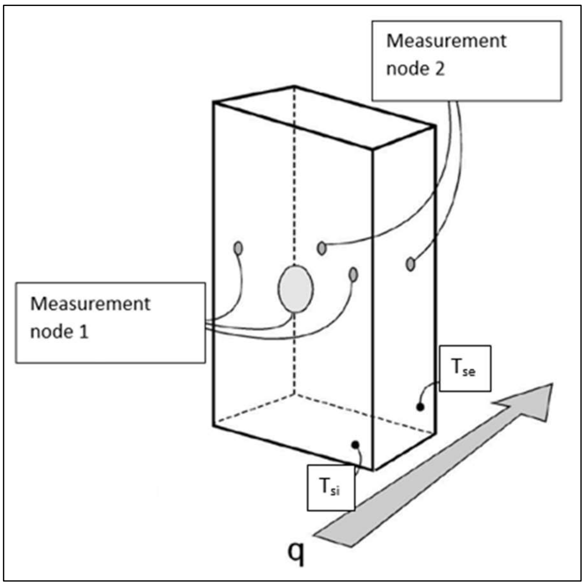

Figure 1. Schematic diagram for the HFM technique.

The measurements have been conducted with the Thermozig Ble heat flow meter – Optivelox (heat flow meter sensor: 0.01 W/m^2 resolution, ±5% accuracy; temperature sensor: 0.01 °C resolution, (0.15+0.001 |t|), [t]=[°C] accuracy). Following the UNI ISO 9869-1 approach, each test met the conditions to consider the results reliable:

- 72 h of minimum duration for each test;
- the conductance computed considering all the test duration does not deviate by more than ±5% from the value obtained 24 h before;
- the conductance calculated over a duration D (D = 2/3 of the total duration of the test) does not deviate by more than ±5% from the conductance obtained at the end of the measurement, considering all the test duration.

In addition:

- a relevant difference in temperature within the range of 5 K and 10 K between the two sides was granted to measure a significant heat flux;
- the instrumentation was installed in walls with strong obstructions or north facing, to avoid direct solar irradiation;
- each region was formerly investigated by means of thermography to assess the absence of thermal bridges or other interferences which could negatively affect the results.

The accuracy of the results can be estimated between 14% and 28%, since the measurements are compliant with section 9 of UNI ISO 9869-1. More in detail, the following aspects lead to the indicated range.

- HFM accuracy: the error is about 5% according to both the standard and the technical information of the calibrated instrumentation.
- Data logging system accuracy: according to Annex E of UNI ISO 9869-1, its precision has been checked in a previous work [20] showing good accuracy between measured and expected values for a bare stone wall and a weakly insulated, multilayer brick wall. Moreover, the minimum measurable flux (0.01 W/m^2) is far smaller than the measured heat fluxes (i.e. within the range of 4-30 W/m^2). Anyway, a further accuracy of 5% has been assumed.
- Random variations caused by slight differences in the thermal contact: it is assumed equal to 5% in accordance with the UNI ISO 9869-1, since the measurements have been repeated and particular attention was spent to install the instrumentation properly.
- The local influence represented by the added thermal resistance of the HFM on the wall can be considered negligible: the instrumentation has a maximum thermal resistance of 0.006 m^{2}K/W, while the enquired thermal resistances are about 1-1.3 m^{2}K/W. However, an accuracy of 3% is assumed on the safe side.
- Errors associated to temporal variation of heat flow and temperatures: since the measurements have been performed according to UNI ISO 9869-1, the accuracy can be assumed equal to 10%.

In conclusion, the total uncertainty shall be between the two limit values provided in the formulation below (Eq. 2 – minimum; Eq. 3 – maximum):

$$(\sqrt{5^2+5^2+5^2+3^2+10^2})\% = 14\% \tag{2}$$

$$(5+5+5+3+10)\% = 28\% \tag{3}$$

3 Measurement of thermal conductance of an insulated wall built in 1995 with an inner polystyrene layer

3.1 Description of the wall and expected thermal conductance

The element under analysis is a 33 cm thick brick wall, designed in 1995, which has a 4 cm thick internal layer of polystyrene insulation. The thermal performance of each layer reported in the project is in accordance with the technical standards in force at the time (Annex A of UNI 10351 [3]), as summarized in Table 1.

Table 1. Stratigraphy and thermal properties of the multilayer wall.

Layer	Thickness s [m]	Conductivity λ [W/(m K)]
External cement mortar	0.05	1.4
Solid brick (ρ = 1800 kg/m^3)	0.14	0.72
EPS (ρ = 15 kg/m^3)	0.04	0.045
Solid brick (ρ = 1800 kg/m^3)	0.07	0.72
Internal gypsum mortar	0.03	0.35

The expected thermal conductance can be computed considering the thermal resistance of each layer in serial asset:

$$\Lambda_{theo} = \left[\sum_i (s_i / \lambda_i)\right]^{-1} \tag{4}$$

Where:

Λ_{theo} is the expected thermal conductance [W/(m^{2}K)];
λ_i is the conductivity of the i-th layer [W/(m K)];
s_i is the thickness of the i-th layer [m].
Starting from the data reported in Table 1, it results: Λ_{theo} = 0.768 W/(m^{2}K).

3.2 Installation of HFM and results

The HFM has been installed according to Figure 1, as shown in Figure 2.

Figure 2. HFM installation on the external (on the left) and internal (on the right) sides.

Figures 3÷5 show the results of measurements in terms of surface temperatures (Figure 3), heat flux (Figure 4) and thermal conductance (Figure 5).

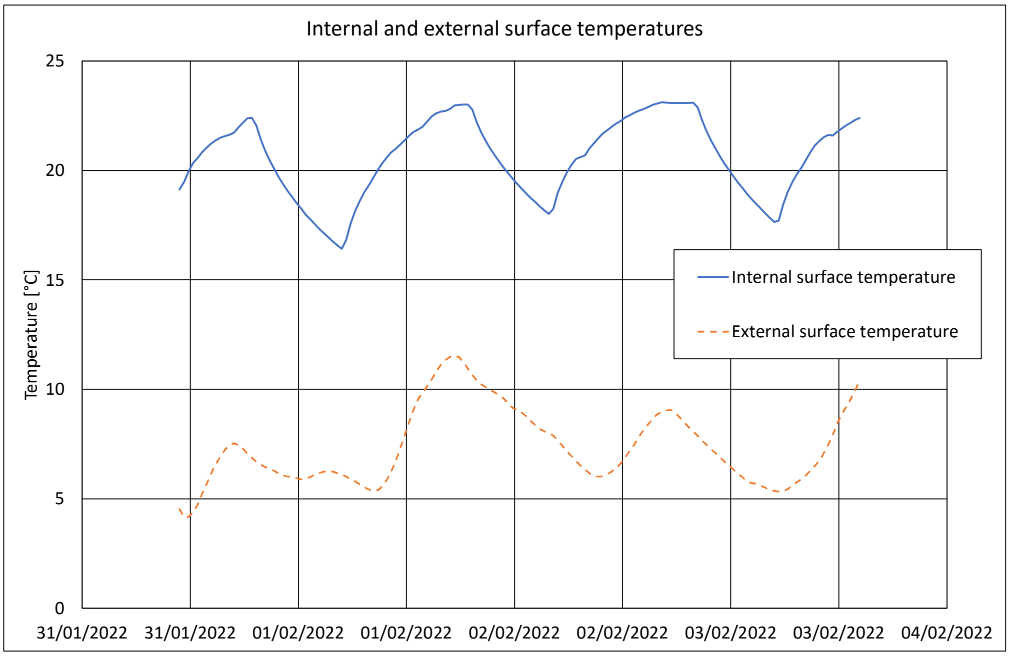

Figure 3. Measured internal (solid, blue line) and external (dashed, orange line) surface temperatures.

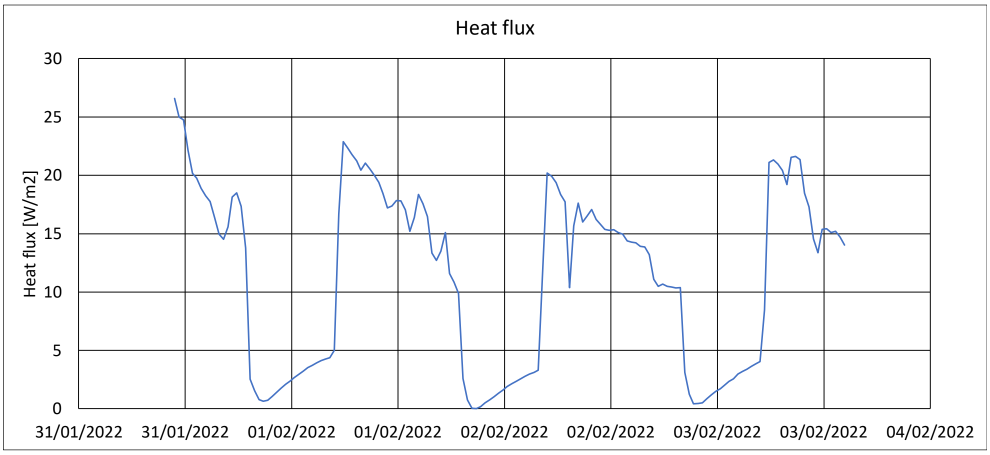

Figure 4. Measured heat flux.

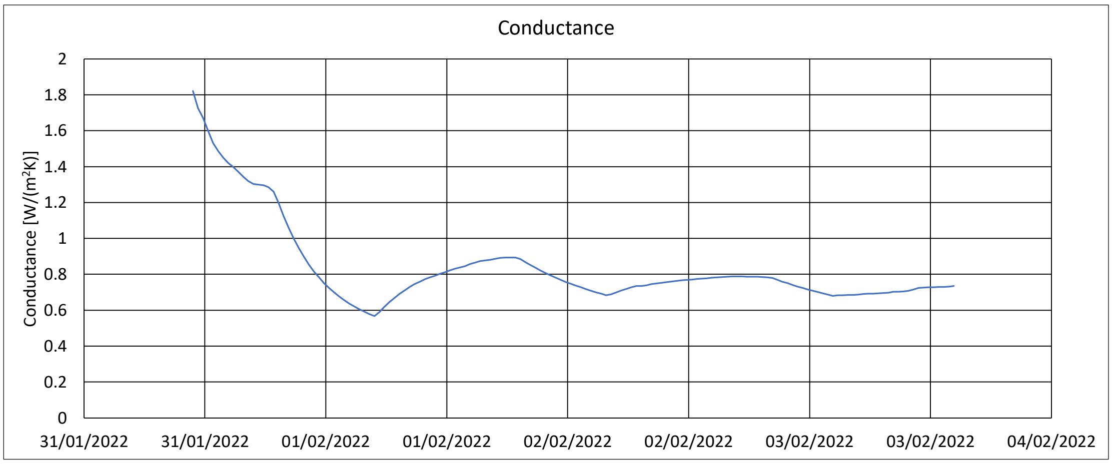

Figure 5. Measured thermal conductance computed with the average method, plotted over the duration of the test.

The measured thermal conductance for the brick wall insulated with polystyrene is 0.734 W/(m^{2}K), with a variation of only 4% with respect to the expected result of 0.768 W/(m^{2}K).

4 Measurement of thermal conductance of a stone wall with a nanotechnological mortar installed in 2022

4.1 Description of the wall and expected thermal conductance

The element under analysis is a stone wall 70 cm thick with two layers of standard mortar on both sides. Then on the external, an additional layer of nanotechnological mortar 1 cm thick was installed according to the Producer's instructions by an authorised, third-party mason.

The nanotechnological mortar provides a technical sheet with no information about durability and a self-declared conductivity of 0.0019 W/(m K). Moreover, the initial conductance of 2.536 W/(m^{2}K) for the bare wall was determined in [20] using the HFM approach. Basing on Eq. (4), the added thermal resistance provided by the nanotechnological mortar should determine an expected conductance of 0.177 W/(m^{2}K). The assessment of durability is based on two measures: the former performed immediately after the end of the installation cycle and the latter two years later. Before the measurements took place, a visual check over the surface was performed to check the absence of evident deteriorated or damaged regions (e.g. due to accidental impacts).

4.2 Installation of HFM

The HFM has been installed according to Figure 1, as shown in Figure 6 and Figure 7, which refers to outside part of the wall. In particular Figure 6 deals with the situation immediately after the end of the installation cycle of the mortar, while Figure 7 two years later.

Figure 6. HFM installation to measure the contribution of the nanotechnological mortar. Outside view, just after the end of the installation cycle.

Figure 7. HFM installation to measure the contribution of the nanotechnological mortar. Outside view, two years after the end of the installation cycle.

4.3 Results immediately after the end of the installation cycle

Figures 8÷10 show the results of measurements in terms of surface temperatures (Figure 8), heat flux (Figure 9) and thermal conductance (Figure 10), immediately after the end of the installation cycle.

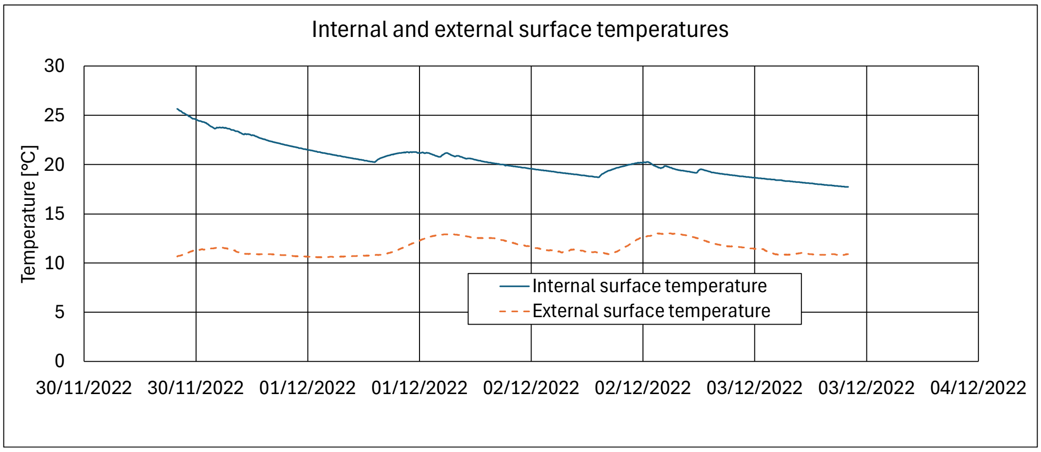

Figure 8. Measured internal (solid, blue line) and external (dashed, orange line) surface temperatures.

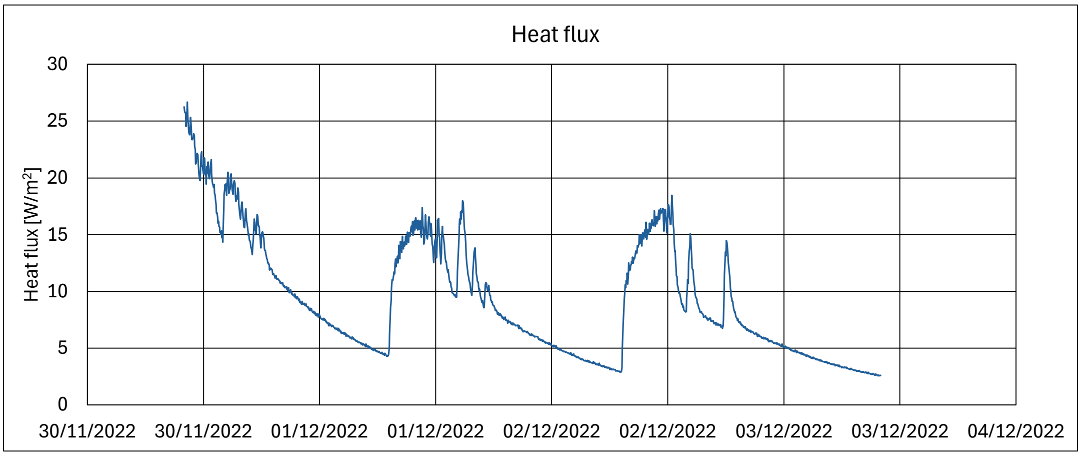

Figure 9. Measured heat flux.

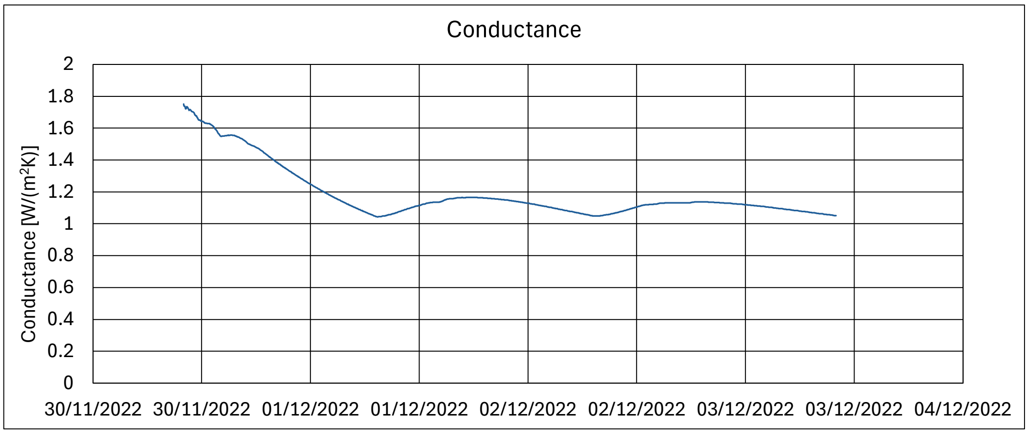

Figure 10. Measured thermal conductance computed with the average method, plotted over the duration of the test.

The measured thermal conductance for the stone wall coated with an external layer of nanotechnological mortar 1 cm thick immediately after the end of the installation cycle is 1.051 W/(m²K), about five times greater than the expected value of 0.177 W/(m²K).

4.4 Results two years after the end of the installation cycle

Figures 11÷13 show the results of measurements in terms of surface temperatures (Figure 11), heat flux (Figure 12) and thermal conductance (Figure 13), two years after the end of the installation cycle.

The measured conductance for the stone wall coated with an external layer of nanotechnological mortar 1 cm thick two years after the end of the installation cycle is 2.08 W/(m²K), about twice the measured value of 1.051 W/(m²K) and ten times the original expected value of 0.177 W/(m²K).

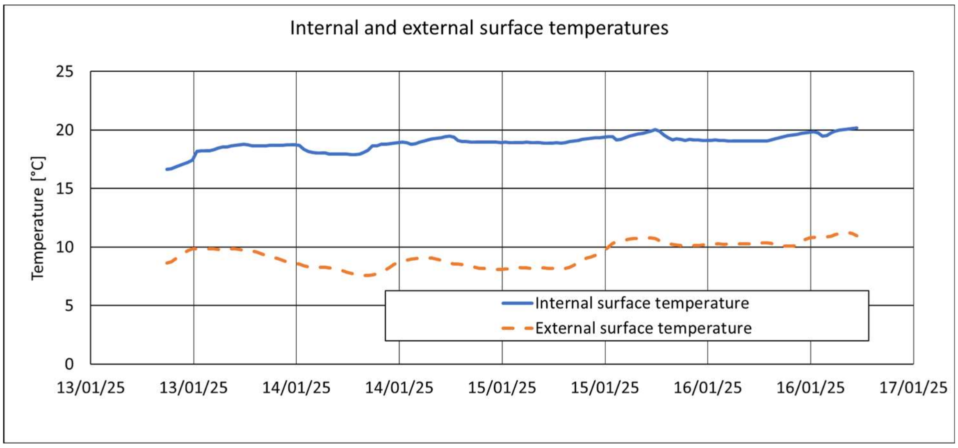

Figure 11. Measured internal (solid, blue line) and external (dashed, orange line) surface temperatures.

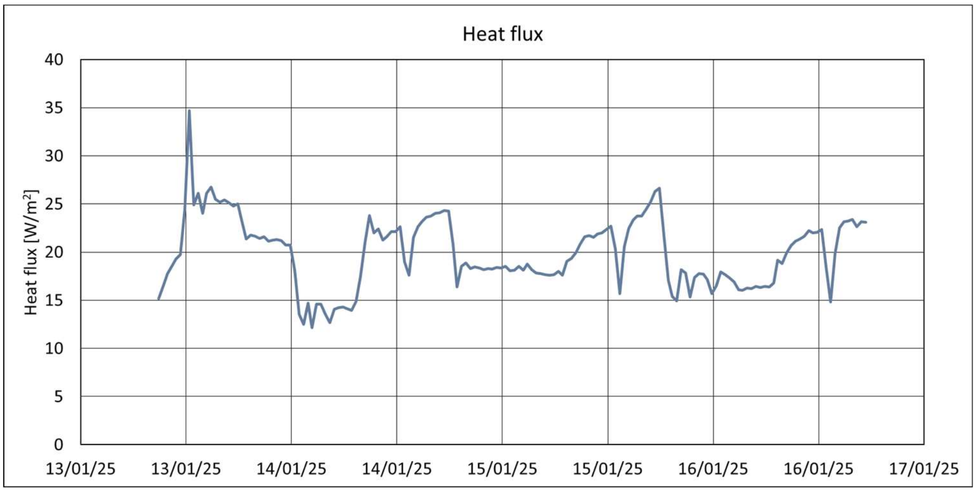

Figure 12. Measured heat flux.

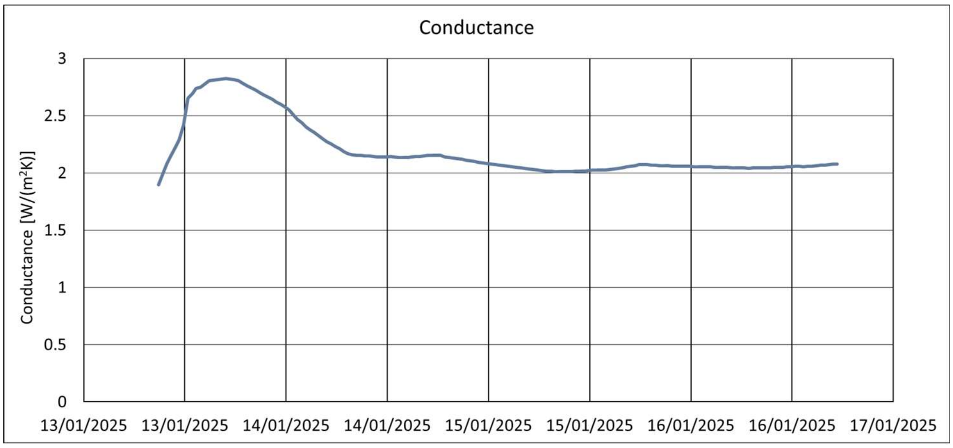

Figure 13. Measured thermal conductance computed with the average method, plotted over the duration of the test.

5 Conclusions and future developments

In the present work, the heat flow meter approach was used to carry out a study about durability of thermal insulators.

Two case studies were considered: the first is a brick wall with polystyrene insulation, about 30 years old, while the second is a stone wall coated with a nanotechnological mortar installed in 2022. The measurements and calculations of thermal conductance were performed according to UNI ISO 9869-1, with an accuracy between 14% and 28%. In both cases there were no apparent damages or deterioration of the investigated regions, and no intervention or refurbishments had been performed since the installation of the mortar. Therefore, the obtained results represent the on-site variation of conductance of two different materials, due to the ageing and the effects of external weather. Table 2 resumes the obtained results.

Table 2. Comparison between expected and measured thermal conductance Λ [W/(m^{2}K)] for the two case studies: brick wall insulated with polystyrene and stone wall coated with nanotechnological mortar.

Wall	Expected	Measured short term	Variation with the expected value [%]	Measured long term	Variation [%]
Brick wall + polystyrene	0.768	-	-	0.734 (about 30 years)	4
Stone wall + nanotechnological mortar	0.177	1.051	494	2.08 (2 years)	1075

The results of Table 2 clearly show the long-term durability of the traditional insulator represented by the polystyrene layer, even about 30 years later. On the other hand, the nanotechnological mortar presents dramatic differences already starting from the completion of the installation cycle: the thermal conductance of 1.051 W/(m^{2}K) is about five times greater than the expected one, 0.177 W/(m^{2}K). Such divergence becomes even larger after only two years, leading to a conductance of 2.08 W/(m^{2}K) that is very close to the one of bare wall, 2.536 W/(m^{2}K), and ten times greater than the expected one. Such result shows that neither the thermal performance nor the durability of the material are satisfactory with very poor performances, leading to global transmittances that are not compliant with the minimum requirements concerned with mandatory laws and energy efficiency even after the end of the installation.

According to the Authors' experience, the variations highlighted in the nanotechnological mortar only just two years later might be related both to the moisture content and to the eventual breakage of the microspheres that should ensure the high thermal performance. Anyway, these assumptions should be specifically enquired by means of dedicated laboratory tests, belonging to the topic of future developments.

In addition, more materials, both standard and nanotechnological, should be tested both by means of laboratory and in situ analyses. In particular, in situ measurements are highly representative since the insulating material is naturally aged and exposed to the weather, without relying on fictitious ageing methods. Moreover, the current tax incentives (i.e. Superbonus) have led to widespread installations of different insulating materials, providing a very large in situ database on which test the issue of durability in the future years.

Nomenclature

q	Heat flux per unit area	W/m^2
R	Thermal resistance	m^{2}K/W
s	Thickness	m
T	Temperature	K
U	Thermal transmittance	W/(m^{2}K)
Λ	Thermal conductance	W/(m^{2}K)
λ	Thermal conductivity	W/(m K)
ρ	Density	[kg/m^3]
Subscripts		
se	referred to external surface	
si	referred to internal surface	
theo	theoretical	

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