Aerogel-Based Plasters

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Aerogel has entered the construction field in the last two decades as a component of many insulation products, due to its high thermal performance. Aerogel-based plasters allow the matching of high thermal performance and limited thickness. This makes them suitable when retrofitting an existing building and also when restoring a heritage building. This entry presents the state of the art of the research on aerogel-based plasters as a part of the aerogel-products for the building sector.

aerogel | aerogel-based | plaster | building conservation | energy efficiency | thermal retrofit | sustainability

1. Introduction

Research on silica-aerogel insulating materials is part of the broader issue of environmental sustainability. Energy demand has increased globally for the last three decades due to industrial development and population growth. Despite reserves being limited, non-renewable resources still dominate the energy market [1]. The construction sector is responsible for 42% of the total energy consumed [2] and for the use of 50% of the natural resources extracted from the earth's crust [3]. Following the latest European regulations, e.g., standards 2010/31/UE, 2012/27/UE, 2018/2002/UE, the attention has increased towards low- and zero-emission buildings, construction techniques that allow CO_2 emissions to be lowered, the use of fossil fuels, and the amount of waste [4][5]. The interest in the renovation and energy improvement of existing buildings considerably grew in the last decade [6][7].

Keeping old buildings in use is a goal for contemporary restoration. A regular use indeed avoids abandonment and ensures permanent maintenance. To update old buildings to the needs of a current lifestyle, technologies compatible with their constructive features are demanded, e.g., insulation materials able to improve the thermal performances of the ancient structures. New research on innovative products for restoration is, therefore, encouraged [6]. The renders obtained from mixing natural lime and amorphous silica aerogel can play a role in preserving historic buildings and their energy improvement. They are based on traditional material and techniques that are fully compatible with the historic structures, despite being innovatively used in the form of a low-impact and highly insulating product [8][9][10][11][12][13][14][15].

Research on aerogel-based products has grown over the last decade. Given the innovative nature of these products, most of the research was experimental. The results are promising, although necessarily still quite heterogeneous, especially with regards to the experiments based on both laboratory and on-field tests.

2. Aerogel-Based Products for Buildings: An Overview

Amorphous silica aerogel products have been investigated, and several applications have been carried out for about two decades. Attempts at a literature review were made in recent years [9][16][17]. Aerogel was discovered in the early 1930s [18] and entered the building sector in the late 1980s, thanks to its high performance as a thermal insulator [9][19]. Until that time, aerogel was used in the space industry, chemical industry, and sports equipment, but not that much in the building field. A limiting factor was its high cost, and the lengthy tests needed to produce a ready-to-market product [19][20][21]. Aerogel can be used for making slabs, pellets, or other building components. Silica aerogel is the best solid insulator by mass and volume since it transmits one-hundredth of the heat compared to a normal density glass [21]. Aerogel-based building products are currently considered to be promising insulation materials mostly due to the fact they have high thermal performances with limited thickness. Furthermore, they have a deficient embodied energy, lower than traditional insulation products. Commercial aerogel-based products have low thermal conductivity up to 0.013 W/(mK). Silica aerogels combine an extremely high porosity with an intrinsic low pore size (nanopores can be up to 90 vol.%). As a result, the gaseous thermal conductivity has a large influence on aerogels' overall thermal conductivity [9]. Aerogel is nowadays used as a component for several insulating solutions and building products: glass, vacuum insulation panel (VIP), boards, blankets, wallpapers, wall paintings, reinforced concrete, mortars, plasters [22] (figure 1).

Silica aerogel-base renders are obtained by embedding the aerogel as a porous material component. Renders with silica aerogel have proven to be a super-insulating coating. They are particularly useful when insulating a wall without increasing thickness too much [10][13][15]. Plasters are relatively easy to implement, both on internal and external wall surfaces, and can fill gaps and joints to create a continuous insulation layer [10]. Insulation plasters are suitable for many applications, including outdoor and indoor wall systems. Aerogel-based insulating plasters have been developed as high-performance insulation materials and are easy to use in several situations. These products, made of lime or concrete mortar and silica aerogel, are commercially available and constantly under technical evolution. Lightweight plaster can be used for several applications, thanks to its weight ratio, heat insulation, and sound insulation performance, higher than traditional plasters [12]. Aerogel is an aggregate that contributes to lowering weight, increasing thermal and acoustic insulation, and improving fire resistance.

In 2012, Koebel et al. [23] described the innovative aerogel-based render developed at the Swiss Federal Institute for Materials Science and Technology (Empa) together with the Fixit group. The plaster contained more than 80% silica aerogel granulate in volume and could be sprayed on walls using conventional industrial machine-based systems. Thermal conductivity values below 0.025 W/mK were measured. Koebel et al. also cited the plaster-based products by Parexlanko and MINES ParisTech/AR-MINES/CEP. Their goal was to obtain a good thermo-mechanical compromise for external application, using methods as close as possible to traditional ones (e.g., cement-based mortars, traditional techniques). Some mortars with thermal conductivity values close to 0.050 W/mK (hot-guarded plate method) and a flexural strength larger than 0.5 MPa were produced at the preindustrial level [23]. Ibrahim et al. (2015) developed an insulating render with low thermal conductivity based on the (super)-insulating capability of silica aerogels. It is a plaster made of a light mortar that consists of a hydraulic binder (mineral and/or organic) and an insulating filler comprising hydrophobic silica aerogel powder or granules, structuralizing filler (optional), and additives (optional). The aerogel granules are produced in a specialized plant. Simultaneously, the mortar is prepared industrially as a dry composition by mixing hydraulic binder and additives. The mixture of the above-mentioned components is stored in bags and transported to the site for use. The product is mixed with water on the construction site to obtain a viscous paste suitable for the application, which may be by spraying. Thermal conductivity is measured using a guarded hot plate and a heat-flow meter. Thermal conductivity is 0.026 W/mK. WUFI and EnergyPlus software produced numerical simulations. Results show the moisture risk significantly decreases by applying the aerogel-based plaster on a non-insulated wall [24].

3. Silica Aerogel Applied to High-Performance Plasters for Historic Building Restoration

Contemporary conservation is based on continuous maintenance and keeping historic buildings in use, which contributes to ensuring their physical preservation. A respectful improvement of thermal performance enhances the possibility of continuing the use of a historic building, contributing to its preservation. On the other hand, thermal retrofitting may be a source of risk for historic buildings since adding insulation layers may affect their authenticity and integrity [25][26]. Thermal insulating plasters may represent a good compromise between the needs of preservation and energy improvement [10][11][17][27]. Thanks to their easy installation and reversibility, they are suitable to apply on non-aligned walls, out of square surfaces, and curved areas typical of historic buildings, naturally aside from the case of frescoed walls, stuccoes, or other historic wall decorations. They allow for creating a continuous thermal insulation layer by filling the gaps and irregularities of a pre-existing wall, exactly as in the case of a historic building [4][26]. However, while research about aerogel-based panels and mats is already promising, a specific approach is required to study how to embed aerogel into a lime-based or cement-based mortar [27]. Among the aerogel-embedded products, natural binder plasters are preferable when restoring a historic building. Indeed, thanks to its composition, the silica aerogel-based hydrated lime plaster is highly compatible with the traditional massive structure from both a mechanical and hygrothermal point of view.

Stahl et al. (2012) studied a render consisting of hydrophobized granular silica aerogel (60–90 vol.%) and a cement-free binder since cement is hardly compatible with the pre-industrial materials used in a historic wall, on both a chemical and physical level [10]. Cement increases a wall’s impermeability, makes humidity stagnate, and favors salt efflorescence [13][28]. This render consists of hydrophobized granular silica aerogel (60–90 vol.%), purely mineral and cement-free binder, plus some additives which enhance workability. It can be applied both manually and via plastering machines. Its thermal conductivity has been measured by a hot plate device and 25 (±2) mW/mK at a density of approx—200 kg/m^3. The authors stated that thermal conductivity is probably affected because liquid water enters the aerogel granulates’ nanopores. Water partially damages the aerogel structure, remains trapped, and needs a long time to dry. According to the authors, cement binders may reduce this risk thanks to their higher resistance than lime. Nevertheless, cement may affect breathability and mechanical compatibility with the masonry of the pre-existing building. This cement-free product has low resistance to water vapor. It may reduce moisture accumulation on the insulation layer's cold side (in summertime) and the warm side of the insulation (in wintertime).

The investigations by Buratti et al. (2014) [11] are interesting in refurbishment as the tested product is currently marketed primarily as a restoration product, Tillica pasta® by Arte e Mestieri s.n.c. [11][29]. They studied aerogel-based renderings and tested the hydrated lime plaster called Tillica pasta, a good restoration material due to its components. In particular, the properties of the naturally mature lime. The composition determines the natural property of water repellent and vapor permeability. Thermal conductivity was measured with a heat flow meter apparatus, and it resulted in being proportional to the percentage of granular silica aerogel, as shown in Table 2. The authors tested three solutions with different percentages of aerogel, up to 99 vol.%. The proposed plasters' thermal properties were evaluated, employing a heat flow meter apparatus—the 50 vol.% aerogel plaster had a range of thermal conductivity of 0.08–0.06 W/mK [11]. Tillica pasta is a silica aerogel-based render developed by Arte & Mestieri and commercialized by Ibix S.r.l. The product is an aerogel-based mortar obtained by manually mixing slaked natural hydrated lime with granular silica aerogel. Thank this combination, the product has high porosity (>90%) and interesting thermal behavior and breathability. It is also not putrescible and antibacterial, thanks to the presence of hydrated lime. Declared data: thermal emissivity $\varepsilon = 0.87$ (standard ASTM C 1371-04 a), thermal conductivity = 0.00175 W/mK (UNI 10456), average solar reflectance = 0.47 (standard ASTM1980-11) [29].

The above-cited Ibrahim et al. (2015) [24], with their aerogel-embedded plaster with a hydraulic binder, focused on how the aerogel-based render contributes to lowering the risk of moisture in historic structures. Indeed, due to the aerogel's hydrophobic nature, aerogel-based renders reduce water absorption, keeping stable both the volumetric composition and thermal behavior [13]. However, it is necessary to consider the risk of low breathability linked to hydraulic use instead of hydrated lime.

The Swiss Federal Institute EMPA investigated a pre-mixed aerogel-enhanced plaster commercialized by Röfix with the name of FIXIT 222. This material uses more than 50% silica aerogel granules in volume and declares a thermal conductivity of 0.028 W/mK [15][27]. Nosrati and Berardi (2017) investigated aerogel-enhanced plasters with different percentages of silica aerogel [30]. The aim was to assess the performance of the proposed renders as insulation materials. The experimentation was performed at the Building Science Laboratory at Ryerson University in Toronto. The samples were prepared by mixing hydraulic lime-based plaster with granular silica aerogels P300 in different percentages (from 25% to 95 vol.%). Three groups of aerogel-enhanced plasters were considered: FIXIT 222, NHL 3.5 hydraulic lime by CHIRAEMA s.r.l., NHL 3.5 Saint Astier by TransMineral USA. The thermal conductivity of the samples was measured with a heat flow meter apparatus. Samples had different thicknesses, and they were placed between a hot and a cold plate. Thermal conductivity was measured to reach the thermal equilibrium at a pre-defined difference of temperature between the plates. The results highlight a direct relationship between plaster density and thermal conductivity [30].

Ghazi Wakili, Stahl et al. (2015) investigated the long-term behavior of an aerogel-based plaster applied without reinforcement meshes. The test was made on a wall of the historic main building of TU Wien. Temperature, humidity, and heat flux were monitored within different wall layers by using a wireless sensor system [12]. Fixit 222 aerogel plaster was applied to four testing areas on the southern façade, dating back to the 1950s. Wall stratigraphy before testing was: 1.5 cm gypsum plaster on the indoor side, 5 cm hollow bricks, 2 cm cement rendering on the outdoor side. Sensors were installed on both the indoor and outdoor surface in late 2013 to measure temperature, moisture, and heat flux before the retrofit. Five months later, in 2014, the F222 plaster (thickness = 4 cm) was applied to each of the four areas with different finishes (difference in grain and finish, painting, water repellent, etc.). After retrofitting, Area 1: Before = 0.97 W/m^{2}k, U_{after} = 0.78 W/m^{2}k (−20%). Area 2: Before = 1.04 W/m^{2}k, U_{after} = 0.58 W/m^{2}k (−45%). The U-values decreased less than expected, probably because the drying process was not yet completed [12]. The on-field research was, therefore, further implemented two years later.

Shuss et al. (2017) tested different aerogel-based plaster systems thanks to ten sample areas on the façades of the TU Wien's main building: four test areas on the southern façade (S), four on the western façade (W), two on the northern façade (N). Temperature and humidity were constantly monitored, along with the weather conditions. The parameters declared by the datasheet were experimentally verified on-site. The U-value measured on-site was similar to what was declared, and close monitoring of the water content proved crucial to confirm these data [31]. A 4 cm aerogel-based plaster was applied to both sides of an existing 42 cm brick wall. As a result, U-value lowered from 1.25 to 0.46 W/m^{2}K (−64%) [14]. This confirmed the high thermal performance of the aerogel-based plasters, even at a minimal thickness. On this side, confirmation was obtained of its suitability for the energy retrofitting of heritage buildings.

Besides the advantages, the aerogel-embedded renders and the method used to characterize their properties present some criticalities that are still under investigation. Stahl (2012) confirmed the role of water is crucial to assess plaster behavior over time. Measuring the pore size and distribution, mapping their microscopic structure helps better understand how moisture penetrates within the porous material [18]. Durability is a significant issue for aerogel-based renders. Nosrati and Berardi (2017) compared the durability of three aerogel-based plasters available on the market: FIXIT 222, Saint Astier, Chiraema. The samples were exposed to different aging stressors, including high temperature and high humidity, freezing-thawing cycle. The thermal properties of each product were measured before, during, and after the aging period, by using a heat flow meter apparatus, according to standard ASTM C518. The thermal resistance of all samples decreased by about 17% after a nine-year equivalent aging time. Similarly, the thermal conductivity of all samples significantly increased after a 15-year equivalent aging time. According to the authors, aerogel-based plasters lose their thermal resistance faster than aerogel boards and blankets. This is due to physical changes in the aerogel-based plasters' porous structure over time, as shown by the SEM images taken before and after the aging process. Results thus demonstrate that thermal performance depends on both sample composition and aging factors [30] The same authors (2018) continued this research by simulating 20 years of aging [32]. Each stress condition was individually tested and then combined to understand better the effect of each factor of decay (high temperature, high humidity, freeze-thaw cycle, UV exposure combined with high temperature and high humidity). Although the combination of different elements made thermal conductivity rise, high humidity resulted as the main factor affecting this parameter. The authors tested samples of plaster made of natural hydraulic lime (NHL 3.5–55 lbs, by Sustainable Innovative Products and Chireama Corp.) enhanced with a percentage of hydrophobized silica aerogel granules (P-300, supplied by Cabot Corp) from 25 to 90 vol.%. Samples had dimensions of 15 × 15 × 2 cm. After 20-years of equivalent aging time with high humidity levels, 70% of samples increased thermal conductivity up to 10%. However, despite the aging-driven rise, aerogel-based plasters' thermal conductivity stayed much lower compared to not-aged conventional materials [30][32].

Following this literature overview, future research will further analyze silica aerogel plasters' physical and mechanical features and the connection between product composition and environmental conditions of use. The authors want to stress that understanding the thermal performance related to using conditions and the product thickness is still limited by the lack of a long-term experience [33][32]. Analyzing the porous structure (e.g., pore diameter, total pore volume) and assessing market products' vapor permeability is crucial, as they greatly affect both indoor and outdoor durability. The effects of acid rain should also be more thoroughly investigated [34][35].

The second significant criticality highlighted in the specific literature [13][15] is the higher cost of aerogel-based products than traditional building materials. Indeed, this feature is a disincentive for the adoption of aerogel-embedded plaster systems. Opaque aerogel-based products may cost ten times a common insulation material such as mineral wool [16]. However, the aerogel market has exponentially increased together with the number of companies that produce patents. The global market for silica aerogel products was estimated at $307.5 million (US) in 2014, $427 million in 2016, and is expected to reach 1.92 billion by 2022, with an annual growth of over 10% [22]. The overall review of thermal insulating plasters in the European market, carried out by Barbero et al. (2014) [36], considered the costs of aerogel-based renders. They considered technical data and prices directly supplied by producers, without publishing names of manufacturers and commercial products for reasons of privacy [13]. This analysis was resumed by Buratti et al., 2016 [13]. Barbero et al. determined the average cost of a product to exclude the higher parameters in each system analyzed [35]. The incidence of the cost of plasters was assessed by considering both the cost per square meter of each plaster necessary to obtain the same final thermal resistance (equal thermal resistance R_x for 1 m^2 K/W) and the cost per functional unit (the reference unit is the money required to make 1 cm of thickness) [13][36] (see table 3). It is useful to analyze the influence of aerogel costs on the optimum thickness of the render. The cost analyses by Barbero et al. allowed a price range to be determined, which constitutes the optimum. A new thermal insulating plaster should have a cost of around 45–60 €/m^2, with the same thermal performance with Rx values [36]. It is, therefore, important to understand the optimal thickness related to the render cost. Buratti et al. explained that as the cost increases the optimum, the thickness value decreases [13]. Further research developments should further investigate the relationship between thickness and costs, considering the thermal conductivity and durability of the final render. It is necessary to test plaster with different compositions and different percentages of silica-aerogel.

The increasing interest in the building products described above largely depends on the certified thermal performance parameters. This information is the only data that the manufacturers can use to demonstrate the features and the benefits of their products, so it is necessary to obtain results calculated with formulas and laboratory tests, as that corresponds as much as possible to the performance of the product in use. Sample manufacture is relevant to understanding the thermal behavior of the building product. The thickness of the aerogel plaster influences the material's final behavior in the relative condition of use, and this feature is fundamental for the quality-cost ratio, especially in the case of restricted historical construction. From the literature review, it is clear that there is no single guideline for laboratory thermal tests (the type of tests and the manufacture of specimens).

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