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Aerogel-enhanced systems for building energy retrofits: Insights from a case study

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ABSTRACT

The development of innovative materials aiming to achieve energy savings is a main focus in the building technology sector. In this context, aerogel-enhanced products are often indicated as promising materials for increasing the thermal resistance of the building envelope. In particular, aerogel blankets have already started showing their effectiveness in retrofitting projects, while the development and adoption of aerogel-enhanced renders and aerogel-incorporating glazing systems is progressing. Based on the state of the art, this paper describes several new aerogel-enhanced systems that have been developed over the last few years at Ryerson University in Toronto, ON. In particular, the paper presents the recent results regarding aerogel-enhanced plasters, lightweight concretes, blankets, and glazing systems. Thermal characterization tests of these new materials confirm the superior performance for building retrofits. For example, the thermal conductivity of plasters with more than 80%vol. aerogel is below 0.025 W/(mK), a tenth of the respective value for traditional plasters, while mortars with more than 30%vol. aerogel show a thermal conductivity as low as 0.23 W/(mK). The newly presented aerogel-based systems are then assessed for the retrofitting project of an educational building located in Toronto. An extensive energy audit was conducted through measurements of the envelope thermal characteristics, the building airtightness, and several indoor environmental parameters. The audit helped to build an accurate energy model that was used for analyzing the energy consumptions of the building and assessing several energy saving measures. The study showed that high thermal resistance values could be obtained installing thin aerogel-enhanced products in the opaque and transparent envelope, with overall building energy savings up to 34%, with limited impacts and interruptions on the building functionality and internal usable space. However, the high costs of aerogel-enhanced products made their payback times of several decades and represented a barrier for the adoption of most of the systems presented in this paper.

1. Introduction

The increasing building energy demands together with the concerns for the rising Greenhouse gas emissions are pushing the need for new energy-saving building materials and systems worldwide [1]. In particular, while new buildings typically incorporate advanced building envelopes to meet recent stringent codes, the energy retrofitting of existing buildings remains a critical goal. Several countries have started promoting policies aiming to the retrofit of existing buildings, as retrofitted buildings would provide energy savings, lower maintenance costs, and higher comfort levels. Accordingly, building material research is investigating new insulating systems to support retrofit projects [2–5]. In this context, the present paper describes recent researches about several new aerogel-enhanced building materials and systems, which are then assessed for a retrofit case study located in the cold climate of Toronto.

The aerogels are among the most promising insulating materials given their extremely low thermal conductivity (~0.01–0.02 W/mK), resulting from a well-balanced relationship among the low solid skeleton conductivity, the low gaseous conductivity, and the low radiative infrared transmission [6,7]. The aerogels are dried gels with an exceptionally high porosity, which permits them to have a lower thermal conductivity than air [8,9]. Nanopores with diameters of a few tens nanometers occupy more than 90% of the total volume of the aerogel, whose bulk density often ranges between 70 kg/m^3 and 150 kg/m^3. Table 1 reports the main properties of silica aerogels, the most common aerogel nowadays in building applications.

In general, the advantage of aerogel-enhanced products for building retrofit is in their space saving benefit, since they provide a high thermal resistance in thin layers [10–15]. For example, already a few year ago, the benefit of a wall retrofit with 1 cm thick

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Fig. 1. Raw materials for aerogel-enhanced plaster and preparation process.

Table 1
Main physical properties of silica (SiO_2) aerogels (data from [7–9]).

Property	Value
Density	3–350 kg/m^3 (typical 70–150 kg/m^3)
Pore diameter	1–100 nm (~20 nm on average)
Porosity	85–99.9% (typical ~95%)
Thermal conductivity	0.01–0.02 W/m K
Primary particle diameter	2–4 nm
Surface area	600–1000 m^2/g
Tensile strength	16 kPa
Coef. of linear expansion	2.0–4.0 × 10^{-6}

aerogel blankets on the interior side was proved to be economically feasible by Shukla et al. [16], although the high material cost at that time.

The superior properties of aerogels suggested their use in buildings initially in insulating layers such as blankets; more recently, aerogels in glazing systems and in other traditional construction materials. The introduction of aerogel in glazing systems has been proposed both using monolithic aerogels and granular ones in the glazing interspace for enhancing high thermal resistance and still high visible transmittance [17–20]. Meanwhile, researchers are trying to reduce the thermal conductivity of aerogel even further to reach values below 0.010 W/(mK). For example, Neugebauer et al. described a technique for compacting a bed of granular aerogel P100 by Cabot in order to reduce the thermal conductivity [21]: different degrees of compression were applied to a bed of aerogel with a density of 68 kg/m^3 and thermal conductivity of 0.0024 W/(mK); the corresponding thermal conductivity reached a minimum value of 0.0013 W/(mK) at a bed density of about 165 kg/m^3. The good sound absorption properties of new commercial aerogels, ranging from small granules (0.01–1.2 mm) to large granules (1–4 mm), promise also new uses of aerogels [22]. Moreover, when compared to other insulation and super-insulation materials, aerogels also show excellent fire resistance, resistance to direct sunlight, and long durability to different aging effects [23,24].

The synthesis of the aerogels was discovered almost a century ago, although only recently new mass production techniques have been developed [20]. In the late 1940s, the first commercial aerogel was produced by the Monsanto Chemical Corp., Everett, MA. Nowadays, North American industries such as Cabot Corporation and Aspen Aerogels (Northborough, MA, US) are the largest worldwide manufacturers of aerogels, with Nano Hi-Tech from China and EM-Power from Korea representing the main Asiatic sol-gel based suppliers. Aerogel granules are the only commercial pure products currently sold, since monolithic pieces of aerogel have not yet found a market given their fragility. Beyond pure aerogel material, aerogel-enhanced plasters and blankets of fibres with embedded aerogel granules are also commercialized [12,25–28].

The next Section 2 will describe commercial products and compare them with several aerogel-enhanced systems that were developed over the last few years at Ryerson University; the advantages of aerogel-enhanced plasters, lightweight concrete panels, blankets, and glazing systems over other existing commercial alternatives will be discussed. Then, in Section 3, the paper presents the retrofit projects of an educational building, and in Section 4, it discusses the benefits of adopting aerogel-based systems for the energy retrofit of this case study. Final conclusions are reported in Section 5.

2. Aerogel-based retrofit solutions

2.1. Aerogel-enhanced plasters

2.1.1. Previous literature and existing products

Given the fragility of aerogel, a commonly adopted approach for their use is represented by the possibility to embed aerogel granules in the mix of a porous mixed material. For example, thermal insulating plasters are being proposed to increase the thermal resistance of the building assemblies [25]. Aerogel-enhanced plasters have the benefit of being simple to implement and flexible with respect to unevenness surfaces allowing to create a continuous thermal insulation layer by filling the gaps and joints in a building envelope. The low density of aerogel-based renders allows the application of thick layers (up to 8 cm) have been realized with internal fiberglass mesh grids, creating adequate insulation, especially in those circumstances where other traditional insulating materials could not be used, for example in historical uneven surfaces or vaults [28–30].

Owing to the hydrophobic nature of aerogel, the aerogel-enhanced plasters have the advantage of being water repellent, which avoids water absorption, while they are water vapour permeable and more breathable than conventional plasters, which prevents surface wetness.

Kobel et al. [13] developed an insulating aerogel-based render with mineral and organic binders with a density of 156 kg/m^3 and a thermal conductivity of 0.027 W/(mK). Stahl et al. [30] developed an insulating plaster based on granular silica aerogel with purely mineral and cement free plaster and additives to enhance the workability of the rendering; the thermal conductivity of the plaster was 0.025 W/(mK) while its density was 200 kg/m^3. More recently, Buratti et al. [25] have carried out a research about aerogel incorporated plasters obtained by mixing natural calk with granular aerogel in different percentages, up to 99% in volume obtaining thermal conductivity values between 0.014 W/(mK) and 0.05 W/(mK).

The most widely adopted used aerogel-enhanced plaster was developed at the Swiss Federal Institute EMPA, and it is commercialized with the name of FIXIT 222. This material uses more than 50%vol. silica aerogel and has a declared thermal conductivity of 0.028 W/(mK). Several thousands of m^2 have been realized already with this product since 2013, meanwhile, its price has significantly dropped, making it a valid alternative among the thermal-insulating plasters [31–33].