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Recent trends in superinsulation materials for building – aerogel-enhanced products

Najnowsze trendy w superizolacyjnych materiałach budowlanych – produkty wzbogacone aerożelem

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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 regard, aerogel-enhanced products are often indicated as promising materials for achieving high thermal resistance in the building envelope. This paper aims to review the current state of the art of the aerogel-enhanced opaque systems. Cement-based products are reviewed as well as aerogel-enhanced renders and plasters. The focuses moves also on aerogel-enhanced blankets, which are among the most promising superinsulating systems. Comparative thermal characterization tests of several aerogel--enhanced blankets confirm their superior performance with a thermal conductivity as low as 0.010 W/(mK). Finally, future research challenges for making aerogel-enhanced products more common in buildings are presented.

Keywords: superinsulation; aerogel; aerogel-enhanced materials; thermal conductivity.

Streszczenie. Jednym z głównych celów obecnie opracowanych innowacyjnych materiałów jest uzyskanie oszczędności energii. W związku z tym, produkty wzbogacone aerożelem są wskazywane jako obiecujące materiały, pozwalające na osiągnięcie dużego oporu termicznego zewnętrznych przegród budynków. W artykule dokonano przeglądu obecnie stosowanych systemów izolacyjnych przegród nieprzezroczystych wzbogaconych aerożelem. Zaprezentowano przegląd materiałów na bazie cementu, a także ulepszone przy użyciu aerożelu materiały wykończeniowe. Skupiono się też na ulepszonych przy użyciu aerożelu matach izolacyjnych, które należą do najbardziej obiecujących systemów superizolacji. Porównawcze badania charakterystyki termicznej kilku mat wzbogaconych aerożelem potwierdzają ich doskonałe właściwości i przewodność cieplną wynoszącą ok. 0,010 W/(mK). Na zakończenie zaprezentowano wyzwania badawcze związane z upowszechnieniem w budownictwie produktów wzbogaconych aerożelem.

Słowa kluczowe: superizolacja; aerożel; materiały wzbogacone aerożelem; przewodność cieplna.

In an effort of setting stringent energy saving targets, the building sector has received increasing attention, as buildings are responsible for consuming up to 40% of the total energy in several developed countries, and contribute 40% to the total greenhouse gas emissions [6]. In this context, insulating material companies and researchers are struggling to create products with the lowest possible thermal conductivity at a reasonable price in order to promote high-performance building envelopes within thin layers. While common insulating materials have typical thermal conductivity values around 0.05 W/mK, materials with a thermal conductivity well below 0.02 W/mK have been consistently presented recently. Super-insulating materials, whose thermal conductivity is well below that of commonly adopted products, have received increasing attention. In particular, aerogels have received an increasing attention over the last decade since they show one of the lowest possible thermal conductivity [1, 2].

Aerogels are synthetic and highly porous nanostructured materials, inspired by a 1931 patent of Steven Kistler. The term „aerogel" comes from the fact that they are produced from gels in which the liquid component of the gel is replaced with a gas, giving to the final product a solid and dry smoked aspect. Compared to any other known material, an aerogel has the highest porosity, the highest specific surface area, and the lowest density, typically 70 ÷ 150 kg/m^3.

The low thermal conductivity of aerogels is a result of the high porosity and the nano-dimensional size of their pores. On the other hand, aerogels are very brittle due to their low tensile strength and are particularly expensive. Consequently, instead of being used alone, they are typically embedded in other materials (Photo 1). This paper is dedicated to present

Photo 1. Aerogel granules (left) and aerogel-enhanced blankets obtained embedding a fiberglass panel with precursor aerogel before the drying process (right); both created at Ryerson University
Fot. 1. Granulki aerożelu (z lewej) oraz maty wzbogacone aerożelem otrzymane przez osadzenie półproduktu w osnowie z włókna szklanego przed procesem suszenia (z prawej) wykonane w Ryerson University

the current state of the art about aerogel--enhanced opaque insulations.

Aerogel synthesis and market

The main reasoning for the use of aerogel insulation is related to the possible space-saving resulting from exceptional thermal properties and to their

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high fire resistance [5, 7]. In particular, aerogel-enhanced products during building retrofits from the inside guarantee the advantage of significant space-saving, providing a high thermal resistance in thin layers. The high cost of aerogels compared to traditional materials is a significant limiting factor for the diffusion of aerogel-enhanced products. The high price of aerogels is due to the low production volume and the high costs involved in the synthesis and the drying processes. Although the high cost, the global market of aerogels is tenfold increased since 2003. For example, these days, a ballpark pricing of aerogel-based blanket 13 mm thick costs around USD 7/m^2, a price just a few times higher than that of panels of traditional materials having the same thermal resistance [3, 4].

The global market for silica-based aerogels was estimated to be USD 307.5 million in 2014, USD 427 million in 2016, and it is expected to reach USD 1.92 billion by 2022, growing annually over 10% [2, 8, 13]. Nowadays, the primary market sector of aerogel products is represented by the oil and gas field, but the building aerogel market sectors are increasing more than the others.

Aerogel properties

The aerogels are dried gels with an exceptionally high porosity, which permits them to have a lower thermal conductivity than air. The extremely low thermal conductivity of aerogels, ~0.01 ÷ 0.02 W/mK, results from a well-balanced relationship among the low solid skeleton conductivity, and the low gaseous conductivity. Nanopores with diameters of a few tens nanometers occupy 85 – 99.9% of the total volume of the aerogel, whose bulk density often ranges 70 ÷ 150 kg/m^3. The high porosity and small pores lead to unique physical, thermal, optical and acoustic properties, but they lead to low mechanical properties too [8, 9].

Table 1 reports the main properties of silica aerogels, the most common aerogel nowadays in building applications. As reported in Table 1, silica aerogels have a relatively good compressive strength of up to 300 kPa. On the other hand, they have very low tensile strength, around 16 kPa, which makes them very fragile. For this reason, aerogels are typically incorporated in a stronger fiber matrix, such as in blankets, to improve the overall tensile strength [2]. The superior properties of aerogels suggested their use in buildings in insulating layers such as blankets, or in renderings such as mortars and plasters. Meanwhile, thanks to the translucent characteristics of the aerogels, their introduction in glazing systems has been proposed both using monolithic aerogels and granular ones for enhancing high thermal resistance and still high visible transmittance.

Table 1. Main physical properties of silica aerogels
Tabela 1. Główne właściwości fizyczne aerożeli krzemionkowych

Property	Value
Density [kg/m^3]	3 to 350 (typical 70 to 150)
Pore diameter span [nm]	1 to 100 (~20 on average)
Pore particle diameter [nm]	2 to 5
Average pore diameter [nm]	20 to 40
Porosity [%]	85 to 99.9 (typical ~95)
Thermal conductivity [W/mK]	0.01 to 0.02
Primary particle diameter [nm]	2 to 4
Surface area [m^2/g]	600 to 1000
Tensile strength [kPa]	16
Compression strength [kPa]	300
Coefficient of linear expansion	2 to 4 × 10^{-6}

Aerogel-enhanced opaque systems

Aerogel-enhanced mortars and concretes. Typically, concrete has a very high thermal conductivity ranging 1.7 ÷ 2.5 W/mK, therefore, it often led to the need to adopt ad-hoc thermal insulation layers in order to reach adequately thermal insualting properties. Ongoing researches on aerogels-incorporated mortars and concrete have hence aimed to design new ligh-weight concrete mixtures which guarantee both adequate compressive strength and low thermal insulating performance [10]. Ryerson University research group investigated new aerogel-enhanced mix concrete designs. General use Portland cement was used to realize many samples of mortars using natural aggregates with a maximum diameter of 4.75 mm together with superplasticizers to maintain consistency and workability of the mix (Photo 2, Figure 1). An alternative approach was the introduction of an air-entraining admixture. This permitted a reduction in mixing water with no loss of slump. Superplasticizers were also used to reduce the amount of water while maintaining a certain level of consistency and workability [3].

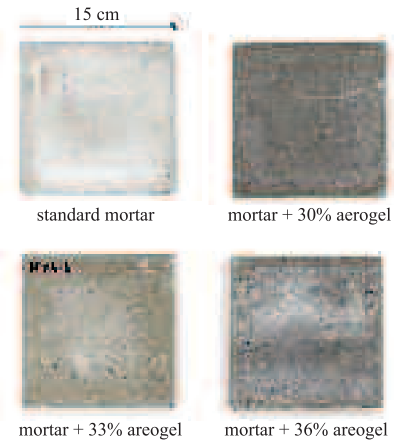

Photo 2. Samples of aerogel-enhanced lightweight concretes [3]
Fot. 2. Próbki lekkiego betonu zawierającego aerożel [3]

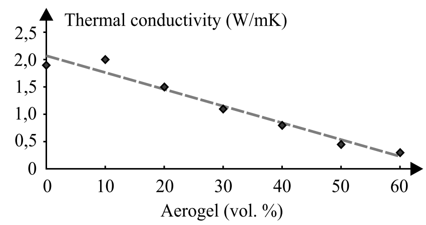

Fig. 1. Aerogel volume content vs. thermal conductivity in mortars
Rys. 1. Zależność przewodności cieplnej od zawartości aerożelu w zaprawie

The compressive strength of the samples of standard mortar without aerogel was around 50 MPa and halved by adding the air-entraining admixture as shown in Figure 2; thermal conductivity decreased linearly by increasing the quantity of aerogel.

Aerogel-enhanced plasters. 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 (of more than 5 cm) 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. Owing to the hydrophobic nature of the aerogel,

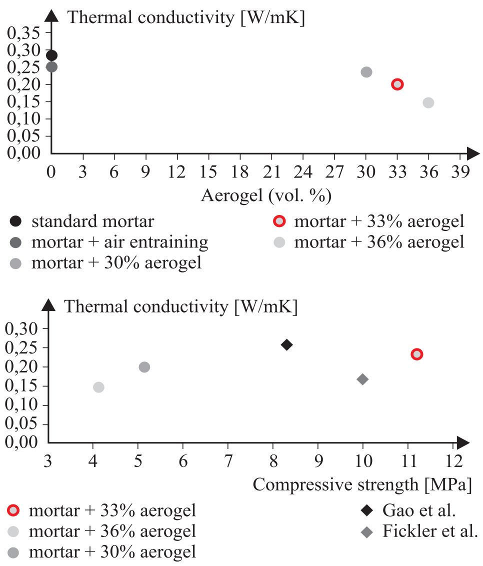

Fig. 2. Properties of aerogel-enhanced lightweight concrete (based on different literature)

Rys. 2. Właściwości lekkiego betonu wzbogaconego aerożelem (na podstawie literatury)

aerogel-enhanced plasters have also the advantage of being water repellent, which avoids water absorption, while they are water vapour permeable and more breathable than conventional plasters. The most widely adopted aerogel-enhanced plaster was developed at the Swiss Federal Institute EMPA, and it is commercialized with the name of FIXIT 222 [11]. This material uses more than 50%vol. silica aerogel and has a thermal conductivity of 0.028 W/mK. This product has been used in several thousands of m^2 since 2013, meanwhile, its price has significantly dropped (current price is around 100 to 150 € for a 50 liters bag, i.e. around 2 to 3 € per dry kilogram), making it a valid alternative among the thermal-insulating plasters.

Ryerson researchers recently produced aerogel-enhanced plasters by mixing hydraulic lime-based plaster with granular silica aerogels supplied by Cabot Corp in different percentages (25 ÷ 95% vol.) as well as using self-created proprietary aerogel granules. Different types of hydraulic lime were utilized. Photo 3 shows some samples of the aerogel-enhanced plasters [12]. The results of thermal conductivity tests of these products confirmed a linear relationship between the density of the plaster and the resulting thermal conductivity (Figure 3, Table 2). The thermal conductivity assumed values below 0.03 W/mK mixing more than 70% vol. of aerogel granules, although this resulted in significant cost increase and lower workability.

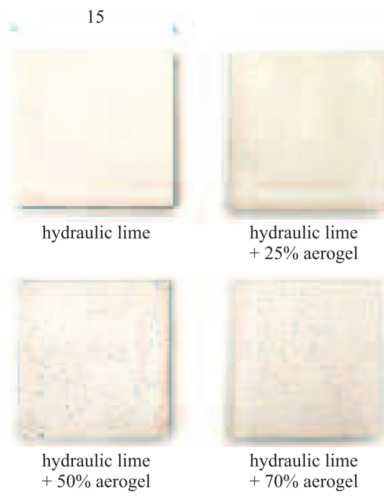

Photo 3. Samples of the different aerogel-enhanced plasters

Fot. 3. Próbki różnych tynków wzbogaconych aerożelem

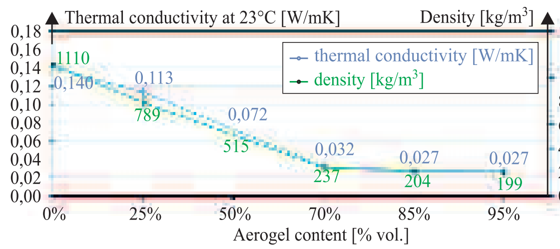

Fig. 3. Thermal conductivity and density of aerogel-enhanced plasters as a function of aerogel content ([12]

Rys. 3. Zależność przewodności cieplnej oraz gęstości tynków wzbogaconych aerożelem od jego zawartości [12]

Table 2. Main properties of different aerogel-enhanced plasters [12]

Tabela 2. Główne właściwości różnych tynków wzbogaconych aerożelem [12]

Mixture	Composition			Aerogel [% vol.]	Density [kg/m³]	Thermal conductivity [W/mK]
	plaster [l]	aerogel [l]	water [l]			
Hydraulic lime	6	0	2.174	0	1109.8	0.2032
Hydraulic lime + 25% aerogel	5	2.5	2.7	25	735.6	0.1151
Hydraulic lime + 50% aerogel	2	3.5	1.26	50	501.0	0.0687
Hydraulic lime + 70% aerogel	0.4	1.5	0.3	70	260.7	0.0311

Aerogel-enhanced blankets. In order to strengthen the tensile properties of the silica aerogels to be used as an insulating material, it has been recently proposed to reinforce the aerogels with mechanically stronger materials and non-woven fiber matrixes such as glass, mineral or carbon fibers. When the fibers or fibrous matrix are added to the pre-gel mixture which contains the gel precursors, the resulting dried composite is an aerogel blanket. The thermal conductivity of aerogel blankets on the market is around 0,015 W/mK. For example, Spaceloft developed by Aspen Aerogels, Inc. (MA, US) is a flexible fiber-reinforced blanket with a declared thermal conductivity of 0,013 W/mK at 0°C; other aerogel blankets are Cryogel®Z by Aspen, available in 5 mm and 10 mm thickness and suitable for industrial application below ambient temperature, and Thermal-Wrap™, available in 5 mm and 8 mm thickness by Cabot Corporation. The thermal conductivity of these last two products is 0.014 W/mK and 0,023 W/mK respectively [2].

The leading manufacturers worldwide of aerogel blankets are Aspen Aerogel, Inc., Cabot Corporation, Svenska Aerogel AB, Acoustiblok UK Ltd., Active Space Technologies, and Airglass AB. The advantages of aerogel-enhanced blankets are that the final panel does not show any granularity of the aerogel, since the aerogel particles are chemically attached to the fiberglass matrix. Most of the commercially available aerogel blankets are made with amorphous silica, and they usually suffer for dust production. Table 3 reports main properties of the different aerogel-enhanced blankets available on the market currently. Figure 4 shows the declared by the manufactures values of the thermal conductivity values across temperature for different commercially available aerogel blankets. Photo 4 presents the application of an aerogel-enhanced blanket on residental building.

Conclusions

The paper has summarized several ongoing research activities, which have already led to manufacturing aerogel-

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Table 3. Main properties of the different aerogel-enhanced blankets available on the world market
Tabela 3. Główne właściwości różnych mat wzbogaconych aerożelem dostępnych na światowym rynku

Commercial name	Provider	Fiber composition	Density [kg/m³]	λ [W/mK]
Thermal Wrap	Cabot	Polyestere and PET	~70	0,023
Cryogel x201	Aspen aerogel	Polyester/fiber glass	~130	0,014
Cryogel Z	Aspen aerogel	PET/fibrous glass	~160	0,014
Dow Corning HPI 1000	Dow Corning	Fiber glass	160	0,015
Pyrogel HPS	Aspen aerogel	Fiber glass	~200	0, 014
Pyrogel XTE	Aspen aerogel	Fiber glass	~200	0,014
Pyrogel XTF	Aspen aerogel	Fiber glass	~200	0,014
Spaceloft	Aspen aerogel	Polyester/fiber glass	~151	0,015
Silica aerogel fiberglass blanket, SACB-0-X	Joda	Fiber glass	<300	0,016
Silica aerogel ceramic fiber blanket, SACTT-X	Joda	Ceramic fiber	<301	0,016

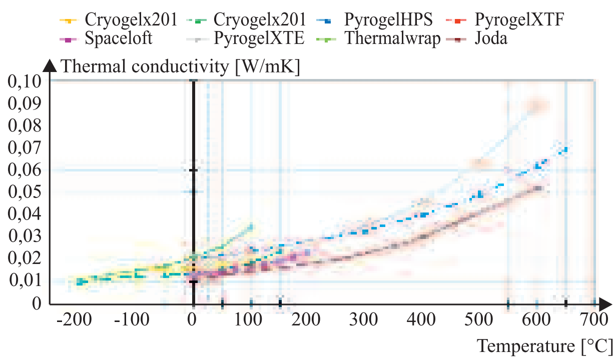


Fig. 4. Thermal conductivity values across temperature for different aerogel blankets (according to values declared by the manufactures)
Rys. 4. Zależność przewodności cieplnej od temperatury różnych mat zawierających udoskonalony aerożel (zgodnie z danymi deklarowanymi przez producentów)

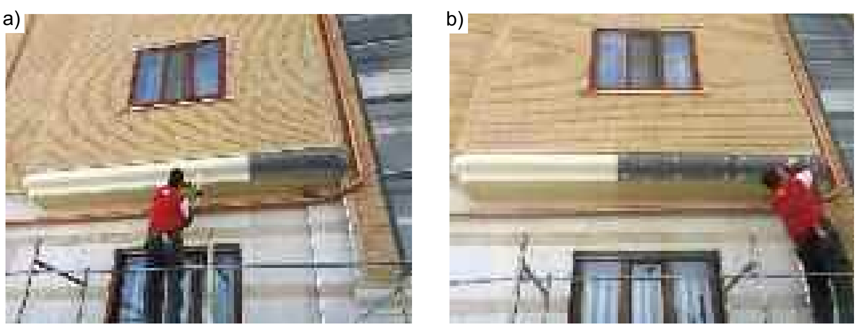
a) b)


Photo 4. Application of an aerogel-enhanced blanket for thermal insulation of a residential building in Troia (Italy): a) the application is done first with glue (a silicone weather barrier sealant); b) then with plastic fasteners
Fot. 4. Zastosowanie mat wzbogaconych aerożelem do ocieplania budynku mieszkalnego w Troia (Włochy); a) najpierw maty mocowane są za pomocą kleju (silikonowa bariera ochronna przed wpływami środowiska zewnętrznego; b) następnie przy użyciu łączników z tworzywa sztucznego

-enhanced products for building opaque systems. An overview of systems, also including products available on the market, has been done with the intent of providing an updated review of current state of the art and possible use of aerogel-enhanced products. Meanwhile, research conducted in both research centers and private companies is proposing new aerogel-enhanced products. For example, in Europe, international research projects have been financed within the Horizon 2020 scheme, to look at new formulations of aerogel-enhanced systems, by specifically focusing on the long term performance of new products, their mechanical strength and thermal conductivity. Moving forward, the following three aspects seem to represent the most valuable research challenges:

- further development of aerogel-enhanced thin layers, such as coatings and paints, is needed to broad the possibilities of using aerogel in building envelopes almost everywhere in order to improve thermal efficiency in existing buildings and new constructions. In this regard, water based paints and pastes with aerogel have recently been proposed, but still, limited knowledge has been disseminated about them;
- lowering the price for example by looking at the potentialities of other than supercritical drying processes remains critical to guarantee more competitive advantages in adopting aerogel-enhanced products;
- finally, the adoption of new aerogel-enhanced products will need to be carefully monitored to further verify their long-term performance and provide the building stakeholders all the needed insurances about the resilience of these innovative building materials.

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