# HYGROTHERMAL ANALYSIS AND PREDICTION OF LONG-TERM THERMAL PERFORMANCE OF AEROGEL-ENHANCED SUPERINSULATION PRODUCTS

By

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# Abstract

## Hygrothermal Analysis And Prediction Of Long-term Performance of Aerogel-enhanced Superinsulation Products

**Master of Applied Science 2017** 

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Aerogel-enhanced insulating materials provide significantly higher thermal resistance per unit of thickness compared to conventional insulating materials. These superinsulation materials are relatively new in the construction industry, and their thermal properties under different hygric conditions and their durability are still unknown. In this study, the main characteristics of a variety of aerogel-based materials under different climatic conditions were studied. Furthermore, the samples underwent accelerated aging tests, and the impact of aging on the thermal performance of aerogel-based products was investigated.

The results showed that the thermal properties of aerogel-based products are affected by moisture content and their thermal resistance degraded under extreme humidity conditions. The analysis of the aging effects showed that aerogel-based products would maintain their superior thermal performance over time. The average increase in the thermal conductivity (compared to the pristine condition) was below 10% after the equivalent of twenty years of aging under various climatic factors.

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# **1. Introduction**

Today, our mother earth is facing numerous irreversible environmental impacts which are primarily caused by greenhouse gasses (GHGs). Scientific evidence indicates that climatic changes are leading in raising the sea level, an increase in the intensity and frequency of extreme weathers, food and water shortage, disease outbreaks and deforestation (UNEP, 2009). GHGs are mainly generated by human activities such as fossil fuel use and industrial processes (National Academy of Science, 2011). Statistics show that the buildings are the largest energy consumers and are responsible for more than 30% of the total GHG emissions, both in the developed and developing countries (Baetens, Jelle, & Gustavsen, 2011; Soares et al., 2017; UNEP, 2009). GHGs from buildings are primarily produced through consuming fossil fuel based energies such as gas or electricity. Aside from GHG concerns, limited fossil fuel reserves and increasing energy costs all around the world call attention to immediate energy conservation solutions (Thapliyal & Singh, 2014).

To reduce energy consumption in buildings, various measures and methods have been implemented, while numerous technical and economical methods are under study. In particular, reducing the energy loss through heat transfer by conduction through the building envelope is typically recognized as the most effective way to reduce the building thermal loads. Therefore, proper insulation of the building envelope to achieve higher thermal resistance has been targeted as one effective strategy to lower the heating and cooling loads and consequently decrease energy consumption of the building. Apart from energy saving and reduction in CO<sub>2</sub> emissions, high-performance building life. However, to obtain desired thermal resistance for sustainable development, thicker layers of conventional insulating materials are required which consequently leads to heavier constructions and complex building details as well as occupying living space (Koebel, Rigacci, & Achard, 2012; Lyons, 2007).

In this regard, the development and utilization of new high-performance insulating materials with better thermal properties, such as aerogel-based products, is a crucial need for the insulation market.

#### 1.1.Background

Aerogel which is also known as frozen-smoke "is a synthetic porous ultralight material derived from a gel, in which the liquid component of the gel has been replaced with a gas" (Macan, 2011). Aerogel was synthesized for the first time in the early 1930s by Dr. Samuel Stephens Kistler (Kistler, 1931). There is an intimate link between aerogels and thermal insulations. Aerogel synthesis and implementation have undergone extensive improvement in the early eighties and during the nineties (Koebel et al., 2012). Aerogel has been employed in different sectors for a wide range of applications including buildings, automotive, aerospace, electronics, clothing, etc. (Cuce, Cuce, Wood, & Riffat, 2014b). Silica aerogel has a high potential to be used for building construction applications considering its low thermal conductivity which has been reported to be 0.013 (W/m·K) (Aspen Aerogels Insulation, 2015). These high-performance insulations are primarily used where not much space is available while high thermal resistance is desired (Karim Ghazi Wakili et al., 2015; Straube, 2012; Thapliyal & Singh, 2014).

Also, it should be considered that for a target R-value the required thickness of aerogel-based insulations is significantly less than conventional insulations. For instance, the required thickness of aerogel blanket to achieve  $RSI = 2.1 \text{ m}^2$ .K/W is 1.2 cm, which is approximately three times of the required thickness (3.5 cm) for fiberglass batt insulation (Shukla, Fallahi, & Kosny, 2014). In retrofit projects which usually face limited space utilization of wall insulations such as aerogel-based materials with minimal occupying space is of great importance. Furthermore, application of compact, high-performance insulations such as aerogel-based products required minimum interior rearrangement in retrofit related tasks, which reduces restoration costs (Shukla et al., 2014).

Many efforts are being carried out to develop new products based on aerogels, and many products have emerged in the market. Currently, opaque and translucent aerogel insulating materials are commercially available for insulating window glazing systems and the building envelope(Cuce et al., 2014b). Opaque aerogel panels and blankets have been developed as insulation layers for building envelope, and aerogel-glazing windows are developed thanks to aerogels' high optical transparency. Also, some studies employed granular aerogels to develop aerogel-based renders, such as Aerogel Incorporated Plaster (AIP), Aerogel Incorporated Mortar

(AIM), and Aerogel Incorporated Concrete (AIC) to achieve low density and low thermal conductivity.

The global market share of aerogels was reported to be USD 352.6 million in 2014; quadrupled to USD 83 million in 2008. Growing demand for superinsulation products (materials with thermal conductivity <0.02 W/m·K) is expected to drive demand for aerogel over the next few years. The aerogel market share is expected to reach USD 1.92 billion by 2022 (Grand View Research, 2016).

The low thermal conductivity was the key property for the aerogel-enhanced materials similar to any other high-performance thermal insulation materials such as vacuum insulation panels (VIP), gas-filled panels, gas insulation materials, nano-insulation materials and dynamic materials (Baetens et al., 2010, 2011; Jelle, 2012).

The long-term performance of any newly developed materials or solutions need to be investigated, and extensive testing is required to check their ability to withstand aging with the satisfactory durability of several crucial properties. Conducting accelerated climate aging studies will be of vital importance for materials science and engineering advances during development, characterization, and testing of these new materials and solutions, and before determining its potential in building applications. These advances will not represent real progress in materials science unless a satisfactory performance concerning climate aging durability has been demonstrated. Aerogel-based products, as new materials and solutions for buildings, must fulfill the requirements of a building envelope to deal with the different climate exposure factors, i.e., air, humidity, UV, and heat. Also, various physical aspects of them like heat and moisture transport need to be clarified.

# **1.2.** Objectives and research questions

Although aerogel-based products show remarkable characteristics at standard laboratory conditions (50% RH and 23.8 $^{\circ}$ C) compared to traditional thermal insulation materials, there are still work remaining to be done to understand their thermal performance under various climatic

conditions and over time. Desirable performance under different climatic conditions and during the anticipated service life must be proven to gain and maintain the widespread application.

It is important to choose high performance robust and durable materials or materials with appropriate protection. Failure in the material may cause failure in building components, increase need of maintenance, and may cause building damages. Some products such as polyisocyanurate and polystyrene foams are reported to have superior thermal performance, while the advertised value refers to standard laboratory condition, and they perform worse than batt insulation in extreme low/high temperatures. When superinsulations are targeted in a building, and the owner has spent much more money aiming high performance, the material should offer superior qualities on paper and in use condition under different conditions and over time. Therefore, it is important to select building products which have proven and properly documented adequate and satisfactory performance under various conditions and in long-term.

Aerogel-based products are considered among high-performance thermal insulation materials and have a high potential to occupy a dominant place in the building insulation market. Investigating the influence of temperature and moisture on the thermal properties of the aerogelenhanced products would give us a better understanding of how aerogel-based products would perform under various climatic conditions and identify the need for protection systems. Also, aging aerogel-enhanced products would allow for a better understanding of how these newly developed insulations would perform in 20-25 years from now by evaluating their thermal performance. The aging results will either help to approve their durability and to specify the possible protection methods or will expose the weak points which will require modifications in the materials.

The following research questions will be addressed in this study:

- How does the thermal performance of aerogel-based products is affected by various hygric conditions?
- How do the aerogel-based products perform in terms of thermal conductivity after accelerated climatic aging?
- Which climatic aging factor has the greatest impact on the thermal performance of aerogel-based products?

# 2. Literature review

## 2.1.Synthesis of silica aerogels

Aerogels were synthesized for the first time in the early 1930s by Dr. Kistler [5,6] and have been in constant development ever since. Although aerogels are initially made from gel, they are rigid and dry materials and do not resemble a gel in their physical properties (Tewari, Hunt, & Lofftus, 1985). The produced gel in the first step has a spongy structure which is filled with liquid; then special drying techniques are applied to replace the liquid with air while maintaining the network structure of the gel (Nicola & Schubert, 1998). Different type of aerogels can be prepared using alumina, chromium, tin oxide, carbon, and silica; however, silica aerogel is the most common commercially available product, as its preparation is comparatively easier and more reliable (Thapliyal & Singh, 2014); for this reason, the discussion of chemical synthesis method and further studies in this research has been limited to this class of aerogels.

Silica aerogels are synthesized by low-temperature sol-gel chemistry. Sol-gel materials are metastable solids that are formed in kinetically controlled reactions from molecular precursors, which constitute the building blocks for the later materials. Sol is a stable suspension of nanoparticles in a liquid. The gel is a porous, three-dimensionally continuous solid network (Schubert, 2015).

The main chemical compounds to produce silica aerogels are silicon alkoxides. The synthesis of silica aerogel as shown in Fig. 2-1 consists of three main steps: gel preparation, aging of the gel, and drying the gel. The first step consists of hydrolyzing and condensing alkoxides. Afterward, repeated steps remove the alcosol to form aerogels by using methods which permit to preserve the porous texture of the wet phase (Baetens et al., 2011).

Equation 2-1 represents the simplified production reaction of the most common silica aerogel for insulation purposes (Baetens et al., 2011):



Figure 2-1. General scheme for preparing aerogels by  $sol \pm gel$  processing.

The production of aerogels always involves the following three general steps. However, some other compounds might be added to the production reactions; e.g., aerogels can be reinforced with some mechanically stronger material, such as glass fiber, mineral fiber, and carbon fiber. Also, they can be cross-linked with polymers. Although by adding additional compounds the mechanical strength of aerogels would increase, on the other hand, their thermal resistance decreases to some degree (Cinzia Buratti, Moretti, & Belloni, 2016).

#### 2.1.1. Sol-Gel preparation

In the first step, the gel is prepared by a sol-gel process which is a method to produce solid materials, the alcogel, from nanoparticles (Cuce et al., 2014b). In this process, the solid components of the gel are dissolved in liquid agglomerate, the alcosol, and form a uniform three-dimensional network throughout the solution. The solution acts as the precursor that leads to an integrated product structure. Gels are classified according to the solution used: hydrogel for

water, alcogel for alcohol and aerogel for air (Shukla et al., 2014). The sol becomes a gel when the nanoparticles dispersed in it stick together and form a continuous three-dimensional structure throughout the liquid. Generally, alkoxysilanes such as tetraethoxysilane or tetraethylsilicate TEOS and tetramethoxysilane TMOS and Polyethoxydisiloxane are the most common sources of silicon (Table 2-1), known as precursors, however, some inexpensive alternatives such as oil shale ash, rice husk ash or fly ash have been explored, recently (Koebel et al., 2012).

| Constituent          | Chemical formula                         | Abbreviation |
|----------------------|--|--------------|
| Tetraethoxysilane    | Si (OCH <sub>3</sub> ) <sub>4</sub>      | TMOS         |
| Tetraethoxysilane    | Si(OC2H <sub>5</sub> ) <sub>4</sub>      | TEOS         |
| Polyethoxydisiloxane | SiOn(OC2H <sub>5</sub> ) <sub>4-2n</sub> | PEDS-Px      |

Table 2-1. Main precursors used to synthesize silica aerogels.

#### 2.1.2. Gel Ageing

The second step is the aging process where the fragile gel obtained in step 1, is aged in its mother solution to become stiffer and stronger. Sufficient time must be given to improving the mechanical and permeability properties of the gel network. In this phase, a relatively stronger porous solid is created, where the solvent is trapped inside the pores (Rao & Bhagat, 2004).

#### 2.1.3. Gel Drying

The final and the most critical step is the drying process where the liquid inside the gel network is replaced by air. Due to the strong surface tension forces between the solid part of the pore and the inner liquid, drying is very challenging, because cracking and shrinkage of the gel network might occur due to capillary forces (Gurav, Jung, Park, Kang, & Nadargi, 2010b). Supercritical drying, ambient pressure drying, and freeze drying are the three common implemented drying processes (Gurav et al., 2010b).

Supercritical drying is the first and most conventional drying method for aerogels. It is done above a critical point to eliminate the capillary forces which may cause shrinkage and deformation of the gel rigid body. Supercritical drying is performed either at high temperature or low temperature, based on the solvent; however, being above the critical pressure is a required factor. In supercritical drying, the trapped solvent can evaporate freely without applying any tension to the solid structure of the gel (Gurav et al., 2010b). High-temperature supercritical drying minimizes the deformation of the gel and is the most appropriate approach. High cost, process discontinuity, and safety issues due to high-temperature and high-pressure requirements are the major limitations of supercritical drying method (Gurav, Jung, Park, Kang, & Nadargi, 2010a; Kirkbir, Murata, Meyers, & Chaudhuri, 1998).

Due to the certain limitations of the supercritical drying, Brinker (1991) introduced a more convenient technique called ambient pressure drying. In this technique, the chemical structure of the wet gel is modified through replacement of hydrophobic functional groups with a hydroxyl group (Gurav et al., 2010b). The drying process in this approach is performed at ambient pressure; as a result, this method is much safer and less expensive. When wet gels are dried under ambient temperature and pressure, the resulting materials have higher density and are referred to as "xerogels" (Esquivias, Pinero, Morales Florez, & Rosa Fox, 2011).

Another option for drying the aerogel is freeze drying in which the liquid within the gel network is frozen, and then the frozen liquid is sublimated in a vacuum (Mathieu et al., 1997). The drawback of this technique is the long aging period, and also the solvent must have unique features such as minimal expansion coefficient and high sublimation pressure (Cuce et al., 2014b).

### 2.2. Physical properties of silica aerogels

The unique cross-linked internal structure of SiO<sub>2</sub> chains with plenty air-filled pores lead to outstanding properties of silica aerogels. Silica aerogels have very low thermal conductivity (0.01-0.02 W/m·K), low density (~100 Kg/m<sup>3</sup>), high porosity (~95%), high surface area (600-1000 m<sup>2</sup>/g), low refractive index, and low dielectric constant. Also, silica is non-flammable, and silica aerogels are amorphous (Yoldas, Annen, & Bostaph, 2000). Main properties of silica

aerogels have been summarized in Table 2-2 (Riffat & Qiu, 2012; Schmidt & Schwertfeger, 1998).

| Property  | Value                           |
|---|---------------------------------|
| Primary particle diameter                       | 2-4 nm                          |
| Pore diameter span                              | 1-100 nm                        |
| Average pore diameter                           | 20- 40 nm                       |
| Porosity  | 85-99.9% (typical ~95%)         |
| Internal surface area                           | 600-1000 m <sup>2</sup>         |
| Bulk density                                    | 3-350 kg/m <sup>3</sup>         |
| Volume shrinkage                                | <10%                            |
| Coefficient of linear expansion                 | 2.0-4.0 × 10 -6 1/°C            |
| Compressive strength                            | 300 kPa                         |
| Tensile strength                                | 16 kPa                          |
| Thermal conductivity                            | 0.01- 0.02 W/m·K                |
| Normal-hemispherical transmittance of radiation | 0.80- 0.95                      |
| Longitudinal sound speed                        | 100-300 m/s                     |
| Thermal tolerance temperature                   | 500 °C (m.p <sup>1</sup> >1200) |

Table 2-2. Physical properties of silica aerogels

Jelle (Jelle, 2011) reviewed properties, advantages, and disadvantages of conventional, state-ofthe-art and future building thermal insulations. A comprehensive review of different aspects such as thermal conductivity, site adaptability, the cutability, mechanical strength, fire protection, fume emission during fire, robustness, durability, costs and environmental impact for various

<sup>&</sup>lt;sup>1</sup> Melting point

thermal insulating materials have been studied by Bjørn Petter Jelle (Jelle, 2011). This study has shown that, currently, none of the available thermal insulations can fulfill all the requirements. Therefore, selecting the best material among all available options, improving existing insulating material, and discovering and developing novel high-performance thermal insulating materials such as Nano Insulating materials (NIM) and Dynamic Insulating Materials (DIM), is crucial. Based on recent developments in the field, aerogels offer the most promising non-evacuated thermal insulating materials (Baetens et al., 2011; Hostler, Abramson, Gawryla, Bandi, & Schiraldi, 2009; Jelle, 2011). Aerogels can be produced as opaque, translucent or transparent; which increase the potential widespread utilization of aerogel-based products for a wide range of building applications. Therefore, besides high potential of silica aerogels for opaque insulations, they can be used for transparent insulating components and daylighting services, if they can be mechanically reinforced.

The compressive strength, tensile strength, and elastic modulus of silica aerogels are very low; these properties are largely depended on the network connectivity and density of aerogels. To improve the mechanical strength of silica aerogels, many synthesis alternatives are investigated. The most popular approach is hybridization when mixing a silicon alkoxide with hybrid precursors such as polydimethyl siloxane (STODOLNA, JACOB, LEROUX, & BURCHELL, 2012).

The high cost of aerogels is its primary limitation to be among common thermal insulations and targeting mass productions (Jelle, 2011).

# 2.3. Thermal conductivity

One of the main characteristics of silica aerogels is their very low thermal conductivity, typically  $\sim 0.015 \text{ W/m} \cdot \text{K}$  at ambient temperature, pressure, and relative humidity (Yoldas et al., 2000). This value is less than that of the still air under the same condition ( $\sim 0.025 \text{ W/m} \cdot \text{K}$ ); therefore, silica aerogels are among the best known thermal insulating materials (Nicola & Schubert, 1998; Riffat & Qiu, 2012; Yoldas et al., 2000).

The thermal conductivity values ( $\lambda$ ) of conventional thermal insulating materials, as summarized in table 2-3, are in the range of 0.03– 0.05 (W/m·K) (Aegerter, Michel A, Leventis, Nicholas, Koebel, 2011). Aerogel-enhanced materials with a thermal conductivity of less than 0.02 W/m·K are considered as superinsulation materials (Cuce et al., 2014b).

| Insulation Product             | Chemical composition                                 | $\lambda (W/m \cdot K)$ |
|--------------------------------|--|-------------------------|
| Mineral wool                   | Inorganic oxides                                     | 0.034-0.045             |
| Glass wool                     | Silicon dioxide                                      | 0.031-0.043             |
| Foam glass                     | Silicon dioxide                                      | 0.038-0.050             |
| Expanded polystyrene (EPS)     | Polymer foam   | 0.029-0.055             |
| Extruded polystyrene (XPS)     | Polymer foam   | 0.029-0.048             |
| Phenolic resin foam            | Polymer foam   | 0.021-0.025             |
| Polyurethane foam              | Polymer foam   | 0.020-0.029             |
| Silica aerogels                | SiO <sub>2</sub> based aerogel                       | 0.012-0.020             |
| Organic aerogels               | Aerogels derived from organic compounds              | 0.012-0.020             |
| Vacuum insulation panels (VIP) | Silica core sealed and evacuated laminate foil       | 0.003-0.011             |
| Vacuum glazing (VG)            | Double glazing unit with evacuated space and pillars | 0.003-0.008             |

Table 2-3. Overview of thermal insulating materials

The superior thermal properties of aerogel are attributed to the presence of nanoscale pores and minimal solid volume fraction in the aerogel composition (Shukla et al., 2014). The thermal conductivity of a material ( $\lambda_T$ ) is determined by four factors as stated in equation 2-2:

$$\lambda_T = \lambda_S + \lambda_G + \lambda_C + \lambda_R \tag{2-2}$$

where  $\lambda_s$  is the conduction through the solid network,  $\lambda_G$  is the conduction through the pore medium, the entrapped gas,  $\lambda_C$  is the convection transport by the pore medium, the gas

component, and  $\lambda_R$  is the radiation transport from the solid surface through the pore fluid and from the solid through the solid network or bulk.

Aerogel is a porous non-crystalline solid material with a pore diameter of 10 to 100 nm (Shukla et al., 2014). Since heat follows a random walk across neighbor oscillators, considering the dimensions of the pores in aerogel, the intrinsic thermal conductivity of aerogel is one to three orders of magnitude less than crystalline materials. Fricke et al. (Frick, Hummer, Mprper, & Scheuerpflug, 1989) formulated the thermal conductivity of a porous material as:

$$\lambda_s = \left(\frac{\rho_s v_s}{\rho_0 v_0}\right) \lambda_0 \tag{2-3}$$

where  $\lambda o$  is the thermal conductivity of fully dense solid,  $\rho s$  and  $\rho o$  are the densities of porous material and fully dense solid,  $v_s$  and  $v_o$  are the speed of sound in the porous material and fully dense solid.

The high porosity of aerogel leads to lower the density and speed of sound in the aerogel relatively to the fully dense material. In fact, the solid conduction of aerogel ( $\lambda_S$ ) is 100 to 1000 times lower than conventional solid materials (Scheuerpflug, Morper, & Neubert, 1991). Also, the small pore size of the aerogel particles (10 to 100 nm) prevents the Brownian motion of the gas molecules, and as a result, the convective heat transport ( $\lambda_C$ ) can be neglected (Shukla et al., 2014). The thermal conduction through the gas, ( $\lambda_G$ ) is also inversely proportional to the pore diameter. The pore sizes of air pockets in aerogels are about 20 nm, which is less than the mean free path of air molecules (~68 nm), that leads to virtually no gaseous conduction (Gao, Jelle, Gustavsen, & Jacobsen, 2014), however, the exact contribution of the gaseous phase to the thermal conductivity is complicated and the coupling effect, which depends on the structure of the aerogel and the gas pressure, must be considered (Ebert, 2011). Heat transfer through radiation ( $\lambda_R$ ) is minimized by the addition of opacifiers such as iron oxide or carbon black to the aerogel network during the synthesis to ensure that all the energy in the infrared range is absorbed or scattered, and the heat transfer through radiation is minimized (Shukla et al., 2014).

## **2.4.Acoustic properties**

Silica aerogels are indeed superb acoustic insulators (Cuce et al., 2014b; Forest, Gibiat, & Woignier, 1998; Gibiat, Lefeuvre, Woignier, Pelous, & Phalippou, 1995). The acoustic properties of silica aerogels are closely related to their texture, structure, and density. The acoustic propagation in aerogels also depends on the interstitial gas nature and pressure. The propagation of an acoustic wave is weakened through amplitude and velocity; the wave energy is significantly transferred from the gas to the solid network of aerogel, over the entire thickness of aerogels (Conroy, Hosticka, Davis, & Norris, 1998). The longitudinal sound velocity in silica aerogels is typically 100 m/s (Gross & Fricke, 1992), which makes them suitable for applications in acoustic devices and components.

### **2.5.Embodied energy**

Regarding embodied energy data, the embodied energy of aerogel has estimated around 53 MJ/kg, which is quite favorable in comparison with conventional insulating materials (Table 2-4). Cuce et al. (Cuce et al., 2014b) have compared the embodied energy of aerogel with several conventional materials such as EPS, XPS, glass wool, foam glass, and cork, where the same overall thermal resistance is considered. The result has indicated that after glass wool, aerogel has the lowest embodied energy among all conventional insulations (Cuce et al., 2014b).

| Insulation material    | Density $(kg/m^3)$ | Embodied energy (MI/kg)  |
|------------------------|--------------------|--------------------------|
|                        | Density (Kg/III )  | Embodied energy (Wij/Kg) |
| Cork                   | 120                | 26.3                     |
| Foam glass             | 110                | 27.1                     |
| Glass wool             | 40                 | 39.4                     |
| Aerogel                | 100                | 53.0                     |
| XPS                    | 30                 | 67.2                     |
| EPS                    | 30                 | 100.2                    |
| polyurethane (PUR/PIR) | 30                 | 101.5                    |
|                        |                    |                          |

Table 2-4. Embodied energy of the insulating materials.

## 2.6. Health and safety issue

Aerogel insulations are composed of amorphous silica (non-crystalline), and the IARC<sup>2</sup> classifies it as non-carcinogenicity to human (Aspen Aerogels Insulation, 2011; Warheit, 2001). Although the product is not classified as a dangerous material, however, it gives off some powder (dust) when handled, as the produced dust is hydrophobic, it may cause drying sensation and mechanical irritation of eye or skin (Warheit, 2001). Aspen Aerogels Inc. has provided a report on potential aerogel related health issues along with exposure controls and personal protection guidelines (Aspen Aerogels Insulation, 2011). Aerogels are noncombustible due to their extremely high melting point (1200°C) and their non-organic structure.

# 2.7. Mechanical properties

Pure silica aerogels have a relatively high compressive strength (~300 KPa), while they have a very low tensile strength (~16 KPa) and are very fragile (Baetens et al., 2011). For this reason, whenever the translucent optical properties of the aerogels are not important, they are reinforced by other materials. To strengthen the tensile properties of the silica aerogels, they are reinforced with a mechanically stronger material such as fiber matrix (glass, mineral or carbon fibers) or are mixed in rendering materials such as mortars or plasters (Barbero, Dutto, Ferrua, & Pereno, 2014; Cinzia Buratti et al., 2016; Cinzia Buratti, Moretti, Belloni, & Agosti, 2014; Hoseini, McCague, Andisheh-Tadbir, & Bahrami, 2016; Ibrahim, Biwole, Achard, Wurtz, & Ansart, 2015).

Another approach to providing mechanical support for aerogels is through the construction of aerogel-filled truss-core sandwich panels to strengthen the tensile properties of the aerogel while minimally affect its thermal performance with a lightweight structure (Chen et al., 2014).

Hoseini et al. (Hoseini, Malekian, & Bahrami, 2016) conducted research to assess the effect of compressive loads on the thermal resistance and deformation of aerogel-enhanced blankets. Commercial aerogel blankets (Cryogel®Z and ThermalWrapTM) were subjected to compressive

<sup>&</sup>lt;sup>2</sup> International Agency for Research on Cancer

loads up to 8 kPa and several compression-decompression cyclic loads (0.7-4.5 kPa). This study showed that compression has no significant impact on thermal resistance of the aerogel blankets. The greatest compression that was applied in this study was 20% which resulted in 10% degradation of the thermal resistance.

# 2.8. Applications and cost-effectiveness

In general, the advantage of utilization of superinsulation products is their energy and space saving benefits; they can provide a higher thermal resistance with a thinner insulation layer, or, a much better insulation performance for the same thickness of insulation. This particular excellence is in contrast with the significantly higher cost of superinsulation products, which result in concise utilization of them (Koebel et al., 2012). However, application of superinsulation materials is justified economically or environmentally in some industries. For instance, in the case of off-shore oil and gas pipeline insulation, when the pipes are insulated by aerogel-based products, their diameters are significantly smaller which reduce the assembly weight. Thereby, ships can carry remarkably more pipeline in each trip, the number of trips is cutting down, and the overall cost would be significantly lower. This was a model example of the opportunity for the application of high-performance high-cost products (Koebel et al., 2012).

Following applications of aerogel-based insulations are enumerated:

- Off-shore oil and gas
- Aeronautics/aerospace
- Building insulation
- High-temperature insulation
- Cryogenic applications
- Appliances and apparel

Despite superior insulation properties of aerogel, its high cost is the main barrier for practical application of aerogel in construction. Aerogel synthesis process involves expensive precursors, the sources of silicon, and chemicals; also, the supercritical and complex drying of the gel makes its production more expensive than conventional materials. Shukla et al. (Shukla et al., 2014)

have proposed different approaches to lower the aerogel cost including using less expensive raw materials such as rice husk, clay and oil shale ash, application of low vapor pressure solvents and using atmospheric pressure drying. The cost-effectiveness of aerogel as an insulator for wall retrofit has been studied by Shukla et al. (Shukla et al., 2014).

The cost of a wall retrofit with aerogel blanket installation on the interior side of the wall on top of existing gypsum board has been estimated by Shukla et al. (Shukla et al., 2014). To achieve practical and cost effective approaches for retrofit of an interior wall, the R-values of 0.7, 1.14 and 2.11 m<sup>2</sup>.K/W were targeted. Aerogel blankets with 10 mm thickness each with a thermal resistance of 0.7 m<sup>2</sup>.K/W was used. The cost effectiveness of the proposed approach using aerogel was assessed by targeting a desired R-value and comparison aerogel with a thermally equivalent thickness of conventional interior insulations (fiberglass batt 1 and 2), and for conventional exterior insulations (EPS and XPS). The commercially available batt insulation has a minimum thickness of 88.9 mm (3.5 inches) however Shukla et al. have also evaluated 38.1mm (1.5 inches) for comparison.

The aerogel retrofit approach is very fast and convenient technique that requires minimal alteration of the interior walls requiring readjustment of electric and heating outlets. For conventional internal insulation retrofit, though, in addition to readjustments mentioned above, additional tasks such as new internal frame build up (with the exception of fiberglass), rearrangements of fenestration are required which increase the overall cost of retrofit (Shukla et al., 2014).

Shukla et al. (Shukla et al., 2014) have addressed considering the value of the "saved space" with using much thinner aerogel blankets for the achievement of the target R-value. Shukla has justified the high cost of aerogel blankets with the minimum required retrofit tasks. Although the raw material cost of the aerogel blanket is higher than conventional insulations, the overall cost of aerogel blanket insulations might be comparable to that of both interior and exterior insulations, and the added cost of the materials is compensated significantly.

## 2.9. Aerogel-enhanced products

Several aerogel-based products have been developed as insulation materials for different envelope elements such as roofs, facades, and windows regarding their low thermal conductivity and optical transparency. Also, they are used as sound insulation and fire retardant (Cinzia Buratti et al., 2016).

Aerogel-enhanced superinsulation products can be categorized into the monolithic, granules and beads, and composite materials, based on the mixing procedure of aerogel into the final products (Koebel et al., 2012).

At the time being, the monolithic aerogel products are not commercially available in the market, because the synthesis of monolithic aerogels is time and cost intensive. Although this type of aerogels has high potential application in aerogel glazing owing to its very low thermal conductivity and good optical properties. Aerogel granules, blanket-type materials, and aerogel-enhanced renders are the commercially available products at present.

#### 2.9.1. Commercial aerogel-enhanced products

Today, almost all commercially available aerogel-enhanced products are exclusively based on silica aerogel. In 1940, the first commercial aerogel was produced by the Monsanto Chemical Corp., Everett, Massachusetts, USA., which was based on SiO<sub>2</sub> and was produced with a recipe like Kistler's original procedure (Koebel et al., 2012). The production line was stopped in the sixties and seventies but resumed in early eighties and the nineties. Afterward, various types of aerogels with the different application were produced such as silica aerogels for the agricultural purposes, aerogel paints, carbon aerogels for energy storage and conversion devices, etc. Aerogels can be employed to enhance the thermal resistance of materials for buildings and other industries. From 1890 aerogel-enhanced products were commercialized in a large-scale by the thermal insulation trades. North American industrials Cabot Corporation and Aspen Aerogels (Northborough, MA, US) are the main manufacturers in this field, which both manufacture silica-based aerogel products in the form of granular aerogels or flexible blankets. Nano Hi-Tech in China and EM-Power in Korea are the other sol-gel based superinsulation suppliers at a lower production volume (Koebel et al., 2012).

Aerogel-enhanced products can be categorized into the following classes based on the mixing procedure of the aerogel into the final product (Koebel et al., 2012):

- 1. Monolithic aerogel: larger pieces (>1 cm), homogeneous pieces of aerogels;
- 2. Divided materials: random monolithic pieces of aerogel beads (granules with less than 1 cm diameters and powders with less than 1 mm diameters);
- 3. Composite materials: homogeneous or heterogeneous aerogel-based materials which contain other additives. The additive can be incorporated either into the gel matrix (during aerogel synthesis) or more frequently, during a second separate phase or by a subsequent compounding.

Currently, the monolithic aerogel products are not commercially available in the market as their synthesis is very time/cost intensive (U Berardi, 2015a; Ihara, Jelle, Gao, & Gustavsen, 2015; Koebel et al., 2012). Aerogel granules, aerogel based blanket and boards, and aerogel-enhanced plasters are the commercially available products.

Further research and developments are proceeding worldwide for the development of aerogelenhanced insulating components and systems. Some of the aerogel-enhanced products for building insulation are discussed in the following sections.

#### 2.9.1.1. Aerogel blanket

As mentioned earlier, silica aerogel has extraordinary small pores (1-100 nm) which result in remarkable physical, thermal and acoustical properties; but on the other hand, it has low mechanical strength and stability to be used in any practical application (Aegerter, Michel A, Leventis, Nicholas, Koebel, 2011). In order to strengthen the tensile properties of the silica aerogels to be used as an insulating material, aerogel has been reinforced with some mechanically stronger material such as fiber matrix (glass, mineral or carbon fibers) (Aegerter, Michel A, Leventis, Nicholas, Koebel, 2011; Baetens et al., 2011).

When the fibers or fibrous matrix are added to the pre-gel mixture which contains the gel precursors, the resulting dried composite is the aerogel blanket (Aegerter, Michel A, Leventis, Nicholas, Koebel, 2011; Baetens et al., 2011). Aerogel blankets are flexible, resistance to crushing, and they can be cut, sewn and laminated. The use of aerogel blanket is new to the building industry, but it has been used from 1980 in industrial applications such as pipelines,

aerospace and defense systems, and cryogenics. (Koebel et al., 2012; Riffat & Qiu, 2012). The common applications of aerogel blankets in buildings are continuous thermal and acoustic insulation of the roof, floors, external walls, and balcony construction (Cinzia Buratti, Merli, & Moretti, 2017; Cuce et al., 2014b; Riffat & Qiu, 2012). Aerogel blankets are often considered in retrofitting projects or whenever space and weight constraints exist (Cuce & Cuce, 2016; Galliano, Ghazi Wakili, Stahl, Binder, & Daniotti, 2016; K. Ghazi Wakili, Binder, Zimmermann, & Tanner, 2014; Venkataraman et al., 2014). Aerogel blanket strips are also employed as the thermal bridge treatments for the edges of the windows and framing assemblies. Moreover, aerogel blankets are utilized for service insulation such as pipes and ductwork (Baetens et al., 2011; Cuce et al., 2014b). Aerogel enhanced blankets are known to be hydrophobic materials that repel liquid water while allowing vapor to pass through, which is a benefit for areas susceptible to mold and fungi growth (Koebel et al., 2012).

Several attempts have been made to develop panels and blankets composed of synthetic amorphous silica dioxide. "Spaceloft" (Fig. 2-2) developed by Aspen Aerogels, Inc. (Northborough, MA, US) is a flexible aerogel blanket. Spaceloft is available in thicknesses of 5mm and 10mm and has a thermal conductivity of 0.013 (W/m·K) at 0°C (Aspen Aerogels Insulation Co.), which is about 2–2.5 times lower than the thermal conductivity of the conventional thermal insulating materials (Cuce et al., 2014b). Figure 2-3 shows the comparison of thermal conductivity of aerogel blanket with some conventional insulating materials. "Proloft", thermal barrier strips, is another commercially available aerogel blanket and is designed to provide thermal bridging protection in walls, roofs, floors, and door and window

framed (Advaned



insulation Inc., 2010).

Figure 2-2. Spaceloft an example of aerogel blanket (Aspen Aerogels Insulation Co.).



Figure 2-3. Comparison of aerogel blanket with conventional insulating materials.

#### 2.9.1.2. Aerogel-based renders

Researchers aim to improve the insulation performance of the building coatings such as for render and concrete. Utilization of lightweight aggregates such as pumice, diatomite, volcanic cinders, and perlite in the mixture in place of normal aggregates (i.e., sand and rocks) has been recognized as an effective solution to improve the thermal performance of the building renders (i.e., plaster and mortar). The advantage of these renderings is the better thermal insulation properties when compared to conventional solutions, due to a large amount of air void in the matrix. Aerogel has an extremely low density (3–100 kg/m3 depending on the porosity) and low thermal conductivity (0.003–0.02 W/m K), also it has a good fire and acoustic resistances. Owing to these extraordinary properties, aerogel was recognized as a perfect aggregate for lightweight and thermal insulating plaster, mortar and lightweight concrete (Cinzia Buratti et al., 2016).

Granular aerogel can be employed as an additive to increase the thermal resistance of a variety of building renders such as plasters, concrete, and coatings (Cinzia Buratti et al., 2014). Plaster and

coatings are considered among finishing layer materials; thereby they are non-structural components of the buildings and can be composed of lightweight materials. Development of new high-performance materials in the field of render composites can be achieved by utilization of Nano Insulation Materials (NIMs). Aerogel-enhanced renders such as Aerogel Incorporated Plaster (AIP), Aerogel Incorporated Mortar (AIM), and Aerogel Incorporated Concrete (AIC) are typical composites of aerogels where the granular aerogels are employed as an additive to increase their thermal resistance (Cinzia Buratti et al., 2016, 2014; Ibrahim et al., 2015; Rao & Bhagat, 2004). Aerogel-based renders are known as one of the most promising solutions to improve the thermal performance as well as fire and acoustic resistance of the renders. Aerogel-enhanced renders would reduce energy losses through the building envelope with the least ecological impact, owing to the low embodied energy of aerogel.

Thermal insulation plasters/mortars are being used to increase the thermal performance of the building assemblies, especially for retrofitting of old and historical buildings. Aerogel-based renders are mainly considered when the thermal insulation of buildings would improve with a small thickness increase of the wall (Cinzia Buratti et al., 2014). However, by adding an embedded layer of reinforcing mesh, thicker layers of plaster can be applied in layers. The minimum thickness of each layer is reported 30 mm, and the maximum is 60 mm; the overall thickness of the layers can reach to 150 mm (Fixit AG, 2013; High & Insulating, 2016).

Aerogel-based plasters are easily producible at construction sites; however, several application post-application treatments must be considered. Insulating plaster should be applied to the surface, which has been previously prepared, with a machine specially equipped for use with insulating plaster. If the required thickness demands an application of more than one layer, then the surface of each layer should be well roughened before it hardens. After aerogel-based plasterwork is applied indoors, adequate ventilation must be provided in the room. Industrial dehumidifiers are not recommended for drying this type of plaster as they may cause cracking of the insulating plaster layer. Measures should be taken to protect the newly applied insulating plaster under extreme conditions such as elevated temperatures, or when surfaces are directly exposed to the sunshine or the wind, (e.g., pre-wetting the substrate, providing shade, keeping the surfaces moist, and protecting them from air currents and driving rain, etc.). A leveling layer

and a reinforcing layer must be applied to the surface of hardened aerogel-enhanced plaster (Fixit AG, 2013; High & Insulating, 2016).

Insulating plasters are very useful for situations where rigid insulations are not practical such as uneven surfaces, wall cavities, and restoration of historic buildings. Several advantages have been proposed for utilization of the insulation renders over insulation boards. The board type insulations require a plane surface, gluing, adjustment, fastening and precise dimensioning. In contrast, rendering has the benefit of having simple implementation, flexible with respect to unevenness and creating a continuous thermal insulation layer by filling all the gaps and joints; moreover, the very low density of aerogel-based renders (about 200 Kg/m3) allows applying thick layers (Stahl, Brunner, Zimmermann, & Ghazi Wakili, 2012).

Numerous attempts have been made to date to introduce new aerogel-based renders with better thermal and mechanical properties. Achard et al. (Achard et al., 2011) developed an insulating aerogel-based render with mineral and organic binders which showed a thermal conductivity of 0.0268 W/m·K with a density of 156 kg/m<sup>3</sup>. In another study, Stahl et al. (Stahl et al., 2012) developed an insulating plaster based on granular silica aerogel (with different concentration varying from 60 to 90 vol.%) with purely mineral and cement free plaster, attaining the thermal conductivity of 0.025 W/m·K with a density of 200 kg/m<sup>3</sup>. Recently, a pre-manufactured aerogel-based plaster was developed at the Swiss federal institute of material science and technology Empa together with the Fixit group. This render, commercialized as FIXIT 222, advertised to have more than 50% silica aerogel granules in volume which results in the thermal conductivity of 0.028 W/m·K (Fixit AG, 2013). Production of aerogel-based plasters is a significant improvement in the thermal conductivity of conventional insulating plasters, which have a thermal conductivity between 0.06 and 0.15 W/m·K (Cinzia Buratti et al., 2016). Table 2-5 shows the thermal conductivity comparison of commercialized FIXIT 222 (aerogel-based plaster) and conventional plasters (Barbero et al., 2014; Cinzia Buratti et al., 2016).

Owing to the hydrophobic nature of aerogel, the aerogel-enhanced plasters have the advantage of being water repellent, while being water vapor permeable and much more breathable than conventional plasters (Cinzia Buratti et al., 2016).

| Plaster type                      | Thermal conductivity range (W/m·K) |
|-----------------------------------|------------------------------------|
| Insulating cement-based plasters  | 0.055 - 0.111                      |
| Insulating lime-based plasters    | 0.06 - 0.2                         |
| Aerogel-based plaster (FIXIT 222) | 0.028                              |

While the application thickness of these aerogel-based products is much lower than conventional insulating plasters to obtain the same thermal resistance, their production cost is comparatively higher than traditional ones (Cinzia Buratti et al., 2016). The other concern about aerogel-based renders is their mechanical properties, which is still not sufficient and reinforcing mesh must be added (Maia, Ramos, De Freitas, & Sousa, 2015). Parexlanko (Parexlanko, 2016) the French mortar and plaster producer, together with Mines Paristech/Armines/CEP followed an approach to target satisfactory thermos-mechanical properties, instead of minimizing just the thermal conductivity by adding the highest volume fraction of granular hydrophobic silica aerogel. They used similar production method as traditional renders (i.e., cement based mortars with traditional projection techniques), as the result their product could achieve the thermal conductivity values close to 0.05 W/m.K with flexural strength larger than 0.5 MPa (Koebel et al., 2012).

#### **2.10.** Long-term performance

#### 2.10.1. General overview

Building insulations must fulfill thermal resistance of the building envelope during the lifetime of a building. Therefore, it is important to require satisfactory durability of these materials. Lack of durability results in large and increased costs caused by increased thermal loads of the envelope, energy loss, need for maintenance, extensive replacements of the building thermal insulations and any possible consequential building damages. Failure in the building thermal control may also lead to thermal bridge risk, condensation issue, mold and decay, and health hazard. Satisfactory durability against the climate strains has therefore direct influence on both safety aspects and economical throughout the lifetime of a building (Jelle, 2012). Therefore, it is important to select building materials which have proven and properly documented adequate and satisfactory long-term durability.

To effectively evaluate the aging effects, building materials should be subjected to long-term natural outdoor climate exposure. However, natural aging might be time-consuming. Alternatively, accelerated laboratory aging tests, in which the material is subjected to extreme conditions to speed up the normal aging processes have been proposed in research works (Cinzia Buratti, Moretti, Belloni, & Lascaro, 2010; Escobar & Meeker, 2007; Jelle, 2012; Jelle, Nilsen, Hovde, & Gustavsen, 2008). Accelerated aging tests have some limitations; they may alter the degradation mechanism, which results in unreal decays or misleading results from comparable real environment condition exposure (Ihara, Jelle, et al., 2015). The accelerated test design must be specific for each material and may be different depending on the corresponding climate condition of exposure.

The following climate strains have been defined as aging factors for building materials (Jelle, 2012):

- Solar radiation; i.e., ultraviolet (UV), visible (VIS), and near-infrared (NIR) radiation;
- Ambient infrared (IR) heat radiation;
- Extreme temperatures;
- Temperature changes/cycles;
- Water; e.g., moisture, relative air humidity, rain (precipitation), and wind-driven rain;
- Physical strains; e.g., snow loads;
- Wind;
- Pollutions; e.g., gases, dirt, and dust;
- Microorganisms, e.g., mold and bird droppings;
- Oxygen.

The importance of each one of previous factors depends on the climate conditions as well as the actual building material and to its resistance versus climate exposure conditions. It is not possible to simulate all possible weathering stresses in a lab, and it might not be even necessary. As a result, test considering only heat, light, and moisture are often sufficient, unless the material is going to be used in a particular environment with some specific stresses (Jelle, 2012).
As mentioned, according to the previous studies, the most important weathering elements for non-metallic building materials are light (solar radiation quantity and quality), temperature (quantity and cycles), and water (quantity and phase) (Brancato & Staff, 1978; Ihara, Jelle, et al., 2015; Jelle, 2012; Singh & Coleman, 2007). These weathering factors were considered as aging factors for the ABPs, as briefly presented in following sections.

#### **2.10.1.1. Elevated temperature**

Elevated temperatures rapidly increase the kinetic reaction rates within the molecules of the materials, which might accelerate the chemical degradation processes (Jelle, 2012). A higher temperature causes higher reaction rate and can be used as a method for acceleration them. In fact, the time of the accelerated climate aging may be shortened by increasing temperature and the corresponding acceleration factor. However, exposing material samples to extremely high temperature, which would never be accomplished in natural outdoor climate conditions should be avoided. For this reason accelerated aging temperatures from 60°C to 70°C are often chosen for accelerated aging of building materials (Jelle, 2012).

#### 2.10.1.2. Freeze-thaw cycles

The volume of water expands by about 9% when it freezes, so that repeated freeze-thaw cycles may cause significant deterioration of certain building materials. Frost weathering due to water phase change has shown several issues in composite materials due to ice volume expansion and pressure increase. Therefore, testing the resistance of materials towards freeze-thaw cycles is extremely important especially in climates which experience a high number of freezing points during winters.

#### 2.10.1.3. Water, moisture, and humidity

Water in different forms. e.g., free water, precipitation, wind-driven rain, air relative humidity and water vapor, often plays a significant role in the degradation of building materials and components. The decay might be intensified through dissolution reactions, dilutions, mechanical degradation and erosion, freezing and thawing cycles and temperature gradients. On the other hand, also very low relative humidity might degrade the performance of hygroscopic building materials, for example, polymers require moisture to maintain their pliability or plasticity.

## 2.10.1.4. Solar radiation and photo-degradation

Solar radiation is one of the main climate exposure factors which affect the behavior of building materials and degrade their performance or appearance. Light might cause fading, peeling, cracking, embrittlement, delamination, and loss of tensile strength and thermal performance.

As shown in Fig. 2-4, the solar radiation is categorised to five regions: ultraviolet C (UVC) between 100 nm and 280 nm, it is mostly absorbed by the atmosphere and very little reaches to Earth's surface; ultraviolet B (UVB) between 280nm and 315 nm, also greatly absorbed by the atmosphere; ultraviolet A (UVA) between 315nm and 400 nm, which causes remarkable damage to DNA (Naylor & Farmer, 1995); visible range between 380nm and 780nm, which is the strongest output range of the Sun's total irradiance spectrum on the Earth's surface; and infrared range that lies between 780 nm to 1,000,000 nm and accounts for the significant part of the electromagnetic radiation. The infrared spectrum is also commonly divided into three regions: infrared-A (from 700nm to 1,400 nm), infrared B (from 1,400 nm) and infrared-C or



Figure 2-4. Solar irradiance spectrum above atmosphere and at surface. Extreme UV and X-rays are produced (at left of wavelength range shown) but comprise very small amounts of the Sun's total output power.

thermal radiation (from 3,000 nm to 1,000,000 nm) (Jelle, 2012).

The higher energy parts of the solar spectrum, i.e., the UV radiation and short wave VIS light, may break the chemical bonds of the building materials, especially the organic ones, and cause solar degradation which varies from discoloration to loss of mechanical integrity (Jelle, 2012). The photo degradation process may start when the single photon energy (E) of the solar radiation is larger than the chemical bond energy of the specific material (Jelle, 2012).

The choice of the light source to conduct accelerated aging tests in a laboratory is crucial since different lamps reproduce different spectrum of sunlight with various wavelengths so the lamp should be selected concerning the application and type of the material or product being tested. A common choice is to have the least changes respect to natural aging processes; for example, the metal halide global lamps simulate the solar radiation in the entire spectrum of sunlight, including ultraviolet, visible ranges, and infrared with enough accuracy (Ihara, Jelle, et al., 2015). The xenon arc also reproduces the full-spectrum sunlight. UV-A lamps simulate the effect of sunlight in the critical short-wave UV region. UV-B lamps produce short-wave UV, which is more severe than the UV at earth surface, resulting in faster degradation than UV-A lamps, but their short wavelength output, which is below the solar cut-off, can cause unrealistic results (Escobar & Meeker, 2007; Ihara, Jelle, et al., 2015; Wegger et al., 2011).

#### 2.10.2. Aging of aerogel

Aerogel-based products (ABPs) are increasingly spreading into the building insulation market with the promise to reduce the building energy demand with a minimal increase of the thickness of building envelopes. In fact, ABPs provide significantly higher thermal resistance per inch than conventional building insulating materials (Abdul Mujeebu, Ashraf, & Alsuwayigh, 2016; U Berardi, 2015b; C. Buratti & Moretti, 2012; Cuce et al., 2014b; Dowson, Grogan, Birks, Harrison, & Craig, 2012; Ibrahim et al., 2015; Ihara, Gao, Grynning, Jelle, & Gustavsen, 2015; Jelle, 2011; Riffat & Qiu, 2012). However, these super insulating materials are relatively new in the construction industry and their performance over an extended period of time must still be proven to support their widespread adoption (Cuce, Cuce, Wood, & Riffat, 2014a). In fact, only a few studies have looked at the long-term performance of aerogel granules over time.

Ihara et al. conducted research to assess the durability of aerogel granules against moisture and solar irradiation using accelerated aging tests (Ihara, Jelle, et al., 2015). Commercial aerogel

granules with different granule sizes but similar thermal conductivity (0.018-0.025 W/m·K at - $5^{\circ}$ C to  $+600^{\circ}$ C) were used. To evaluate the moisture aging process, the granules were exposed to 300 moisture aging cycles which were equivalent to 10 years of typical use condition (Ihara, Jelle, et al., 2015), and to assess solar radiation aging, they were exposed for three months to high solar radiation equivalent to 12.5 years under typical use conditions. The solar radiation consisted of a halide metal lamp Atlas SC 600 MHG, with an irradiance of 1200 W/m<sup>2</sup> in the wavelength of 280-3000 nm. The aging cycle consisted of two steps, five hours of radiation at 60°C and 50% RH followed by an hour long water spray at 10°C (Ihara, Jelle, et al., 2015). The moisture content, thermal conductivity, the Fourier transform of attenuated total reflectance (ATR-FTIR) and the contact angle of the non-aged and aged aerogel samples were hence assessed. The thermal conductivity of the non-aged aerogel as a function of granular size and relative humidity showed that granular size has a significant impact, whereas the relative humidity and moisture content had minimal effect on the thermal conductivity of aerogel granules (Ihara, Jelle, et al., 2015). The analysis of the moisture-aged samples revealed that the moisture content of the aerogel increased nonlinearly by moisture aging cycles. Moreover, the thermal conductivity increased during the earlier stages of the moisture-aging process (100 first cycles), probably due to the breakage of the silica network. This study showed that aerogel granules could have  $\sim 10\%$  higher thermal conductivity after a moisture-aging test for an equivalent time of 10 years in use condition. The appearance of the white particles within the fully moisture-aged aerogel sample confirmed the degeneration of the aerogel network. The impact of solar irradiation was investigated through the contact angle of water, the surface hydrophobicity, and the ATR-FTIR. The solar irradiation caused a minimal decrease in the contact angle. The hydrophobicity of the surface was maintained after a solar aging process equivalent to 10 years in a typical condition. Solar radiation only marginally affected the hydrophobicity of the aerogel surface and its thermal performance; it also had no significant impact on the attenuated total reflectance of the aerogel concluding that solar radiation might not be a critical factor during the application of aerogels (Ihara, Jelle, et al., 2015).

The study by Ihara et al. (Ihara, Jelle, et al., 2015) focused on limited climatic stresses for the aerogel granules alone. However, the aging performance of aerogel-enhanced products subjected to various climatic conditions, where the composite material failures or a failure of the linkages

between the pure material and the aerogel might occur too. The objective of this research is to investigate the long-term durability and thermal performance of aerogel-based products.

Further research was necessary on the aging effects of other climate stresses such as thermal cycles or elevated temperature. Also the combined effects of these factors need to be investigated.

## 2.11. Knowledge gap and research plan

Aerogel-enhanced insulating materials are known to provide significantly higher thermal resistance per unit of thickness compared to conventional insulating materials. However, limited studies are available on the thermal performance of aerogel-enhanced materials under different temperatures and moisture content levels, although this knowledge could provide critical information for hygrothermal analysis, consideration of protective strategies, and accurate energy assessment under various climatic conditions. The goal of this study is hence to investigate various aerogel-enhanced insulating materials and assess their thermal properties under different operating temperature and moisture content levels. Moreover, the main characteristics of different aerogel-enhanced materials including density, hydrophobicity level, hygroscopic sorption properties, moisture storage function, and water vapor permeability should be addressed. The findings of this study would provide valuable information about aerogel-enhanced products for building engineers and designers to develop proper envelope design, hygrothermal analysis, and accurate prediction of the building envelope performance.

Another limitation of the reviewed literature is that limited studies have focused on the long-term performance of aerogel-enhanced materials and the consistency of their superior performance over an extended period of time is still unknown.

To address the above mentioned knowledge gaps, in this study, several new high-performance thermal insulating renders, based on aerogels, will be constructed. A series of characteristic tests will be performed and hygrothermal properties of aerogel-based samples under different climatic exposures will be investigated. To assess the long-term performance of the samples accelerated aging tests will be designed to mimic aging process under use condition; the thermal characteristics of the samples will be studied during aging to the minimum of twenty year. A comprehensive comparison will be conducted between pristine and aged aerogel based products and convetional insulations.

The research plan of this study is summarized in Fig. 2-5.



Figure 2-5. Research plan

# 3. Investigated materials

## **3.1.**Commercially manufactured samples

Several commercially available aerogel-enhanced products including aerogel-enhanced blankets, fiberboards, and gypsum boards, composed of amorphous silica with glass fiber web and polyethylene terephthalate (PET), were studied. Figures 3-1 shows the different commercially



Figure 3-1. Samples of aerogel enhanced blanket and boards investigated in this paper.

provided samples subject of this study.

The aerogel-enhanced blanket also known as Spaceloft and aerogel fiberboard were provided by Aspen Aerogel Insulation Co., US, in dimensions of  $150 \times 100 \times 10 \text{ mm}^3$  and  $250 \times 250 \times 30 \text{ mm}^3$  respectively, and aerogel gypsum boards with dimensions of  $300 \times 300 \text{ mm}^3$  with 12 and 24 mm thicknesses supplied by AdermaLocatelli group, Italy, were investigated too. The composition information of the supplied aerogel blanket in summarized in table 3-1. The nominal properties of the all supplied products are summarized in Table 3-2.

| Chemical name                                 | %      |
|---|--------|
| Synthetic Amorphous Silica                    | 40-50% |
| Methylsilylated Silica                        | 10-20% |
| Polyethylene Terephthalate (PET or polyester) | 10-20% |
| Fibrous Glass (textile grade)                 | 10-20% |
| Magnesium Oxide                               | 0-5%   |
| Synthetic Graphite                            | 0-5%   |
|   |        |

 Table 3-1. Spaceloft composition information (Aspen Aerogels Insulation 2015)

| Sample description               | Nominal<br>thickness<br>(mm) | Nominal<br>thermal<br>conductivity<br>(W/m·K) | Nominal<br>density<br>(Kg/m <sup>3</sup> ) | Manufacturer                   |
|----------------------------------|------------------------------|---|--|--------------------------------|
| Aerogel blanket                  | 10                           | 0.0165  | 160  | Aspen Aerogel<br>Insulation Co |
| Aerogel fiberboard               | 30                           | 0.018   | 160  | Aspen Aerogel<br>Insulation Co |
| Aerogel gypsum board<br>(type A) | 24                           | 0.03  | 350  | AdermaLocatelli<br>group       |
| Aerogel gypsum board<br>(type B) | 12                           | 0.03  | 250  | AdermaLocatelli<br>group       |

Table 3-2. Aerogel blanket and boards specifications.

## **3.2.Lab-prepared samples**

One goal of this study was to create new aerogel-enhanced plasters, as insulating materials. Accordingly, besides exploring the commercially available materials, different aerogel-enhanced plasters consisting of hydrophobized granular silica aerogel (with a concentration from 25 to 90 vol.%) and purely mineral and cement-free binders were created and investigated.

Aerogel-enhanced samples were constructed by manually mixing hydraulic lime-based plaster with granular silica aerogels (P300), which were supplied by Cabot Corp. (Cabot, 2013). Their main properties of utilized granular silica aerogel are reported in Table 3-3. Natural hydraulic lime plaster (NHL 3.5 - 55 lbs) were supplied by Sustainable Innovative Products (Saint Astir, 2016) and Chireama Corp (Chireama Co., 2016). Different percentages of aerogel (varying from 0% to 90% in vol.) were used in the mixes; in this way, the thermal conductivity and density variation could be tracked to verify the optimal aerogel content of the samples.

Figure 3-3 shows the preparation process of aerogel-enhanced plasters and Fig. 3-4 shows the created plaster-based samples subject of this study.

The samples were prepared by mixing the components in buckets with a mechanical mixer. Before the mixing process, the ratios were calculated, and all of the ingredients were weighed. In order to get a uniform mixture, water was added slowly; It should be noted that aerogel needs to be mixed thoroughly with the plaster before adding the water, otherwise the mixture would fail to blend and results in a heterogeneous mixture as shown in Fig. 3-2, which all of the components (aerogel, lime-based plaster, and water) was poured simultaneously and they failed to be mixed; this failure might be due to the hydrophobic nature of aerogel.

Samples were constructed with dimensions of  $150 \times 150 \times 20$ mm<sup>3</sup> and dried until weight constancy (<0.1%), with curing precautions to prevent premature loss of water. The sample descriptions, the percentage of aerogel and other components and the average gravimetric densities are reported in Table 3-4.



Figure 3-2. Failed aerogel-based plaster sample.

| Table 3 | 3-3. | <b>Properties</b> | of a       | erogel    | particles | used to | create t | he plaster   | samples in | this paper. |
|---------|------|-------------------|------------|-----------|-----------|---------|----------|--------------|------------|-------------|
|         | •••  |                   | ~ <i>j</i> | er oger j | P         |         |          | proprietore. | sumpres m  | ma puper    |

| Property            | Value                     |
|---------------------|---------------------------|
| Particle size range | 1.2 – 4.0 mm              |
| Pore diameter       | ~20 nm                    |
| Porosity            | > 90%                     |
| Particle density    | 65-85 kg/m <sup>3</sup>   |
| Surface chemistry   | Hydrophobic               |
| Surface area        | 600-800 m <sup>2</sup> /g |



Figure 3-3. Preparation process of the aerogel-enhanced plaster samples; (a) raw materials; (b) pre-processing; (c) mixing; (d) casting; (e) demolding; and (f) drying.



80% Aerogel-enhanced plaster

90% Aerogel-enhanced plaster

Figure 3-4. Constructed aerogel-enhanced plaster samples.

| Sample                           | Percentages in volume |         |       | Percentages in mass |         |       | Average dry<br>density |
|----------------------------------|-----------------------|---------|-------|---------------------|---------|-------|------------------------|
| description                      | plaster               | aerogel | water | plaster             | aerogel | water | (kg/m3)                |
| Pure plaster                     | 73%                   | 0%      | 27%   | 65%                 | 0%      | 35%   | 1109.84                |
| 25% aerogel-<br>enhanced plaster | 49%                   | 25%     | 26%   | 54%                 | 3%      | 43%   | 735.56                 |
| 50% aerogel-<br>enhanced plaster | 30%                   | 50%     | 20%   | 44%                 | 22%     | 35%   | 515.30                 |
| 70% aerogel-<br>enhanced plaster | 15%                   | 70%     | 15%   | 40%                 | 20%     | 40%   | 236.78                 |
| 80% aerogel-<br>enhanced plaster | 6%                    | 80%     | 14%   | 12%                 | 32%     | 56%   | 203.81                 |
| 90% aerogel-<br>enhanced plaster | 3%                    | 90%     | 7%    | 6%                  | 55%     | 39%   | 199.26                 |

## Table 3-4. Specification of the aerogel-enhanced plaster samples.

# 4. Methods

To investigate the performance of aerogel-based samples under various climatic conditions and assess their durability under different aging factors, a series of experimental tests were conducted in the building science lab of Ryerson University.

Accomplished tests were categorized into two sections as following:

- 1) Characteristic tests, including:
  - a. Thermal conductivity measurements
  - b. Hygroscopic sorption and moisture storage function analysis
  - c. Water vapor permeability measurements
- 2) Aging tests, including:
  - a. Elevated temperature aging
  - b. Thermal cycling aging
  - c. Moisture aging
  - d. UV aging

Following sections describe the methodology of the performed tests.

## **4.1.**Characteristic tests

#### 4.1.1.Thermal conductivity measurements

The consistency of the thermal properties under a wide range of temperatures and humidity conditions was investigated. In particular, the temperature and moisture-driven changes of the thermal conductivity of the samples were quantified. The test conditions swung temperature ranges from -20°C to +60°C and moisture content ranges from 0% to 95% in Relative Humidity (RH).

The thermal conductivity of the samples was measured using the heat flow meter apparatus HFM 436 Lambda (Netzsch, Germany) shown in Fig. 4-1. The apparatus was calibrated with a

standard fiberglass board, supplied by NIST<sup>3</sup>. The measurement accuracy of the apparatus was  $\pm 1$  to 3%. Specimens sized with variable thicknesses were placed between the hot and cold plates, and the thermal conductivity was measured by the heat flux sensor upon reaching the thermal equilibrium at defined temperature difference and a uniform temperature gradient throughout the sample. The sample size was  $305 \times 305 \text{mm}^2$ , although the heat flow was measured in the central  $100 \times 100 \text{mm}^2$  area of the sample. The large sample size compared to the measurement area ensured the steady-state thermal conditions for the measuring area, so the surrounding area of the transducer acted as an effective guard against lateral heat flow. For those samples with a dimension less than  $305 \times 305 \text{mm}^2$ , an insulating frame, as shown in Fig. 4-2 was used to create the adiabatic condition as the heat flow meter measures the thermal conductivity of the middle area of the specimen.



Figure 4-1. Heat flow meter (a) NETZSCH HFM 436 Lambda apparatus; (b) schematic design.

<sup>&</sup>lt;sup>3</sup> National Institute of Standards and Technology



Figure 4-2. Insulating frame in XPS used for blocking lateral heat flow during thermal performance tests.

The temperature difference between the hot and cold plates was set to 20°C, and a set of eight temperature points, ranging from  $-20^{\circ}$ C to  $+50^{\circ}$ C was used at 10°C increments

The thermal conductivity of the samples was determined at different temperature set points, and at various moisture content levels. For this, the samples were conditioned at 23°C and 0%, 30%, 70%, 95% relative humidity (RH) in a custom-built humidity chamber (Fig. 4-3). Samples were removed from the chamber at different moisture content levels upon reaching a constant mass, immediately wrapped with a thin plastic film to maintain their moisture content and their thermal conductivity was measured at various temperatures. To keep track of the moisture content, samples were weighed before and after thermal measurement using a digital scale with 0.1g accuracy. The effect of the plastic wrap on thermal conductivity was also assessed.

The statistical significance of the findings was assessed using t-test and one-way ANOVA. The significance level was assumed to be at 0.05.

To derive an equation describing the relationship between the thermal conductivity and the variable experimental condition (i.e., temperature, relative humidity and moisture content) the best fitting regression lines were plotted on each graph. The correlation coefficients ( $R^2$ ) describe how well the equations describe the data (i.e., strength of the relationship).





Figure 4-3. Custom-built humidity chamber.

#### **4.1.2.Hygroscopic sorption properties and moisture storage function**

To analyze the reaction of the aerogel-enhanced samples to the moisture content of the air by absorbing or releasing water vapor, the hygroscopic properties were investigated. Hygroscopic sorption properties of the aerogel-enhanced samples were determined using the climatic chamber method described in the ISO 12571:2013 ("ISO 12571: Hygrothermal performance of building materials and products - Determination of hygroscopic sorption properties," 2013). The moisture content of the samples was investigated to characterize the material state and to compare the actual moisture content with the critical moisture content. Also, the moisture distribution and thermal and moisture related properties of the samples were studied.

The free water content of the samples was determined through the following steps:

- Samples were dried at an elevated temperature based on ISO 12570:2000 ("ISO 12570:Hygrothermal performance of building materials and products Determination of moisture content by drying at elevated temperature," 2000). Specimens were weighed before drying using a sensitive digital weighing scale with 0.1 g accuracy. The precise dimensions of each test specimen were measured using a Vernier caliper to determine the volume of the test specimen. Samples were dried until reach a constant mass, using a ventilated oven capable of maintaining the drying temperature at 70±2°C and a relative humidity of less than 10%. The mass was assumed to be constant when the changes in mass were less than 0.1% between three consecutive weighing 24 hours apart.
- Samples were cooled in a desiccator to reach 30°C to 40°C;
- Samples were weighed before being completely cooled to prevent re-absorption of moisture, and the weight was recorded as the mass of the test specimen after drying (m<sub>0</sub>);
- The dried test specimens were exposed to a series of environments, at a temperature of 23±0.5°C, with four relative humidity levels: 30%, 50%, 70%, and 95% RH;
- Samples were placed in a climatic chamber, which maintained the relative humidity within ±5% RH and the temperature within ±2 °C over the test area. At first, the humidity in the climate chamber was set at 30%RH, the lowest values chosen for the tests;
- Periodic weighing was performed until the sample was in equilibrium with the environment, constant mass;

• The process was repeated for all the selected humidity levels. The sorption curves were drawn after establishing the moisture content at each relative humidity condition, based on the climatic chamber method of ISO 12571:2013 ("ISO 12571: Hygrothermal performance of building materials and products - Determination of hygroscopic sorption properties," 2013).

The moisture content, *u*, was calculated based on the following equation for each specimen:

$$u = \frac{m - m_0}{m_0} \tag{4-1}$$

where u is the moisture content mass by mass (kg/kg), m is the mass of the test specimen before drying,  $m_0$  is the mass of the test specimen after drying.

### 4.1.3.Water vapor permeability measurement

Water vapor permeability is a measure of the passage of water vapor through the material. The water vapor transmission characteristic of building materials needs to be considered for the building envelope design and construction. In the case of vapor diffusion or air movement humid air might condense at a cold surface, which can lead to corrosion, condensation/absorption, moisture accumulation, toxic mold or even building failure or it may affect indoor air quality and occupant comfort level. Therefore, the water permeance of the materials in each assembly must be selected carefully with respect to the permeability of the other layers within the assembly and the given climate zone.

The water vapor permeability of the samples was investigated based on Procedure B (Water method at 23°C and 50% RH) of the ASTM E96 ("ASTM E96/E96M: Standard Test Methods for Water Vapor Transmission of Materials 1," 2002), using a custom-built environmental chamber. The purpose of this test was to quantify the water vapor transfer through the materials which would be useful in designing, manufacturing, and marketing the products. The test procedure was selected based on the similarity with the actual use condition of the insulating material. The following equations were used to quantify water vapor transmission through the samples:

$$WVT = \frac{G}{tA} = \frac{\left(\frac{G}{t}\right)}{A} \tag{4-2}$$

where *WVT* is the water vapour transmission rate  $(g/h \cdot m^2)$ , *G* is the weight change (from the straight line) (g), *t* is the time (h), *G/t* is the slope of the straight line (g/h), and *A* is the test area (cup mouth area)  $(m^2)$ .

$$WVP = \frac{WVT}{\Delta P} = WVT/S(R_1 - R_2)$$
(4-3)

where *WVP* is the water vapour permeance (Perm or ng/m<sup>2</sup>·s·Pa),  $\Delta P$  is the vapour pressure difference, mm Hg (1.333×10<sup>2</sup> Pa), *S* is saturation vapor pressure at test temperature, mm Hg (1.333 × 10<sup>2</sup> Pa),  $R_1$  is relative humidity at the source expressed as a fraction (inside the test dish: 100%), and  $R_2$  is relative humidity at the vapor sink expressed as a fraction.

$$permeability = WVP \times thickness (perminch = \frac{g}{m.s.Pa})$$
(4-4)

Each homogeneous test specimen was sealed to the open mouth of a test dish, which was filled with distilled water to a level of 19.05±6 mm from the specimen ("ASTM E96/E96M: Standard Test Methods for Water Vapor Transmission of Materials 1," 2002). The sealant used for attaching the specimen to the dish was highly resistant to the passage of water vapor. The selected test dishes for this study were plastic containers, made of noncorroding, impermeable and light material. The thickness of each sample was measured in several locations using a digital caliper, to ensure the overall uniformity of the sample thickness. The air gap between the test specimen and water level was adjusted based on the standard ASTM E96 ("ASTM E96/E96M: Standard Test Methods for Water Vapor Transmission of Materials 1," 2002) and was large enough to prevent the water from contacting the test specimen when the dish was relocated for weighting. The assemblies of the permeability dishes were weighted and were placed in an environmental chamber with controlled parameters (Fig.4-4). Periodic weighting determined the rate of water vapor movement through the specimen from the water into the environmental chamber. The temperature and relative humidity of the environmental chamber were kept at the desired level of 23°C and 50% RH using the following equipment (Fig. 4-5):

- a. Humidifier: a compact ultrasonic humidifying fogger with adjustable fog output control and a heating coil, which heats an adequate volume of de-ionized water;
- b. Dehumidifier: Homasy Portable mini dehumidifier 22W air dryer;
- c. Infrared heat lamp: Noma incandescent bulb 250W;
- d. Temperature controller: Inkbird programmable outlet thermostat 1200W;

e. Humidity controller: Inkbird pre-wired plug digital humidity controller.

The permeability dishes were weighed daily throughout the duration of the test, while the relative humidity and temperature of the environmental chamber along were recorded. The weight changes of the assemblies were plotted versus the time (g/hr). The slope of the plot is the rate of weight change. The following factors affect the rate of changes in the weight:

- 1. The area of the test specimen used to calculate the water vapor transmission rate. The larger the area of the opening of the dish (area of the test specimen), the faster the weight change of the dish;
- 2. The driving force or the pressure difference between the permeability dish and the environmental chamber was used to calculate the water vapor permeance. In this method, the air layer between the water in the dish and the test specimen was assumed to be completely saturated. Therefore it had a relative humidity of 100%.
- 3. The thickness of the test specimen was used to calculate the permeability.





Figure 4-4. WVP test (a) custom build environmental chamber; (b) Schematic design of the process



Figure 4-5. Utilized equipment for the permeability test; (a) Digital scale; (b) Digital caliper; (c) Humidifier; (d) Temperature controller; (e) Humidity controller; and (f) Dehumidifier.

According to ASTM E96 ("ASTM E96/E96M: Standard Test Methods for Water Vapor Transmission of Materials 1," 2002), two conditions need to be met for test completion: (1) acquiring minimum of 6 linear points on the plot of weight versus time; (2) the weight change from the beginning of the steady state period to the end must exceed 100 times of the sensitivity of the used scale (in our case considering the scale accuracy, this change had to exceed 10g).

## 4.2. Aging tests

In order to predict the long-term performance of the ABPs, a series of accelerated aging tests were performed in the laboratory to determine the material properties within a much shorter time than with natural outdoor climate aging. Like any insulating material, which is important to sustain its thermal performance relatively constant, the thermal conductivity of ABPs were tested under various environmental loads to make sure they performed as expected.

Various methods to age a product and choosing the right test method or condition exist. Understanding the measurement techniques (precision, sensitivity, and change effect) and choosing the correct exposure and measurement intervals was an important aspect. Moreover, the test stress levels were chosen carefully, so that they could not introduce failure modes which would never occur under use conditions (e.g., too much UV radiation could cause chemical reactions that would not occur during regular aging), while they are high enough to accelerate the aging process within the allowable testing time.

Although different combinations of climatic strains occur in real conditions, to understand the effect of each factor, it was decided to test each stress condition separately. Then, a combination of various aging mechanisms was considered since the ultimate climate strain may be larger than the summation of exposure to single factors (Jelle, 2012). Accelerated tests were performed at stressed temperature fluctuations (freeze-thaw cycles), elevated temperature, high humidity levels, and weathering (combined heat, moisture, and UV exposure).

In order to correlate the accelerated artificial weathering and natural outdoor condition, and estimate the required aging time in each climate aging chamber, the acceleration factors were calculated. These are the ratio between the use-level and a higher test stress-level, and indicate how fast a laboratory test is compared to conventional outdoor real time weathering. The Arrhenius equation, Coffin-Manson relation, and Peck model were utilized as the theoretical basis for the calculation (Ihara, Jelle, et al., 2015; Jelle, 2012; Reliasoft Corporation, 2015; Wegger et al., 2011). The ABP samples were placed in several types of accelerated aging equipment, and their long-term behavior was assessed through accelerated aging tests after an equivalent time of 20 years in natural outdoor conditions.

The thermal conductivity ( $\lambda$ ) was the indicator evaluated across the various aging factors. It was measured before, during, and after the accelerated aging periods according to the standard ASTM C518 ("ASTM C518-10: Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus," 2015) using a heat flow meter apparatus (HFM 436 Lambda, Netzsch, Germany). The long-term performance of the products was investigated in terms of thermal conductivity changes. In order to assess the statistical significance of the observed changes, two-sample student's t-test was used; statistical significance was assumed to be 0.05.

The used HFM is a calibrated instrument designed for measuring the thermal conductivity of low-conductivity materials according to ASTM C518-91 ("ASTM C518-10: Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus," 2015) or the ISO 8301 ("ISO 8301:1991, Thermal insulation- Determination of steady-state thermal resistance and related properties- Heat flow meter apparatus," 1991) standards. Specimens (305 mm  $\times$  305 mm) with variable thicknesses ranging from a few millimeters to 200 mm were placed between a hot and a cold plate, and the temperature difference was measured with a heat flux sensor. Upon reaching the thermal equilibrium and establishing a uniform temperature gradient throughout the sample, the thermal conductivity was based on the heat flux measurement.

The thermal conductivity of the samples was frequently measured over the aging process. When the samples were taken out from each aging chamber, they were allowed to reach equilibrium at the room temperature and relative humidity for a minimum of 24 hours before conducting the thermal conductivity measurements. The experimental details of different aging processes are explained in the following sections.

#### **4.2.1.** Elevated temperature aging

A constant high temperature accelerated aging is used to detect failure modes in short period of time which would show up after many years at normal use temperatures. In order to achieve temperature driven aging, the ABP samples were exposed to a constant temperature of  $70^{\circ}$ C inside a mechanical convection oven (115 VAC, Cole-Parmer, Canada). This device is a microprocessor-controlled which allowed for precise control, good uniformity, and easy setup and monitoring functions (Fig.4-6).

Samples were placed in the thermal chamber in a vertical orientation (Fig.4-6), and samples were separated to facilitate air circulation. The relative humidity of the chamber was maintained at 15% during testing.

In order to determine the relationship between test stresses and the use condition, the acceleration factor was calculated based on the Arrhenius equation (Eq. 4-5). The Arrhenius model relates the exposure time under the experimental temperature to that of use condition temperature (Jelle, 2012):

$$AF_{T} = e^{-\frac{E_{A}}{K} \times (\frac{1}{T_{A}} - \frac{1}{T_{U}})}$$
(4-5)

where  $AF_T$  is the acceleration factor due to stressed temperature,  $E_A$  is the activation energy of the failure mechanism, k is the Boltzmann constant (8.617 × 10<sup>-5</sup> eV/K),  $T_A$  is the accelerated temperature in kelvins, and  $T_U$  is the use condition temperature in kelvin.



Figure 4-6. Mechanical convection oven used for elevated temperature aging.

The activation energy ( $E_A$ ) is the minimum required energy to initiate a chemical reaction, and it is a characteristic of the material being tested (Escobar & Meeker, 2007). The activation energy was assumed to be temperature independent and equal to 70 kJ/mol (Jelle, 2012; Michel A Aegerter, Nicholas Leventis, 2011). To estimate the acceleration factor and the approximate time needed for each product to be under a test condition, the accelerated temperature of 70°C and the constant use condition temperature of 15°C were considered. It should be noted that the location of the material within the building envelope affects the use condition temperature.

Given the conditions in the thermal chamber, the acceleration factor was calculated to be 107. A testing period of 68 days is required to analyze the behavior of the ABPs over 20 years of typical use conditions.

#### **4.2.2.** Thermal cycling aging (freeze-thaw cycles)

Temperature fluctuations are part of the natural weather cycles occurring across the year as well as daily. For example, during the winter season, sunny days with higher temperature and cold nights with below-freezing temperature are common in many parts of the world. Thermal fluctuations cause cumulative stress that may result in failures which compromise materials' performance. Thermal cycling aging test is the process of cycling through two temperatures to accelerate failures and catch early term defects caused by thermal fatigue (Escobar & Meeker, 2007; Ghaffarian, 2000). To evaluate the effect of aging driven by thermal cycling, the samples were placed in a freeze-thaw chamber.

A compact freezer (CF-2060, Salton, Canada) with the incorporation of a fan heater (100W HVL 031, STEGO, England) and a temperature and relative humidity data logger (U10-003, Onset HOBO, Canada), was used as the cycling environmental chamber (Fig.4-8). The cycles were programmed by an electronic time switch (ET1115C 24-Hour 20/30-Amps SPDT clock Voltage NEMA 1, Intermatic Inc., USA).

As shown in Fig. 4-7, the cycling chamber runs on 24-hour cycles as following: 2 hours warm up period to reach a temperature of 40°C, the temperature is maintained at 40°C (~90% RH) for 10 hours, next it takes 2 hours to cool down to -30°C (~10% RH) where the condition stays constant for 10 hours and then the cycle repeats. The upper and lower temperatures were selected based on a cold climate condition.

The acceleration factor resulting from the freeze-thaw cycles was calculated based on the Coffin-Manson equation (Eq. 4-6) (Escobar & Meeker, 2007; Ghaffarian, 2000), which is the ratio of the product life at natural outdoor climate conditions to the life at accelerated test conditions:

$$AF_{(Freeze-thaw)} = \left(\frac{\Delta T_{test}}{\Delta T_{use}}\right)^m \tag{4-6}$$

where  $AF_{(Freeze-thaw)}$  is the acceleration factor due to freeze-thaw cycles,  $\Delta T_{test}$  is the test temperature difference,  $\Delta T_{use}$  is the use temperature difference, and *m* is the fatigue or Coffin-Manson exponent.

The acceleration factor was quantified based on the following test parameters: test temperature difference 70 °C, use temperature difference 20 °C, and Coffin-Manson exponent 3 (Delserro Engineering Solutions, 2015).

Accordingly, the acceleration factor of the actual experimental condition was calculated to be 42.9. The required test time to correspond to 20 years was 170 days.



Figure 4-7. Thermal cycles in the freeze-thaw chamber.



Figure 4-8. Thermal cycling chamber (a) Exterior view, (b) interior view, (c) STEGO 100W Fan Heater HVL 031 and Onset HOBO Data Logger (temp/RH) U10-003, (d) Internatic ET1115C 24hr basic electronic control.

#### 4.2.3. Moisture aging

The performance of the building materials and components might degrade by water in various states such as precipitation, wind driven rain, free water, relative air humidity and water vapor condensation. Although aerogel-based materials undergo a hydrophobic surface treatment to become moisture resistant, the silica skeleton structure can be still prone to collapse due to the ingress of moisture. Constant moisture pressure could degrade aerogel due to the surface tension of the water (Cinzia Buratti et al., 2010; Calisesi & Berardi, 2017; Gurav et al., 2010b; McIntyre, 2012). Exposure to the high relative humidity levels leads to vapor drove into the samples as well as potentially creating condensation on the surface or degrading of the materials.

In order to evaluate the moisture aging behavior, the samples were placed in a custom-built humidity chamber (Fig. 4-9). The chamber was built from 1cm thick acrylic glass, which was encased in 50mm rigid XPS insulation to reduce the amount of heat loss to the ambient air within the laboratory. In order to maintain as high air tightness as possible, the lip of the chamber was lined with closed cell self-adhesive weatherstrip foam tape. Samples were mounted on a perforated galvanized metal shelf. This allowed for uniform moisture and temperature distribution throughout the chamber and all sides of the samples. Also, some parts of the interior surface near the heat lamp were covered with aluminum foil to disperse the heat deeper into the chamber. The temperature and relative humidity of the chamber were kept at the desired level of 45°C and 70%RH, respectively.

The following equipment was used to control the condition of the chamber at the set points:

- Humidifier: a heating coil was kept submerged inside the clear plastic container filled with de-ionized water and increase the RH level of the chamber;
- Dehumidifier: Homasy Portable mini dehumidifier 22W air dryer;
- Infrared heat lamp: Sylvania 13840 175W PAR38;
- Temperature controller: Inkbird programmable outlet thermostat 1200W;
- Humidity controller: Inkbird pre-wired plug digital humidity controller.





Figure 4-9. Custom-built humidity chamber.

The acceleration factor was calculated based on the Peck model (Eq. 4-7) (Escobar & Meeker, 2007; Reliasoft Corporation, 2015). This is a two-stress model based on temperature and relative humidity. Thereby the effect of each stress on samples' life is sought, and the test was performed in a combination manner between different stress levels of the two stress types:

$$AF_{TH} = AF_T \cdot AF_H \tag{4-7}$$

where  $AF_{TH}$  is the combined temperature-humidity acceleration factor,  $AF_T$  is the temperature acceleration factor (Eq. 4-5), and  $AF_H$  is the humidity acceleration factor.

The equation is then further broken down into its components  $FT_T$  (Eq. 4-5) and  $AF_H$  (Eq. 4-8):

$$AF_H = \left(\frac{RH_A}{RH_U}\right)^m \tag{4-8}$$

where  $RH_A$  is the relative humidity of the test (70%),  $RH_U$  is the relative humidity in natural outdoor climate conditions (40%), and *m* is a humidity constant (2.66).

According to the set parameters, the AFTH was calculated to be 69.5. Thereby 104 days were required in the humidity chamber to simulate 20 years of life.

To accomplish the thermal conductivity measurements at different aging intervals, the samples were removed from the humidity chamber, immediately wrapped with a thin plastic film to maintain their moisture content, and after a few hours at room temperatures to reach the moisture equilibrium; their thermal conductivity was measured.

#### 4.2.4. UV aging

To check the durability of the ABP samples against weathering and light exposure, accelerated weathering and UV exposure tests were performed. As most weathering damages are caused by light, water, and temperature weathering elements, the effects of these factors were studied in combination.

The QUV accelerated weathering tester (QUV/se, Q-LAB Corp., US) was used (Fig. 4-10). The samples were exposed to cycles of UV light and moisture at controlled elevated temperatures. The QUV chamber is compatible with a variety of fluorescent ultraviolet lamps and is programmable for different weathering test cycles based on ISO and ASTM standards ("ASTM

G154 - 16: Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials," 2016). For this study, the fluorescent ultraviolet UVA 340 lamps and the cycle based on ASTM G154-16 standard ("ASTM G154 - 16: Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials," 2016) with the following schedule were selected: the cycle consisted of 8 hours of UV radiation at 60°C ( $\pm$ 3°C) black panel temperature and 4 hours of condensation (100% RH) at 50°C ( $\pm$ 3°C) black panel temperature. The ambient temperature and relative humidity of the chamber during each cycle are shown in Fig. 4-11.

The acceleration factor was calculated based on the combination of multiple acceleration factors for the entire test span. The Arrhenius equation, the Peck model, and a simple proportion between the total UV energy during aging ( $\Phi$ A) and the natural outdoor aging process ( $\Phi$ U) were used to calculate the acceleration factor (Escobar & Meeker, 2007; Jelle, 2012; Reliasoft Corporation, 2015):

$$AF_{THUV} = \frac{1}{3} (AF_{T1} \times AF_H) + \frac{2}{3} (AF_{T2} \times AF_{UV})$$
(4-9)

$$AF_{UV} = \frac{\Phi_A}{\Phi_U} \tag{4-10}$$

where  $AF_{THUV}$  is the combined acceleration factor for temperature, humidity, and UV radiation,  $AF_{TI}$  is the temperature acceleration factor during the four hours test cycle where only temperature and humidity are involved (Eq. 4-5),  $AF_H$  is the humidity acceleration factor (Eq. 4-8),  $AF_{T2}$  is the temperature acceleration factor during the eight hours test cycle where only temperature and UV radiation are operational (Eq. 4-5),  $AF_{UV}$  is the UV acceleration factor (Eq. 4-10),  $\Phi_A$  is the total UV energy during accelerated ageing, which the  $\Phi_U$  is total energy during natural outdoor ageing. The  $\Phi_A$  was quantified to be 14935.8 kWh/m<sup>2</sup>, by averaging the multiplied typical irradiance (1.55 W/m<sup>2</sup>·nm) by each wavelength (nm) and the  $\Phi_U$  of 1339.55 kWh/m<sup>2</sup> ("Solar resource data available for Canada," 2016). Using the information provided above, the acceleration factor was calculated to be 265. Accordingly, the required test time to correspond to 20 years of natural outdoor exposure conditions lasted 28 days.





Figure 4-10. QUV accelerated weathering tester.



Figure 4-11. The weathering cycle in QUV chamber.

#### 4.2.5. Calculation of aging period under laboratory condition

To mimic the realistic aging process under use condition the acceleration factors and the required aging time under laboratory conditions were calculated using Eqs. 4-5 to 4-10. The calculated acceleration factors and the required aging time under laboratory condition equivalent to 20 years in normal conditions are presented in Table 4-1.

| Aging factors                               | AF       | Aging time under use<br>condition (years) | Equivalent accelerated aging time (days) |
|---|----------|---|--|
| Elevated temperature                        | 170 *    | 20  | 68                                       |
| Freeze-thaw cycles                          | 42.9 **  | 20  | 170                                      |
| High moisture exposure                      | 69.5 *** | 20  | 104                                      |
| Weathering (UV, heat and moisture exposure) | 265 **** | 20  | 28                                       |

Table 4-1. The required stressed period based on acceleration factors.

\* Calculated based on Eq. 4-5; \*\* Calculated based on Eq. 4-6; \*\*\* Calculated based on Eq. 4-7 and 4-8; \*\*\*\* Calculated based on Eqs. 4-9 and 4-10.

## **5. Results**

## **5.1.Results of the characteristic tests**

#### 5.1.1. Impact of the aerogel content on density and thermal conductivity

Aerogel has low thermal conductivity and very low density, therefore replacing the render's aggregate (i.e., sand with a density of ~ 2600 Kg/m<sup>3</sup>) with aerogel particles (density~100Kg/m<sup>3</sup>) would result in a light-weight thermally improved plaster (Gao et al., 2014). Figure 5-1 shows the changes in the thermal conductivity and density of the samples as a function of aerogel content. As expected, the thermal conductivity and density of the materials are inversely proportional to the aerogel content. The average density of the enhanced-plaster was about 200 Kg/m<sup>3</sup>, at the highest aerogel content, comparing to the 1110 Kg/m<sup>3</sup> of the reference plain plaster, shows about 82% reduction. Similarly, the thermal conductivity of the samples at the highest aerogel content was calculated to be 0.027 W/m·K, which is 82.2% less than that of pure reference plaster with a thermal conductivity of 0.140 W/m·K. It was observed that the thermal conductivity and the density of the aerogel-enhanced plasters are highly correlated (correlation coefficient R<sup>2</sup> ≈ 99%).



Figure 5-1. Thermal conductivity and density of aerogel-enhanced plasters as a function of aerogel content.
### 5.1.2. The relationship between thermal conductivity, temperature, and relative humidity

The thermal conductivity of different aerogel-enhanced samples as a function of temperature under standard laboratory conditions (50% RH) are shown in Figs. 5-2 and 5-3.

Tracking the trend of changes in thermal conductivity as a function of temperature in plaster based samples showed that, the thermal conductivity of high aerogel content samples (including 70% aerogel-enhanced plaster, 80% aerogel-enhanced plaster, and 90% aerogel-enhanced plaster) marginally changed with temperature (p-value = 0.7), however, the temperature-driven changes in pure and low aerogel content samples (pure plaster, 25% aerogel-enhanced plaster, and 50% aerogel-enhanced plaster) were statistically significant (p-value < 0.005). In addition, no significant difference was found in the thermal performance of 80% and 90% aerogel-enhanced plasters (p-value = 0.9), although this might be due to the test errors.

The accuracy of the heat flow measurements was  $\pm 1$  to 3%. As mentioned earlier, the samples were wrapped with a thin plastic film to maintain their moisture content. The impact of the thin plastic film on thermal conductivity was investigated through several tests (through measurement of with and without plastic wrap on the dried samples), and the result showed the plastic wrap has negligible (<1%) impact on the thermal conductivity of the samples.

To study the integrated impact of temperature and relative humidity on thermal performance of the materials, samples were tested at different moisture content levels in the temperature range of  $-20^{\circ}$ C to  $60^{\circ}$ C corresponding to mean temperature of  $-10^{\circ}$ C to  $50^{\circ}$ C. The thermal conductivity measurements are shown in Figs. 5-4 to 5-13, .



Figure 5-2. Thermal conductivity of the aerogel-enhanced plasters as a function of temperature.



Figure 5-3. Thermal conductivity of the aerogel blanket, fiberboard, and gypsum boards as a function of temperature.



Figure 5-4. Integrated effects of temperature and humidity variation on thermal conductivity of pure reference plaster.



Figure 5-5. Integrated effects of temperature and humidity variation on thermal conductivity of 25% aerogel-enhanced plaster.



Figure 5-7. Integrated effects of temperature and humidity variation on thermal conductivity of 50% aerogel-enhanced plaster.



Figure 5-6. Integrated effects of temperature and humidity variation on thermal conductivity of 70% aerogel-enhanced plaster.



Figure 5-8. Integrated effects of temperature and humidity variation on thermal conductivity of 80% aerogel-enhanced plaster.



Figure 5-9. Integrated effects of temperature and humidity variation on thermal conductivity of 90% aerogel-enhanced plaster.



Figure 5-10. Integrated effects of temperature and humidity variation on thermal conductivity of aerogel blanket.



Figure 5-11. Integrated effects of temperature and humidity variation on thermal conductivity of aerogel fiberboard.



Figure 5-13. Integrated effects of temperature and humidity variation on thermal conductivity of aerogel gypsum board (type A).



Figure 5-12. Integrated effects of temperature and humidity variation on thermal conductivity of aerogel gypsum board (type B).

Generally, as shown in Figs. 5-4 to 5-13, the moisture content and thermal conductivity of the samples increased with the relative humidity and temperature. The measured changes showed that the humidity and moisture content has a greater impact on thermal conductivity than temperature. The analysis of the temperature-driven thermal resistivity variations (at 50% constant RH) suggests that all of the aerogel-enhanced samples are marginally affected by temperature ( $\pm$ 7% variation compared to the standard condition). On the contrary, the thermal conductivity of the aerogel-enhanced samples was significantly affected by relative humidity (+46% under high RH and -4% under low RH levels compared to the standard condition). The thermal conductivity of the pure high-performance plaster was significantly affected by the temperature ( $\pm$ 30% in compare with the standard condition) and moisture ( $\pm$ 21% in compare with standard conditions).

Under extremely humid condition (RH~95%), the thermal conductivity of all investigated samples, except aerogel fiberboard, has increased significantly; furthermore, under high relative humidity (95% RH) the effect of temperature on thermal conductivity is amplified compared to lower RH levels.

At higher humidity levels, some deviations in the thermal conductivity and temperature regression lines were observed; and the average correlation coefficients for 95% RH were less than 0.75. Indeed, it seems that under higher humidity conditions (95% RH) all aerogel-based samples (except aerogel fiberboard) show nonlinear behavior at a different temperature. It was noted that the thermal conductivity of the samples with high moisture content was decreased at higher temperature conditions; for instance, as shown by the black line in Figs. 5-8 and 5-9 the thermal conductivity at 50°C is less than that at 30°C and 40°C. This observation can be explained by the evaporation phenomenon at high temperature, that consequently decreases the moisture content and increases the thermal resistance.

In high humidity, water vapor molecules raise the moisture content of the samples and in some cases, condense on the surface of the samples and degrade the thermal resistance, since the thermal conductivity of the water is significantly higher than that of dry air.

The temperature-driven thermal conductivity changes (at constant 50% RH) under different temperature levels (ranging from -20°C to 60°C) are summarized in table 5-1. The moisture-

driven thermal conductivity changes (at 23°C constant) under different RH levels (ranging from  $0\% (\pm 5\%)$  to 95% ( $\pm 5\%$ )) are summarized in table 5-2.

The reading error of the thermometer presented in Table 5-1, was  $\pm 0.005$ °C. The reading error of the HFM device for the thermal conductivity measurement presented in table 5-1 and 5-2, was  $\pm 0.5 \times 10-6$  W/m·K. The uncertainty of the calculated moisture content values in table 5-2, was  $\pm 0.07$  g (calculated by error propagation formulas).

Among all the samples, the aerogel-enhanced blanket and fiberboard had the best performance with the least thermal conductivity alternation (about  $\pm 5\%$  compared to standard condition) under various temperature and humidity variations. The greatest impact of temperature on thermal properties was observed in the aerogel gypsum board samples with 12% degradation at maximum test temperature in comparison to standard conditions. The maximum humidity-induced changes in thermal conductivity were also observed in aerogel gypsum boards with an average of 100% increase compared to the standard condition under 95% RH. These results suggest that the thermal performance of all aerogel-enhanced samples, except aerogel fiberboard, is strongly affected by humidity. Therefore, drying mechanism or providing a protection layer of vapor retarder needs to accompany these materials to prevent moisture accumulation and performance degradation.

| Sample                              | λ@ -10°C<br>(W/m·K) | λ@ 0°C<br>(W/m·K) | λ@ 10°C<br>(W/m·K) | λ@ 20°C<br>(W/m·K) | λ@ 30°C<br>(W/m·K) | λ@ 40°C<br>(W/m·K) | λ@ 50°C<br>(W/m·K) |
|-------------------------------------|---------------------|-------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| Pure plaster                        | 0.1044              | 0.1139            | 0.1307             | 0.1400             | 0.1443             | 0.1637             | 0.1726             |
| 25% aerogel-<br>enhanced<br>plaster | 0.1064              | 0.1092            | 0.1114             | 0.1136             | 0.1161             | 0.1169             | 0.1187             |
| 50% aerogel-<br>enhanced<br>plaster | 0.0707              | 0.0697            | 0.0722             | 0.0713             | 0.0758             | 0.0747             | 0.0772             |
| 70% aerogel-<br>enhanced<br>plaster | 0.0295              | 0.0304            | 0.0314             | 0.0317             | 0.0322             | 0.0337             | 0.0345             |
| 80% aerogel-<br>enhanced<br>plaster | 0.0265              | 0.0267            | 0.0270             | 0.0269             | 0.0274             | 0.0275             | 0.0277             |
| 90% aerogel-<br>enhanced<br>plaster | 0.0244              | 0.0252            | 0.0260             | 0.0268             | 0.0276             | 0.0283             | 0.0290             |
| Aerogel<br>blanket                  | 0.0161              | 0.0166            | 0.0171             | 0.0179             | 0.0183             | 0.0188             | 0.0193             |
| Aerogel<br>fiberboard               | 0.0185              | 0.0187            | 0.0190             | 0.0195             | 0.0196             | 0.0197             | 0.0203             |
| Aerogel gypsum<br>board (type A)    | 0.0359              | 0.0370            | 0.0381             | 0.0391             | 0.0403             | 0.0410             | 0.0419             |
| Aerogel gypsum<br>board (type B)    | 0.0356              | 0.0374            | 0.0388             | 0.0416             | 0.0427             | 0.0446             | 0.0464             |

| <i>Table 5-1.</i> | The dependency | of thermal | conductivity to te | emperature at c | onstant 50% RH. |
|-------------------|----------------|------------|--------------------|-----------------|-----------------|
|                   | 1 2            |            |                    | 1               |                 |

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| 0 1                              | 0% RH     |                      | 30% RH    |                      | 50% RH    |                      | 70% RH    |                      | 95% RH    |              |
|----------------------------------|-----------|----------------------|-----------|----------------------|-----------|----------------------|-----------|----------------------|-----------|--------------|
| Sample                           | MC<br>(%) | $\lambda$<br>(W/m·K) | MC<br>(%) | $\lambda$<br>(W/m·K) | MC<br>(%) | $\lambda$<br>(W/m·K) | MC<br>(%) | $\lambda$<br>(W/m·K) | MC<br>(%) | λ<br>(W/m·K) |
| Pure plaster                     | 0         | 0.1266               | 2.0       | 0.1389               | 2.5       | 0.1401               | 3.8       | 0.1356               | 9.6       | 0.1739       |
| 25% aerogel-<br>enhanced plaster | 0         | 0.1135               | 4.3       | 0.1185               | 4.5       | 0.1138               | 5.9       | 0.1330               | 13        | 0.1608       |
| 50% aerogel-<br>enhanced plaster | 0         | 0.0694               | 1.1       | 0.0708               | 1.3       | 0.0737               | 2.5       | 0.0737               | 9.7       | 0.0947       |
| 70% aerogel-<br>enhanced plaster | 0         | 0.0306               | 1.2       | 0.0320               | 1.8       | 0.0323               | 3.2       | 0.0335               | 12        | 0.0449       |
| 80% aerogel-<br>enhanced plaster | 0         | 0.0261               | 1.1       | 0.0272               | 2.8       | 0.0272               | 3.7       | 0.0277               | 11        | 0.0358       |
| 90% aerogel-<br>enhanced plaster | 0         | 0.0257               | 1.5       | 0.0270               | 1.6       | 0.0270               | 2.8       | 0.0273               | 16        | 0.0415       |
| Aerogel blanket                  | 0         | 0.0171               | 7.1       | 0.0180               | 13.3      | 0.0179               | 13.3      | 0.0178               | 17        | 0.0197       |
| Aerogel<br>fiberboard            | 0         | 0.0192               | 11.1      | 0.0192               | 11.8      | 0.0195               | 12.7      | 0.0195               | 14        | 0.0195       |
| Aerogel gypsum<br>board (type A) | 0         | 0.0388               | 2.7       | 0.0387               | 3.2       | 0.0393               | 4.2       | 0.0417               | 20        | 0.0641       |
| Aerogel gypsum<br>board (type B) | 0         | 0.0407               | 2.7       | 0.0408               | 3.3       | 0.0416               | 5.6       | 0.0425               | 48        | 0.1059       |

*Table 5-2. The dependence of thermal conductivity to relative humidity at constant 23°C.* 

#### 5.1.3. Hygroscopic sorption properties and moisture storage function

The average equilibrium moisture content was gravimetrically determined after conditioning at a relative humidity of 30% ( $\pm$ 5%), 50% ( $\pm$ 5%), 70% ( $\pm$ 5%), and 95% ( $\pm$ 5%). As mentioned in the methodology section, the relative humidity levels were selected based on ISO 12571 ("ISO 12571: Hygrothermal performance of building materials and products - Determination of hygroscopic sorption properties," 2013). It should be noted that water vapor absorption mainly depends on the ambient relative humidity and the ambient temperature has less influence. Therefore, the hygroscopic moisture storage is described using material-specific sorption curves (Hens, 2012).

The sorption curves (also known as sorption isotherms) as shown in Fig. 5-14, were plotted for each sample by exposing the samples to different ambient conditions in the laboratory until equilibrium was reached. The highest reachable relative humidity was 95% since in the climate chamber the climate control was not fine enough to reliably avoid moisture condensing on the samples at higher humidities.

Above 95% RH and up to free water saturation (in the so-called capillary water region), measurements need to be performed with the pressure plate apparatus. Analysis of the measurement results in a capillary moisture storage function would continue the classical sorption isotherm. The capillary moisture storage function of the aerogel-enhanced materials was not investigated in this research.

The adsorption curves characterized the hygroscopic regime of building materials (Karoglou, Moropoulou, Maroulis, & Krokida, 2005). Generally, the proper application and the durability of the building materials are affected by moisture through various aspects. For instance, high moisture absorption behavior may cause reduction of thermal insulation; it may increase mechanical stresses through swelling and shrinkage caused by humidity or by salt crystallization.

Although aerogel-based insulations are known to be hydrophobic (Cinzia Buratti et al., 2014; Riffat & Qiu, 2012; Stahl et al., 2012), our results showed that aerogel-enhanced samples have hydrophilic behavior and are considered hygroscopic. This reflected that the initially dry samples had absorbed moisture from the air until they reach to their equilibrium moisture corresponding to the ambient conditions. Thereby, aerogel-enhanced materials are wettable and can attract and

hold water. For instance, according to Table 5-2 at 95% RH, aerogel blanket adsorbed vapor from the humid air and reached to approximately 17% moisture content. It should be considered that all these materials may store further moisture within their pores structure if wetted by liquid water.



Figure 5-14. Sorption curves (a) aerogel-enhanced plasters; (b) aerogel-enhanced blanket and boards.

### 5.1.4. Water vapor permeability

The water vapor permeability of the samples, which is a property that permits the passage of water vapor through the samples, was measured for each sample according to the gravimetric method (cup method) of ASTM E96 under 50% RH and 23°C. It should be noted that the test conditions which the measurement are made have a considerable impact on the result. A moisture vapor transmission rate result without specifying these conditions is almost meaningless.

The weight of each assembly (permeability dish), as well as the relative humidity and temperature of the environmental chamber, were recorded over a period of time as explained in the methods section. Both the temperature and humidity gradient across the sample were measured and controlled over the test period. Figure 5-15 shows the mass loss over time for different samples. The slope of the plots indicates the water vapor transmission rate, while the water vapor permeance (WVP) and permeability of the samples are reported in Table 6.

The results showed that all of the samples were water vapor permeable products since their permeance is greater than 57 ng/s.m<sup>2</sup>.Pa (equal to 1 perm), so they are diffusion open and allow vapor diffusion.

Higher water vapor permeability values of the samples lead to higher diffusion under given condition. The water vapor permeability of the samples varies between 20 ng/s.m.Pa to 65 ng/s.m.Pa.

The water vapor permeability results have significant importance in building envelope design for managing the moisture barrier and moisture retarder properties of the building components; also, they can be used to ensure the correct moisture levels in the internal space of buildings.

Also, the water vapor permeability of the samples improves by increasing the aerogel content with a correlation coefficient of 91%. A strong linear relationship was observed between WVP and aerogel content.

| Sample                           | Specimen area (cm²) | thickness (cm) | Rate of weight change (g/h) | $WVT \left( g/m^2 h \right)$ | WVT (mg/m <sup>2</sup> s) | WVP<br>ng/(m <sup>2</sup> ×s×Pa) | Water Vapour Permeability<br>ng/(m.s.Pa) |
|----------------------------------|---------------------|----------------|-----------------------------|------------------------------|---------------------------|----------------------------------|--|
| Pure plaster                     | 116                 | 2.17           | -0.06                       | 4.85                         | 1.3                       | 960                              | 20.83                                    |
| 25% Aerogel-enhanced plaster     | 116                 | 2.11           | -0.05                       | 4.72                         | 1.3                       | 932                              | 19.68                                    |
| 50% Aerogel-enhanced plaster     | 120                 | 2.13           | -0.08                       | 6.46                         | 1.8                       | 1277                             | 27.21                                    |
| 70% Aerogel-enhanced plaster     | 144                 | 2              | -0.10                       | 7.01                         | 1.9                       | 1387                             | 27.75                                    |
| 80% Aerogel-enhanced plaster     | 126                 | 2.1            | -0.09                       | 7.46                         | 2.1                       | 1476                             | 31.00                                    |
| 90% Aerogel-enhanced plaster     | 65                  | 2              | -0.05                       | 8.27                         | 2.3                       | 1636                             | 32.72                                    |
| Aerogel blanket                  | 150                 | 0.96           | -0.18                       | 12.17                        | 3.3                       | 2408                             | 23.12                                    |
| Aerogel fibre board              | 115                 | 3              | -0.09                       | 7.76                         | 2.2                       | 1534                             | 46.03                                    |
| Aerogel gypsum board (type A)    | 144                 | 2.16           | -0.22                       | 15.06                        | 4.2                       | 2978                             | 64.33                                    |
| Aerogel gypsum board (type<br>B) | 144                 | 1.23           | -0.19                       | 13.46                        | 3.7                       | 2662                             | 32.75                                    |

 Table 5-3. Summary of the water vapor permeability test results.



Figure 5-15. Plot of the weight loss of the assemblies over the time for water vapor permeability test (a) plaster based samples; (b) blanket and boards' samples.

# 5.1.5. Summary of the characteristic test results

The primary characteristics of all aerogel-enhanced plasters, blankets, fiberboards, and gypsum boards are summarized in Table 5. The presented characteristics were measured under standard laboratory conditions (50% RH and 23.8°C).

The aerogel content is inversely proportional to the density and thermal conductivity. Thermal conductivity decreases with increasing the aerogel content; the thermal conductivity of 70% aerogel-enhanced plaster is significantly less than that of pure, 25% and 50% aerogel enhanced

plasters. However, there is no significant improvement in thermal conductivity of the samples with more than 70% aerogel content (p<0.05) in comparison with 70% aerogel-enhanced plasters. It should be considered that aerogel blankets and fiberboards have superior thermal performance compared to aerogel enhanced plasters and gypsum boards.

The water vapor permeability measurements, which were conducted according to the procedure B of the ASTM E96 ("ASTM E96/E96M: Standard Test Methods for Water Vapor Transmission of Materials 1," 2002), showed that all of the samples are water vapor permeable.

|                                  | Density              | Thermal                 | Water vapor  | Moisture content |  |
|----------------------------------|----------------------|-------------------------|--------------|------------------|--|
| Sample                           | (kg/m <sup>3</sup> ) | conductivity<br>(W/m·K) | permeability | at 50% RH        |  |
| Pure high-performance plaster    | 1110                 | 0.1398                  | 20.83        | 4.5              |  |
| 25% aerogel-enhanced plaster     | 789                  | 0.1278                  | 19.68        | 4.2              |  |
| 50% aerogel-enhanced plaster     | 515                  | 0.0724                  | 27.21        | 2.3              |  |
| 70% aerogel-enhanced plaster     | 237                  | 0.0323                  | 27.75        | 1.8              |  |
| 80% aerogel-enhanced plaster     | 204                  | 0.0272                  | 31.00        | 1.8              |  |
| 90% aerogel-enhanced plaster     | 199                  | 0.0270                  | 32.72        | 1.6              |  |
| Aerogel blanket                  | 160                  | 0.0179                  | 23.12        | 13.2             |  |
| Aerogel fiberboard               | 160                  | 0.0195                  | 46.03        | 11.7             |  |
| Aerogel gypsum board (type<br>A) | 350                  | 0.0392                  | 64.33        | 3.2              |  |
| Aerogel gypsum board (type<br>B) | 250                  | 0.0416                  | 32.75        | 3.3              |  |

Table 5-4. Characteristics of aerogel-enhanced insulations under standard conditions (23.8°C and 50%RH).

# **5.2.Results of the aging tests**

## 5.2.1. Effect of aging on aerogel-enhanced plasters

The initial thermal conductivity ( $\lambda_0$ ) of the ad-hoc created aerogel-enhanced plaster samples was measured to be between 0.15 W/m.K and 0.026 W/m·K for 0% and 90% aerogel content respectively. The thermal conductivity of all aerogel-enhanced plasters as a function of the aging period is shown in Figs. 5-17 to 5-22. As shown, the thermal conductivity of the pure, 25% and 50% aerogel-enhanced plasters increased with aging under different climatic factors. Reversely, aging had no significant impact on the 70%, 80%, and 90% aerogel-enhanced plasters. The consistency of the thermal behavior of the plasters with a higher level of aerogel content provides long-term reliable performance, which is a crucial factor for energy analysis and building envelope design.

Among all of the aging factors, the elevated temperature had the least impact on thermal conductivity of aerogel-enhanced plasters, while high humidity exposure had the greatest impact.

As mentioned elevated temperature did not have any significant impact on the thermal performance of the samples; the greatest effect of aging under elevated temperature was observed in pure high-performance plaster (Fig.5-17), which led to 5% degradation of thermal performance after 20 years of aging. The average induced changes in thermal conductivity of all aerogel-enhanced plasters after 20 years of aging under elevated temperature was only 1.8%  $(\pm 1.64\%)$ .

Similar to the elevated temperature, freeze-thaw cycles did not have any significant effect on the thermal conductivity of the samples. At the worst case, the aging under freeze-thaw cycles resulted in 6% increase in thermal conductivity of the pure plaster (Fig.5-17). The average freeze-thaw effect on all aerogel-based plasters after 20 years of aging was 2.8% ( $\pm 0.84\%$ ).

Unlike elevated temperature and freeze-thaw cycles, high humidity exposure degraded the thermal resistance of most of the samples. Humidity-driven aging, like aging due to elevated temperature and freeze-thaw cycles, had the greatest impact on the pure plaster which resulted in 27% increase in thermal conductivity after 20 years of aging (Fig.5-17). The average induced

changes in thermal conductivity of all aerogel-based plasters after 20 years of aging under high humidity was  $14.6\% (\pm 2.79\%)$ .

In terms of weathering (combined effect of heat, moisture, and UV) similar results to the high humidity were observed. The thermal conductivity of the pure plaster increased by 25% after 20 years of aging under weathering, simulated using a combination of UV radiation, high relative humidity, and elevated temperature. The weathering-driven aging resulted in 9.4% ( $\pm$ 6.19%) degradation of thermal performance of aerogel-based plasters after 20 years of aging. Although in some cases weathering (combinational effect of heat, moisture, and UV) resulted in greater changes in thermal conductivity than high humidity, based on the results of humidity and temperature driven agings and with respect to the previous literatures, it is suggested that humidity as a part of weathering has led to main changes in thermal conductivity. This means that the effect of other factors alone (high temperature or UV) were not significant.

Physical inspection of the samples during and after the aging periods showed that the appearance of the samples was generally unchanged. Although, long-term aging under elevated temperature caused some minor cracks on the surface of the plasters with more than 70% aerogel content (Fig. 5-16).



Figure 5-16. Minor cracks on 80% aerogel-enhanced plaster caused by elevated temperature aging.



Figure 5-17. Effect of aging on the thermal performance of pure reference plaster samples.



Figure 5-18. Effect of aging on the thermal performance of 25% aerogel-enhanced plaster samples.



Figure 5-20. Effect of aging on the thermal performance of 50% aerogel-enhanced plaster samples.



Figure 5-19. Effect of aging on the thermal performance of 70% aerogel-enhanced plaster samples.



Figure 5-22. Effect of aging on the thermal performance of 80% aerogel-enhanced plaster samples.



Figure 5-21. Effect of aging on the thermal performance of 90% aerogel-enhanced plaster samples.

Figures 5-23 to 5-28 show how thermal conductivity changes with temperature for aged and nonaged plaster-based samples. The relationship between thermal conductivity and temperature is linear for all materials; however, for pure plaster (Fig.5-23), 25% aerogel-enhanced plaster (Fig. 5-24), and 50% aerogel-enhanced plaster (Fig.5-25) the slope of the dependence ( $2.4\pm1.4$  e-4) is significantly greater than that of 70% aerogel-enhanced plaster (Fig.5-26), 80% aerogelenhanced plaster (Fig.5-27), and 90% aerogel-enhanced plaster (Fig.5-28) ( $0.47\pm0.3$  e-4). It seems that aging process has no significant impact on the relationship between thermal conductivity and temperature; the slope of the temperature vs. lambda plot for pristine samples is almost equal to the aged ones.



Figure 5-23. Induced effect of climatic aging on the thermal conductivity changes of reference pure plaster samples.



Figure 5-24. Induced effect of climatic aging on the thermal conductivity changes of 25% aerogelenhanced plaster samples.



Figure 5-26. Induced effect of climatic aging on the thermal conductivity changes of 50% aerogelenhanced plaster samples.



Figure 5-25. Induced effect of climatic aging on the thermal conductivity changes of 70% aerogel-enhanced plaster samples.



Figure 5-27. Induced effect of climatic aging on the thermal conductivity changes of 80%aerogel-enhanced plaster samples.



Figure 5-28. Induced effect of climatic aging on the thermal conductivity changes of 90% aerogel-enhanced plaster samples.

## 5.2.2. Effect of aging on aerogel-enhanced blankets and boards

The induced changes in thermal conductivity of aerogel-enhanced blankets and boards as a function of aging time are shown in Figs. 5-29 to 5-32.

Figure 5-29 shows the effect of aging under various stressed conditions on the aerogel-enhanced blanket. The aging under elevated temperature and freeze-thaw cycles had no significant impact on the thermal performance of aerogel-enhanced blanket (1%); while weathering and humidity-driven aging resulted in a higher increase in thermal conductivity by 10% and 8.4% respectively.

Figure 5-30 shows the effect of aging on the aerogel-enhanced fiberboard. Among all tested samples, aerogel fiberboard showed the most persistent thermal conductivity and was minimally affected by climatic aging stresses. The behavior of fiberboard was similar under different aging factors, and none of the factors had any significant effect on the thermal behavior of it. The thermal conductivity of the fiberboard after more than 20 years of age under various conditions increased by  $0.73\% \pm 0.74$ .

The effect of aging on aerogel-based gypsum boards (types A) are shown in Fig.5-31. The humidity resulted in the greatest impact on thermal conductivity of the gypsum boards (7.1%). Twenty years of aging under freeze-thaw cycles, elevated temperature, and weathering led to 1.8%, 2.6%, and 4.6% respectively, increase in thermal conductivity of aerogel gypsum board type A.

The effect of aging on aerogel-based gypsum boards (types B) are shown in Fig.5-32. The humidity resulted in the greatest impact on thermal conductivity of the gypsum boards (9.4%). In the gypsum board type B, the effect freeze-thaw cycles, elevated temperature, and weathering was 3.8%, 3.4%, and 3.6% increase in thermal conductivity respectively.



Figure 5-30. Effect of aging on aerogel blanket samples.



Figure 5-29. Effect of aging on aerogel fiberboard samples.



Figure 5-31. Effect of aging on aerogel gypsum board (type A) samples.



Figure 5-32. Effect of aging on aerogel gypsum board (type B) samples.

Figures 5-33 to 5-36 show the changes of thermal conductivity with temperature for aged and non-aged fiberboard and gypsum based samples. The relationship between thermal conductivity and temperature is linear for all aerogel-enhanced blankets, fiberboards, and gypsum boards. The slope of the dependence is like the high aerogel-enhanced plasters (>70% aerogel-enhanced plaster) ( $0.67\pm0.4$  e-4).



Figure 5-33. Induced effect of climatic aging on the thermal conductivity changes of aerogel blanket samples.



Figure 5-34. Induced effect of climatic aging on the thermal conductivity changes of aerogel fiberboard samples.



Figure 5-35. Induced effect of climatic aging on the thermal conductivity changes of aerogel gypsum board (type A) samples.



Figure 5-36. Induced effect of climatic aging on the thermal conductivity changes of aerogel gypsum board (type B) samples.

# 6. Discussion

In this study, the main objective was to investigate the thermal performance of aerogel-enhanced materials under different temperature and moisture conditions and predict the long-term performance of these innovative, high-performance insulating materials. Also, creating new aerogel-enhanced plasters, consist of hydrophobized granular silica aerogel (25-90 vol.%) and hydraulic lime based plaster, was targeted in this research to assess the capability of the renders regarding insulating properties. Currently, the only commercially available aerogel-enhanced plaster is manufactured in Switzerland by FIXIT group; while the aerogel that they are utilizing is supplied by Cabot aerogel Inc. in the United States. This study showed the feasibility of aerogel-enhanced plaster production in North America using local materials and resources. It should be considered that local manufacture of aerogel-enhanced plaster significantly lowers the related costs. The 70% aerogel-enhanced plaster produced in this study showed similar thermal conductivity of the FIXIT222 manufactured by FIXIT group (Fixit AG, 2013); although FIXIT222 and 70% aerogel-enhanced plaster produced in this research, was stronger adhesive properties of the FIXIT222 compared to 70% aerogel-enhanced plaster produced in our lab.

Currently, plaster renders are not vastly used in the construction industry of North America, unlike European or Asian countries. The investigated aerogel-based plasters may be considered as a basis to develop and evaluate other aerogel-based building materials such as stucco (which is widely considered as interior/exterior coatings in North America).

Besides production of new high-performance insulating plasters, a variety of aerogel-enhanced commercially available aerogel-based materials including aerogel-enhanced blankets, fiberboards and gypsum boards were supplied from industry and investigated.

Before analyzing the thermal performance of the samples, their main characteristics including density, water vapor permeability, hydrophobicity, water sorption behavior, and their moisture storage capacity were experimentally investigated. In next step, the temperature and moisture-driven changes of the thermal conductivity of the samples were investigated and quantified. And finally, the thermal performance of the samples over an extended period under various climatic stresses were analyzed.

The behavior of the aerogel-enhanced plasters under different conditions revealed that the thermal conductivity is strongly affected by the aerogel content of the render. Increasing the percentages of aerogel granules in the plaster content lowered the material density and thermal conductivity. However, there is a trade-off between the aerogel content and the mechanical strength of the material. Therefore, the optimal content needs to be explored depending on the application.

The present study showed that the 70% aerogel-enhanced plaster, had optimal thermal performance and density ( $\lambda \sim 0.032$  W/m·K,  $\rho \sim 230$  kg/m<sup>3</sup>). It was noted that increasing aerogel volumetric content above 70%, marginally improved thermal characteristics while significantly lowered the mechanical strength. Aerogel based blanket and fiberboard showed superior thermal performance ( $\lambda \sim 0.017$  W/m·K and 0.019 W/m·K respectively) at standard conditions (50% RH and 23.8°C) among all tested materials.

The thermal conductivity of pure aerogel granules has been reported by Buratti et al. (Cinzia Buratti et al., 2017) to be 0.0186 W/m·K and 0.0196 W/m·K at 10°C and 23°C respectively; these values are approximately equivalent to the thermal conductivity of aerogel enhanced blanket (0.0171 W/m·K and 0.0179 W/m·K at 10°C and 23°C respectively) and fiberboard (0.0190 W/m·K and 0.0195 W/m·K at 10°C and 23°C respectively) measured in this study. It should be considered that in pure aerogel the space between granules is filled by air, in aerogel-based blanket and fibers the gap is filled by fibers, which have more or less similar thermal performance with air; however, in aerogel plaster based samples, the cavities are filled with plaster which has significantly lower thermal resistance compared to air; therefore, the measured thermal conductivities for plaster based samples are greater than that of pure aerogel granules.

Testing the samples under various temperature and humidity conditions signify that the superior thermal properties might be obtained on specimens that do not contain any free moisture, although in real service life such conditions may not be realized. Similar to the other insulations, the thermal conductivity of aerogel-enhanced products is dependent on variables, such as mean temperature, temperature difference, and moisture content. These dependencies should be measured at conditions typical of use. Based on the results of this study, a linear relationship was found between temperature and thermal conductivity; Thermal conductivity of the aerogel-based samples slightly increased with temperature. The greatest impact of temperature on thermal

conductivity was observed in the aerogel gypsum board samples with 12% degradation at the maximum test temperature (+50°C) in comparison with the standard condition. However, moisture content had a much greater impact on the thermal degradation of the samples and significant degradation in thermal performance of all investigated samples, except aerogel fiberboard, was observed when subjected to extreme humidity levels. In fact, thermal conductivity of aerogel-enhanced materials is highly correlated to their high porosity, and hence to the high amount of air contained within them; if part of the air is replaced by water, which has a significantly higher thermal conductivity ( $0.600 \text{ W/m} \cdot \text{K}$ ) than that of air ( $0.02 \text{ W/m} \cdot \text{K}$ ), a global reduction of material thermal resistance can be reasonably expected. Therefore, considering the effects caused by movements and the distribution of moisture within the products is essential for the assessment of their thermal properties.

The thermal conductivity elevation of aerogel-enhanced insulating materials due to extremely high levels of moisture and temperature (>40°C and >90% RH respectively) was found to be statistically significant. Negligible change in thermal performance of the materials was observed due to moisture content occurring under moderate wetting condition ( $\leq$ 70% RH). The observed changes in thermal properties of aerogel-based insulations may affect the building energy load and need to be considered during the envelope design based on the regional climatic conditions if protection plans are not considered to keep them dry.

Aerogel-based insulations are well-known for their high thermal resistance. Therefore, moistureremoval mechanisms (drying) must be considered to maintain their superior thermal performance under various condition. Water might be built up in diverse ways, i.e., liquid moisture accumulation within the material or vapor diffusion through the assembly. Based on the envelope, a mechanism must be designed to prevent moisture entrapment and accumulation within the aerogel-based insulation. As an example, a vapor retarder can be installed on the warm side of the aerogel-enhanced insulation layer to protect it from excessive moisture flow. The water vapor permeability test results revealed that all of the samples were water vapor permeable, therefore, water vapor movement due to diffusion has the potential to dry the materials; diffusion drying can occur either to the exterior or interior based on the direction of the vapor pressure gradient and the vapor flow resistance of the layers within the enclosure assemblies. However, diffusion drying of moisture is often restricted depending on the local climate and seasonal conditions, and may only be relied upon during certain times of the year. Air movement through the assembly can also contribute to drying.

Aerogel-enhanced materials were found to be water vapor permeable according to the water uptake measured from sorption curves; this reflects the hydrophilic properties of the materials rather than hydrophobic properties which had been suggested by other studies (Cinzia Buratti et al., 2014; Riffat & Qiu, 2012; Stahl et al., 2012).

To validate the findings of this study the obtained results for aerogel blanket were compared against the Aspen database provided in WUFI software (Künzel, 1995). Figures 6-1 and 6-2 show the comparison between observed experimental results versus the Aspen datasheet. It should be considered that in the database provided by Aspen the experimental conditions (e.g., RH and temperature) are not specified, therefore, the comparison may contain some errors due to different experimental conditions. In Fig. 6-1 the experimental results correspond to 50% RH but unknown RH for WUFI data; in Fig. 6-2 the experimental temperature is 23°C. However, the temperature for WUFI data is not specified. Also, the material employed in this study was the white aerogel blanket, while the WUFI datasheet is for gray aerogel blanket (both manufactured by Aspen aerogel), this may also contribute to the observed differences in Fig 14. Although there are minor differences in thermal conductivity between experimental and WUFI data(it seems that the thermal conductivity of aerogel blanket is under estimated in WUFI database) for aerogel blanket, the trend of changes is very similar (p<0.05).



Figure 6-1. Thermal conductivity vs. temperature comparison of experimental and WUFI data



Figure 6-2. thermal conductivity vs. moisture content comparison of experimental and WUFI data.

To evaluate the long-term performance of the samples, a series of accelerated climate aging tests were performed. Several aging apparatuses, which were subjecting the test samples with various climate exposures, were utilized in the laboratory according to different aging methods and standards. The building materials are supposed to withstand these climate exposures for suitable performance in their prospective application. Based on the analysis of the results the elevated temperature and freeze-thaw cycles had a minimal effect on the thermal performance of the aerogel-based samples, while high humidity had the greatest impact on the thermal resistance of the samples. The resistance of the plaster based samples towards freezing points passes during freeze-thaw cycles has a vital importance, while most of the composite structure materials are susceptible to freeze-thaw damages.

The induced percentage changes of thermal conductivity of all investigated samples of aerogelenhanced plasters, blankets, and boards under various aging factors are shown in Fig. 6-3. This figure shows a general lack of "escalation" effects, as the only significant aging process was the high humidity, whereas the elevated temperature, the freeze-thaw cycles, and the UV radiation had limited effects on the thermal conductivity results.



Figure 6-3. Aging effect for an equivalent time of 20 years under various conditions on the  $\lambda$  of the samples.

Pure plaster samples had the weakest long-term thermal performance, having the greatest degradation of the thermal conductivity (25% under weathering-driven aging) compared to all other samples. The aerogel fiberboard showed that the superior long-term thermal performance is minimally affected by the different aging factors. Aerogel-gypsum board type A showed overall better performance than type B. In the aerogel boards and 70%, 80% and 90% aerogel-enhanced plasters, high humidity resulted in the greatest changes in thermal conductivity compared to the other aging factors. In pure, 25%, and 50% aerogel-enhanced plaster and aerogel blanket, the most significant changes were observed after aging under weathering.

The elevated temperature and freeze-thaw cycles had the smallest impact on the long-term thermal behavior of the aerogel blanket compared to all other samples (excluding the fiberboards).

Figure 6-4 illustrates a comprehensive comparison between thermal conductivity of aerogelbased insulations including aerogel-based plaster (70%), blanket, fiberboard, and gypsum board (before and after aging) and non-aged conventional insulation materials (including polyisocyanurate foam, polystyrene foam, mineral wool, fiberglass batts and blown insulation).
The thermal performance of aerogel blankets and fiberboards even after 20 years of aging is superior to that of conventional insulations. The 70% aerogel-enhanced plaster (before and after aging) has more efficient thermal performance than the mineral wool, fiberglass batts, and blown insulation. The thermal performance of 70% aerogel-enhanced plaster is inferior to the polyisocyanurate and polystyrene foams when their nominal thermal conductivity under standard



Figure 6-4. Comparison between thermal conductivity of aerogel based insulations (before and after aging) and non-aged conventional insulation materials.

laboratory conditions are compared. However, it should be noted that the thermal performance of the polyisocyanurate foam is not linear and has minimal value at standard laboratory condition of 24°C and 50% RH (~0.023 W/m·K); however, at lower/higher temperatures (-20 °C and +50 °C) it has significantly higher thermal conductivity (~0.037 W/m·K) (Umberto Berardi & Naldi, 2017). On the other hand, the thermal conductivity of the aerogel-based insulations is stable and showed consistent values at a lower temperature. Therefore, at lower temperatures than the standard condition when realistically aerogel-enhanced products are used, aerogel-enhanced plasters still perform significantly better than other traditional materials (e.g., a traditional gypsum plaster has a thermal conductivity typically above 0.15 W/m·K).

Except thermal degradation driven by high humidity or water exposure, the aerogel-enhanced materials showed outstanding resistance towards other climate factors including heat, UV, and freeze-thaw cycles. Maintaining a key property, which is thermal conductivity, over time and under various climate condition has significant importance for all Superinsulations. However, not every material shows such a high durability over time; i.e., the thermal resistance of the vacuum insulation panels will reduce over time, based on several factors and variables; and this is unavoidable as VIP depends on an ideal barrier and seal system, where no absolute barrier and seal materials exist in reality (Morlidge, 2012). The aluminum coating, which protects the core material, is always prone to puncturing which significantly increases the internal air pressure and thus worsens the thermal performance. The thermal performance of VIPs is highly affected by the boundary conditions (De Meersman, Van Den Bossche, & Janssens, 2015). Lorenzati et al. investigated the effect of temperature on the thermal performance of funed silica based VIPs. Their experimental analyses showed that thermal conductivity of VIPs could increase up to 45% when the average temperature ranges from 2 to 50°C (Lorenzati, Fantucci, Capozzoli, & Perino, 2017).

Physical inspection of the samples during and after the aging periods showed that the appearance of the samples, observed with naked eye, remains unchanged. However, regarding the linear relationship between the extraordinary properties of aerogel-based materials and their porous structure, the physical structure of the samples was studied before and after aging periods. The increase in thermal conductivity of the samples after aging time might be due to the breakage of the silica network (Ihara, Jelle, et al., 2015). The surface morphology and composition of the fully prepared samples before and after aging were scanned by Scanning Electron Microscope (JSM-6380LV, JEOL, Germany). Figure 6-5 shows the SEM images of one of the samples before and after aging under different stressed factors. The primary analysis of the images showed no notable change within the physical structure of the samples, however a comprehensive study in this field is suggested.



Figure 6-5. SEM images of 70% aerogel-enhanced before and after aging.

The findings of this research such as thermal conductivity - moisture dependence and temperature dependence, moisture storage function, water vapor permeability, and durability are very useful to improve the database of simulation studies in building energy software (i.e. Energy Plus) or hygrothermal studies of building components (i.e. WUFI), where aerogel-based insulations are employed in the building envelope. Engineers and designers can reliably predict the behavior of aerogel-enhanced products at different climatic contexts and estimate the performance decay.

## 7. Limitation of the study

Although this research provides new insights into the hygrothermal performance and long-term behavior of new high-performance of aerogel-enhanced products, various problems and limitation were encountered in conducting the research, which must be viewed regarding caveats. The topic of accelerated aging tests to demonstrate the long-term performance will raise interest for material research. However, the available standards and literature on the aging of building materials are rare and difficult to find. Most of the literature was related to the appliances, and in the case of materials, they have focused on the coatings, which reduced the scope of literature.

Another limitation is the number of the specimens for the tests. On the one hand, it was a challenge to get enough number of samples from the manufacturer for the commercially provided ones, which did not offer a lot of samples. On the other hand, the created samples were dependent on the availability of the base components; silica aerogel granules and hydraulic lime based plaster, as well as the ability to construct them in the university laboratory (workshop). The commercial products, as well as base components of the prepared samples, were supplied from overseas which was a time-consuming process.

Aerogel releases a lot of dust and requires strong ventilation systems and protective mask and gloves to work effectively in a closed laboratory. It was challenging to ventilate the strong dust, which was produced in the laboratory when aerogel-based plaster samples were constructed. Therefore, there was a limitation on sample construction.

Furthermore, the accelerated aging machines, as well as the humidity and environment chambers, were supposed to maintain their controlled environment (humidity and temperature) within the test period; however, the chambers were opened time to time. Either one or more samples needed to be removed from the chambers for thermal conductivity test and gravimetric analysis or the other students were opening the equipment to access their samples. Therefore, although it was attempted to maintain the required conditions, but still, there was some inconsistency, which could compromise the results to some degree.

There also may be some errors in the measurements contributed by the uncertainty of the test apparatus. Although reading errors of measurement devices are unavoidable, utilization of more accurate devices with smaller uncertainties would reduce experimental errors.

## 8. Conclusions

While aerogel-enhanced products are still in a trial phase for the building insulation market, their durability and reliable long-term performance are crucial for their widespread adoption. Long term behavior may be assessed over a lengthy process of natural aging, however in this study accelerated laboratory aging was employed to simulate the effect of several years of aging under use condition in only a few months.

The different aerogel-based samples (plasters, blankets, and boards) showed outstanding characteristics such as lightweight, high thermal resistance, water vapor permeability, and durability which make them optimal insulation choices.

Testing the samples under various hygric conditions signified that the thermal performance of the samples in minimally affected by temperature; however, the thermal conductivity of all of the samples, except aerogel fiberboard, increased significantly when the samples are subjected to high humidity levels or are aged due to moisture exposure. Therefore, adequate provisions are required to accommodate moisture content levels of the aerogel-based materials to achieve their optimal performance. Proper moisture management strategies through continuous moisture retarder layer, drainage plane, a capillary break, and balance of wetting and drying, must be considered in envelope design. It should be mention that in general, moisture management is a prerequisite consideration for envelope design as the thermal performance of all building materials and insulations degrades under higher moisture content and the possibility of condensation increases.

The long-term performance of the aerogel-based products under various climatic stresses was evaluated through the changes in thermal conductivity of the samples. The main finding of the present study is that the performance of the aerogel-enhanced materials after being aged under various climatic stresses is still very close to their pristine condition, which indicates the acceptable durability of aerogel-enhanced materials in maintaining their superior thermal performance over time.

Among all the studied climatic aging factors, high humidity had the greatest impact on the thermal performance of aerogel-enhanced materials. The performance degradation was also the results of the residual moisture in the material exposed to such a conduction and which definitively contributed to higher values of the thermal conductivity. Although in some cases weathering (combinational effect of heat, moisture, and UV) resulted in greater changes in thermal conductivity than high humidity, it is suggested that humidity as a part of weathering has led to main changes in thermal conductivity. Therefore, the effect of other climatic factors alone (high temperature or UV) were not significant. As shown in Fig. 6-4, after 20 years of aging under high humidity, the thermal conductivity of 70 %aerogel-enhanced plaster increased by 0.003 W/m·K and reached to 0.035 W/m·K, which is still comparable to the thermal conductivity of conventional insulations, including polyisocyanurate and polystyrene foams. Among all assessed aerogel-based products, blankets and fiberboards showed superior long-term performance compared to all other aerogel-based samples and conventional materials.

Among all tested materials, aerogel based blanket and fiberboard showed outstanding thermal performance ( $\lambda$ ~0.018 and 0.019 respectively) and the least thermal conductivity alternation under various temperature and humidity variations.

Outstanding thermal performance, low density, form and shape adaptability, simple installation and water vapor permeability factors of aerogel-enhanced materials made them promising products for the building insulating market. The next step towards making widespread usage of aerogel-enhanced products would be the research efforts on time and cost optimized synthesis and manufacturing process of these materials.

## 9. Future work

To investigate the correlation between degradation of aerogel-based materials and the changes in their physical structure a comprehensive SEM study needs to be conducted.

Material characterization by Fourier transform infrared (FTIR) analysis before, during and after an accelerated climate aging is suggested. FTIR analysis may provide additional information about both the extent of the aging and the degradation mechanisms. The attenuated total reflectance (ATR) technique utilized in FTIR spectroscopically investigations make it possible in principle to measure chemical changes directly in the material.

Conducting structural tests on aerogel-enhanced renders to investigate the stress-strain behavior is recommended.

Also, a comprehensive cost-effectiveness analysis on aerogel-based products is recommended. Currently, aerogel-based products are relatively expensive due to their complex production process and costly raw materials, a research project could be focused on feasibility of different methods to lower the overall cost of aerogel-based superinsulations.

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