BYGT2900 Bacheloroppgave bygg

Gjennomsiktig, gjennomskinnelig og ugjennomskinnelig aerogel til bygningsanvendelser: En oversikt over dagens produkter og framtidige forskningsretninger

Transparent, translucent and opaque aerogels for building applications: A state-of-the-art review and future research pathways

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Problemdefinering/prosjektbeskrivelse og resultatmål:

I prosjektet skal gruppen lage en artikkel med oversikt over eksisterende aerogel-produkter. Målet i prosjektet er å lage en oversikt over egenskapene til aerogel-produktene som er tilgjengelig på markedet. Dette innebærer hvilke styrker og svakheter de har og hva som er viktig å forbedre gjennom framtidig forskning.

Keywords:

Silica aerogel

Super critical drying

Aerogel glazing systems

Building application

Material properties

State-of-the-art review

Aerogel incorporated concrete, mortar, and plasters

Future research pathways

Preface

This article is submitted to *Energy and Buildings*. The authors have chosen to write a scientific article on aerogel and its building applications. It is written as a scientific article with an aim of publishing as a journal article to give the public access to the information provided. The motivation for writing this article was to reduce the barrier for engineers to incorporate aerogel products into new projects. The authors' hope is that this can contribute to lowering the CO_2 emissions from heating and cooling of buildings, which is a substantial part of the global emissions. An overview of commercially available aerogel products for building applications was assembled, to facilitate easy access for engineers and thus reducing the search time required to incorporate such products in future projects. The article is a bachelor's thesis as a final assignment in the bachelor's education. It has taken about 5 months to assemble the products in the appendices and write the article.

We would like to thank our supervisor Bjørn Petter Jelle for his quick and thorough feedback to our enquiries throughout the work with this paper. Your patience and encouragement have been crucial for our motivation and workflow. Your willingness to share your knowledge has been invaluable.

Abstract

An extensive review of commercial aerogel products is provided, devoted to products with properties intended for use in the building sector. Opaque, translucent, and transparent aerogel products are accounted for, along with miscellaneous mixtures with aerogel and other materials. Thermal, optical, acoustic, fire and mechanical properties are included for the different aerogel products where the manufacturer has provided such information. Firstly, the process for production of aerogel is explained briefly. Then, the various properties of aerogel are presented, followed by a state-of-the-art review including constructions with aerogels and retrofitting examples. Finally, possible pathways for future research are explored with an aim of improving the aerogel properties for building purposes and decreasing the high production costs which currently are preventing aerogel products from spreading across the commercial market.

Sammendrag

En omfattende oversikt over aerogel produkter er gitt. Den fokuserer på egenskaper som egner seg for bruk i byggeindustrien. Ugjennomskinnelige, gjennomskinnelige og gjennomsiktige aerogel produkter er tatt i betraktning, sammen med diverse blandinger av aerogel og andre materialer. Termiske, optiske, akustiske, brann og mekaniske egenskaper er gjort rede for, i de tilfellene produsentene har gitt tilgang til det. Først forklares kort produksjonsprosessen for aerogel. Deretter presenteres de ulike egenskapene til aerogel, etterfulgt av en oversikt over produkter og kompositter som er utviklet som er tilgjengelige på markedet i dag. Her nevnes det også eksempler på bruk av aerogel i bygninger og under renovering. Til slutt utforskes mulige framtidige forskningsretninger med mål om å forbedre egenskapene til aerogel for bygningsanvendelser og å redusere de høye produksjonskostandene, som foreløpig forhindrer aerogelprodukter fra å spre seg i det kommersielle markedet.

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Abbreviations

AGU = Aerogel glazing unit

AIC = Aerogel incorporated-concrete

AIM = Aerogel incorporated-mortar

APD = Ambient pressure drying

DGU = Double glazing unit

FRL = Fire resistance levels

HPAC = High performance aerogel concrete

HRR = Heat release rate

LSF = Light steel frame

PHRR = Peak heat release rate

SA % = Silica-aerogel-percentage

SCD = Super critical drying

SHGC = Solar heat gain coefficient

STC = Sound transmission class

TEOS = Tetraethyl orthosilicate

THR = Total heat release

TSET = Total solar energy transmittance

TTI = Time to ignition

VIP = Vacuum insulation panels

VLT = Visible light transmission

Transparent, translucent and opaque aerogels for building applications: A state-of-the-art review and future research pathways

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Abstract

An extensive review of commercial aerogel products is provided, devoted to products with properties intended for use in the building sector. Opaque, translucent, and transparent aerogel products are accounted for, along with miscellaneous mixtures with aerogel and other materials. Thermal, optical, acoustic, fire and mechanical properties are included for the different aerogel products where the manufacturer has provided such information. Firstly, the process for production of aerogel is explained briefly. Then, the various properties of aerogel are presented, followed by a state-of-the-art review including constructions with aerogels and retrofitting examples. Finally, possible pathways for future research are explored with an aim of improving the aerogel properties for building purposes and decreasing the high production costs which currently are preventing aerogel products from spreading across the commercial market.

1 Introduction

The building and construction sector account for approximately 40 % of the world's CO_2 emissions (UN, 2019). This substantial contribution to global warming must be reduced in pursuance of achieving the United Nations goal of less than two centigrades warming defined in the Paris Agreement (UN, n.d.).

Heating and cooling of buildings is the most energy consuming exercise which is performed in the building industry. Electricity and heating in buildings account for 18 % of the global energy and process-related CO_2 emissions (IEA, 2021). The global energy demand is expected to increase with close to 50 % by 2050 (Kahan, 2019).

To decelerate this future energy consumption, new and more energy efficient materials and solutions are required. A part of the solution may be better thermal insulation technologies for buildings, thus reducing the necessity of energy used for heating and cooling.

Aerogel (Jelle & Gao, 2019) is an insulation material, discovered in 1930 by Dr. Samuel Stephen Kistler (Ayers, 2000). In the following years considerable technological advances have been made in the field. Aerogel is likely the product that has the lowest mass density, but also the lowest thermal conductivity of any solid with air-filled pores at atmospheric pressure. With these properties, the application range widens (He et al., 2016). Aerogel is currently used in sectors such as the oil, building, medical transportation, and space travel industries.

Aerogel is of great interest in the building sector due to its low thermal conductivity, acoustic properties and optical properties. Aerogel comes in three different forms: opaque, translucent and transparent. Therefore, aerogel may be applied to various building parts. For example, both transparent and translucent aerogel can be used for windows and solar walls. Opaque aerogel can be used as thermal insulation in walls, floors and ceilings.

The most common type of aerogel is silica aerogel. The solid component in silica aerogel consists of three-dimensional intertwined clusters of SiO2 (InsulTech, 2017). Aerogel contains up to 99.8 % air by volume (Thomas, 2012). Due to these characteristics, aerogel is a very light solid and has good thermal insulation properties. However, aerogel is not widely applied in the building industry yet. Two of the main causes are probably the low mechanical strength and high production costs.

To exploit the low thermal conductivity many studies have been focusing on mixing aerogel with other materials, such as aerogel incorporated-concrete (AIC) ((Gao, Jelle, Gustavsen, et al., 2014), (Ng et al., 2015)) and -mortar (AIM) ((Ng, Jelle, Zhen, et al., 2016), (Ng et al., 2014)) (Wang et al., 2019). Compared to regular concrete, AIC has a substantially higher thermal conductivity, but also lower mechanical strength by up to 90 % depending on the silica-aerogel-percentage (SA %) (Shah et al., 2021). Another example is aerogel incorporated insulation tape and coating. When applied to hot ovens and dryers it is claimed to reduce the energy consumption by 30 % (RovaCorporation, 2019b). This could be used for buildings with further modifications of the product. To the authors' knowledge, products mixed with aerogel are still in an early stage of development and the supply is quite limited in the commercial market.

The objective of this study is to provide an overview of the state-of-the-art aerogel technologies for building applications, and furthermore to explore possible future research pathways. Characteristics of aerogel-incorporated products are also highlighted. The production of aerogels is briefly examined, in addition to the different properties of the material. Building applications with aerogels for both retrofitting and new constructions are treated. Moreover, tables with the market's existing aerogel products and their properties are provided to give the building and construction industry a general overview over accessible products which may be purchased and applied.

2 The making of aerogels

2.1 Aerogel synthesis in general

No solid has yet been discovered with as low conductivity as air. When Kistler invented aerogel early in the twentieth century, his goal was to remove all the water from the gel, resulting in a solid component full of air pockets. Aerogel has been made with several different substances such as gelatin, agar, cellulose, thoria, alumina and silica(Kistler & Caldwell, 1934). The properties of all these products are well qualified to be a good insulating material and can easily get up to 95 % air by volume (Kistler & Caldwell, 1934). However, silica seems to be the most cost efficient and easiest to prepare substance(Kistler & Caldwell, 1934) . Much progress has been made in modern times, but the process still consists of the same steps as in the 1930s, gel preparation, aging and drying. In the following a brief description of the main steps of the process is provided. This paper focuses on silica aerogel.

2.2 Gel preparation

A gel is prepared by mixing a solution with different liquids. First a silica source, for example tetraethyl orthosilicate (TEOS), ethanol, water and catalyst are mixed. Different silicon alkoxides can be used as the silica source, but the most common alkoxide used is TEOS. TEOS, ethanol, water and a hydrochloric acid reacts further in a polycondensation reaction (Pico et al., 2017). The polymerization reaction is a multistep reaction shown in Figure 2.1. The solution hydrolyses with the acid as catalyst in pursuance of forming the gel matrix. Particles of silica are then formed, resulting in a colloidal solution (sol). When the particles attach to each other, a sol chain is formed (Buratti et al., 2021). During the polymerization the viscosity is strengthened, and the sol (chain) changes into a wet gel during its aging(Pico et al., 2017) .

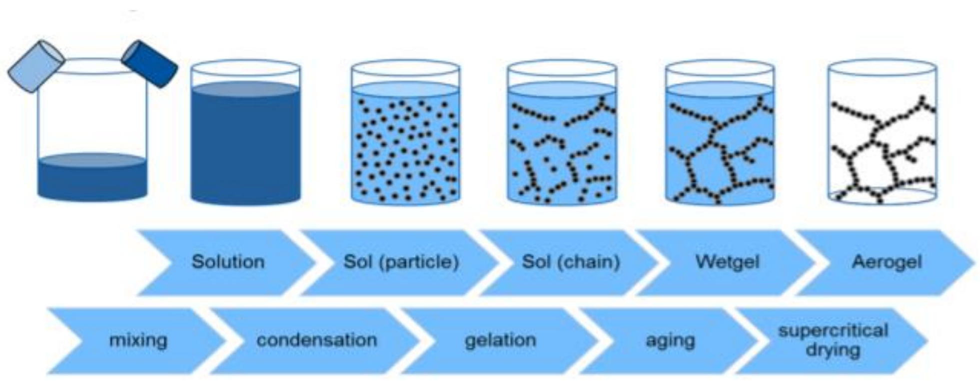

Figure 2.1: *Primary steps for the production process of silica aerogel (Pico et al., 2017).*

2.3 Aging

During condensations and hydrolysis, the gel still contains a large volume of unreacted alkoxide groups (Omranour.H et al., 2014). Therefore, longer aging time is essential for the strengthening of the silica chain (Iswar et al., 2017). Normally, the silica gel ages in the initial solution to dissolve the remaining particles into larger ones (Omranour.H et al., 2014). This process contributes to prevent the gel from shrinking during the drying phase. A possible shrinkage of the gel can cause fractures in the final aerogel product (Iswar et al., 2017).

2.4 Drying

2.4.1 Super critical drying

Wet sol gel is being converted into an aerogel during the supercritical drying (SCD) process (Pico et al., 2017). The structure of the wet sol gel must be preserved to replace the liquid with air. Due to the fragile structure of the wet state gel, this phase needs to be done with careful and accurate precision. The drying phase is critical due to the shrinking and possible fracturing problems. During the SCD-process, some shrinkage will always occur. By removing the liquid part of the gel and filling the voids with air, the surface becomes very fragile to shocks (Tajiri et al., 1995).

Removal of the alcoholic liquids needs to be done under high pressure. An approach for the drying process is using CO_2 as a drying agent to replace the solvent in the aerogel. The carbon dioxide is then heated above the critical point where the required pressure is obtained. CO_2 is well suited for this task, because of the automatic phase transition into gas when the pressure is lowered (sublimation) (Błaszczyński et al., 2013). Depending on the chosen solvent used, SCD can be completed under low temperature or high temperature (Buratti et al., 2021). The various temperatures can further affect the chemical composition and the structure of aerogels.

2.4.2 Ambient pressure drying

Ambient pressure drying (APD) is the drying process that takes place under high temperature, with no added pressure(Shi et al., 2006) . The wet sol gel is exposed to high temperature which then causes the liquids to evaporate, the liquid voids are then filled with air. Therefore, the structure of the wet sol gel needs to be intact during this critical phase. To reduce surface tension effects, a solvent exchange with multiple processing steps is necessary. This causes a long processing time (Buratti et al., 2021). The long processing time is necessary for allowing the liquid to exit to the exterior slowly. APD is nevertheless the most cost-effective way of drying. This is due to the high energy requirement used in the super critical drying phase (Calisesi, 2017).

2.4.3 Freeze-drying

Like the other drying methods, pressure and low temperature is applied during freeze-drying to extract the liquid from the gel. Freeze-drying is known as one of the most efficient methods of extracting the solvent from the wet gel. What distinguishes this from other methods is that the quality of the finished dry product is better preserved (Simón-Herrero et al., 2016). The drying consists of a three-step process: freezing, primary drying and secondary drying.

The freezing occurs at temperatures between -50 and -85 ℃, and is the most critical process (Simón-Herrero et al., 2016). The wet gel is quickly frozen to reduce water vapor and control the size of the ice crystals formed during freezing. The ice crystals that are formed are closely related to how fast the gel freezes and how low the temperature is. In this process all drying is performed by sublimation. Sublimation is the transition from solid to gas, without first becoming liquid.

During the sublimation step, approximately 95 % of all the liquid is converted to gas and evaporates (Simón-Herrero et al., 2016). The temperature is now raised in this step to contribute to a better sublimation. At the same time the pressure is reduced to very low levels. This is the most tedious step of the drying process.

Secondary drying consists of removing the remaining water from the gel. In the previous process, the temperature was increased, which means that the remaining water is in liquid form. The temperature now increases even more to facilitate the removal of residual solvents. At the same time the pressure decreases. When this process is complete, the aerogel contains as little liquid as 1 to 4 % (Simón-Herrero et al., 2016), depending on how successful the drying process is.

2.5 Cost and energy consumption of silica aerogel production

At the current price level silica aerogel is not likely to spread across the commercial market. A study from 2019 mapped the production costs to the different stages in the production cycle for hybrid silica aerogel using ambient pressure drying (Garrido et al., 2019). The study was performed in a laboratory and was not subject to the cost advantage that a scaled manufacturing procedure has. The results showed that aerogel is very expensive compared to other insulation materials. A scaled manufacturing process (Koebel et al., 2016) will reduce the costs, but probably not enough to achieve a satisfying price level for the commercial market.

In the experiment they found that the raw materials for aerogel powder cost 640 EUR per kilogram. Sodium silicate, bis(timethylsilyl)amine (HMDZ), nitric acid (HNO_3) and n-hexane was used. HMDZ was the most expensive additive, summing to 450 EUR. For monolithic aerogel, tetraethyl orthosilicate (TEOS), isopropyl alcohol (i-PrOH), hydrochloric acid (HCl), ammonium hydroxide (NH_4OH), HMDZ and distilled H_2O was used. The cost for TEOS, NH_4OH, and HMDZ was 255, 120 and 300 EUR per kilogram of aerogel, respectively.

The production cost of the aerogel powder was negligible. In the synthesis stage for monolithic aerogel, two different incubators were used. Using only one of the incubators for both stirring and drying cost 70.53 EUR, while a combination of the two resulted in 12.17 EUR per kilogram of aerogel. This is a drastic decrease and could be important to reduce the costs in a large-scale manufacturing process. The energy consumption in the drying stage was 24.2 kWh/kg for powder and 99.3 kWh/kg for monolithic aerogel (Garrido et al., 2019).

3 Properties of silica aerogel

3.1 Thermal conductivity

Aerogel has a low thermal conductivity (Kistler & Caldwell, 1934). Heat transfer mechanisms through a material is dependent on multiple types of transportation. The types are heat transfer in the gaseous state, heat in gas transferred to heat in the solid component, heat radiation and heat convection. It is difficult to find an overall thermal conductivity because the types of transportation are strongly dependent on each other. The total thermal conductivity λ_{tot} is given by the sum:

$$\lambda_{tot} = \lambda_{solid} + \lambda_{gas} + \lambda_{rad} + \lambda_{conv} + \lambda_{coup} + \lambda_{leak} \tag{3.1}$$

where λ_{solid} is the conductivity of the solid state, λ_{gas} is gaseous conductivity, λ_{rad} is the radiative conductivity, λ_{conv} is the convection conductivity, λ_{coup} is the contribution of coupling effects of the mentioned conductivities and λ_{leak} is conductivity due to air leakage (Gangåssæter et al., 2017)

Results from a study shows that convection has a minimal impact on the U-value of aerogel granulate glazing windows (Ihara, Grynning, et al., 2015). A vacuum can be applied to the aerogel or the glazing units can be filled with low-conductive gases to further reduce convection (Baetens et al., 2011). However, in many cases convection is negligible. In these cases, heat transfer is dependent on differences in local temperature, the effective thermal conductivity λ_{eff} is given by the sum:

$$\lambda_{eff}(T, p_g) = \lambda_s(T) + \lambda_g(T, p_g) + \lambda_r(T) \tag{3.2}$$

where λ_s is the thermal conductivity of the solid, λ_g is the effective thermal conductivity of the gaseous state and λ_r is the radiative conductivity (Ebert, 2011). For aerogel, the transportation of heat from the gas to its solid component and the thermal conductivity in the gaseous state are the main causes for its low thermal conductivity. Both are accounted for when calculating the Knudsen effect, discovered by the Danish physicist Martin Knudsen (Pedersen, 2021).

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3.1.1 Transportation of heat via gaseous phase and from gas to the solid component – The Knudsen effect

The thermal insulation properties of aerogel are mainly caused by the Knudsen effect. Aerogel is a highly porous material, with pores in the nanometer scale. Air particles with high kinetic energy must pass through these pores on their path through the material. The probability of a particle passing through in the direction parallel to the pore channel is very low. It is more likely to enter the pore channel with an angle. This causes the particle to collide in the pore's walls. For every collision, kinetic energy is absorbed by the pore wall (β). At the end of the path, the kinetic energy will be reduced to some degree, depending on the length of the pore compared to the pore diameter. The Knudsen effect occurs when the mean free path (l_g) is much longer than the pore diameter (Φ). A longer mean free path will give more opportunities for a particle to collide in the pore walls, reducing its kinetic energy for every collision. This is the main reason aerogel has good thermal insulation properties (Ülker et al., 2014). Mathematically, the Knudsen effect is calculated by:

$$\lambda_{Kn} = \lambda_{g0} V_g / (1 + \beta Kn) \tag{3.3}$$

where λ_{Kn} is the Knudsen thermal conductivity, which is gas conductivity including the gas/solid state interaction, λ_{g0} is the thermal conductivity of air, V_g is the volume fraction of air voids in the aerogel, β is a simplified parameter for inefficiency taking energy transfer from air molecules to the solid material into account (Ülker et al., 2014). The Knudsen number Kn is given by:

$$Kn = l_g / \Phi \tag{3.4}$$

where l_g is the mean free path of the pores and Φ is the pore diameter. A higher value of the Knudsen number, results in a lower thermal conductivity. The Knudsen number is higher than 1 if the mean free path is longer than the pore diameter. In silica aerogel the mean free path can be much longer than the pore diameter. Division with a Knudsen number larger than one (Eq.3) will cause a reduction in the Knudsen thermal conductivity (Eq.2), resulting in a lower thermal conductivity for silica aerogel (Eq.1) (Ülker et al., 2014).

3.1.2 Radiative heat transfer

Aerogel has a low radiative infrared transmission at low temperatures (Ramakrishnan et al., n.d.). Since the pore diameter of aerogel is much smaller than infrared wavelengths, the amount of scattering is very small. However, the aerogel can absorb and reemit radiation (Caps & Fricke, 1986). Aerogel is optically thick, which is a statistical measure of how many interactions a photon will have with the material on its path through it (Ebert, 2011). For optically thick, absorbing materials, radiative heat transfer is described by radiation diffusion. Therefore, the radiative heat transfer coefficient (λ_r) is given by:

$$\lambda_r(T) = n^2 \, (16/3) \, \sigma \, T_r^3 \, / \, E(T_r) \tag{3.5}$$

where n is the refraction index, which is close to 1 for silica aerogel, E is the temperature dependent absorption coefficient, T_r is the radiation temperature, σ is the Stephan-Boltzmann constant for surface tension (Caps & Fricke, 1986) (Sohn, 2014).

3.2 Optical properties

Aerogel glazing systems ((Gao, Jelle, & Gustavsen, 2014), (Zhao et al., 2020)) are either transparent or translucent. You can see through a transparent aerogel glazing system. Translucent aerogel glazing systems lets light shine through, but there is no visibility through the glass. Transparency is often obtained in monolithic aerogel glazing systems. Granular aerogel ((Ihara, Gao, et al., 2015), (Ihara, Jelle, et al., 2015), (Huber et al., 2017)) glazing systems are translucent. However, both granular and monolithic aerogel holds the same light transmittance properties (Zinzi et al., 2019). These properties are mainly two different scatterings of light: Rayleigh and Mie scattering (Buratti et al., 2021).

3.2.1 Rayleigh scattering in aerogel

Rayleigh scattering occurs when the particle diameter is much smaller than the wavelength of the light (Nave, n.d.). Aerogel easily fulfills this criterion with pores in the nanometer scale. White light contains all colors of the visible spectrum. When white light enters the particle, longer wavelengths (red part of the visible spectrum) will be scattered in the direction of the light source. Shorter wavelengths (blue part of the spectrum) will be scattered in a direction orthogonal to direction of the light source. Most of the passing light received by a viewer will be scattered with a large angle relative to the light source's direction. Therefore, aerogel is perceived as a smoky blue material for a person looking at it.

3.2.2 Mie scattering in aerogel

Mie scattering occurs when white light enters larger particles (Nave, n.d.). In aerogel there are also pores that fulfill this criterion. Scattering in larger particles are not very wavelength dependent. Therefore, the scattered light beam will still be white when exiting the particle. However, the white light is still scattered in different directions, but mostly in the incident direction of the light. This causes a white glare to appear around a light source when looking through monolithic, transparent aerogel. In granular aerogel glazing systems, this phenomenon will arise multiple times over when light travels from particle to particle. Consequently, the scattering in granular glazing systems will distribute light evenly in every direction. For this reason, granular aerogel glazing systems diffuse the light evenly, resulting in a white, cloudy, and translucent appearance.

3.2.3 Optical parameters

The structure of silica aerogel can be either granular or monolithic. Granular aerogel glazing systems and monolithic aerogel glazing systems have different optical properties. For granular aerogel glazing systems, the granule size impacts the optical properties of aerogel-filled glazing units. Former studies have assessed that transmittance values increase with increasing granule size. These transmittance values are the light- and solar transmittance, in addition to the g-value (also named solar heat gain coefficient (SHGC) and total solar energy transmittance (TSET))). For the smaller sized granules, the light is diffused.

Increasing the thickness of the glazing of aerogel-filled double-glazing units leads to a loss in transmittance and an increase in reflectance. For the same layer thickness, large granules permit higher transmittance values compared to smaller sized granules. Furthermore, the larger sized granules have lower reflectance. Studies have shown that monolithic aerogel has higher light and solar transmittance than granular aerogel. Aerogels optical properties in glazing systems relies on these parameters (Buratti et al., 2021):

- the manufacturing procedure
- the structure (granular or monolithic)
- the size of the granules
- the thickness of the glazing unit
- the characteristics of the transparent sheets, enclosing the aerogel layer

3.3 Acoustic properties

Noise is characterized as a sound that is unpleasant to a human. Noises must be restrained, to avoid damaging the ears and to create satisfactory, acoustical surroundings. To achieve this, sound insulation or sound absorption is required. Sound insulation is acquired when the acoustic energy is reflected or absorbed before entering the system that it insulates. Absorption happens when the acoustic energy is transferred to other types of energy so that the noise in a system is reduced by scaling down the reflectance. Sound waves are fractionally reflected, absorbed, and transmitted when they collide with a material (Mazrouei-Sebdani et al., 2021). The proportion of each fraction depends on the material it collides with. Incoming sound is decreased when transmittance is decreased. For transmittance to decrease, reflection and absorption must increase.

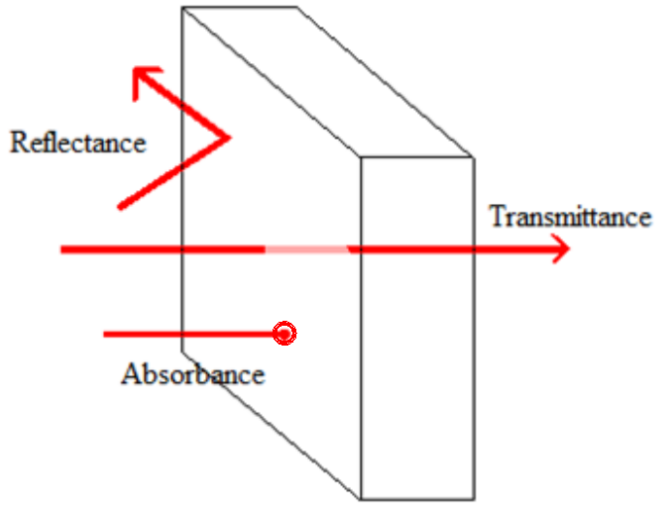

Figure 3.1: *Reflectance, absorbance and transmission of an impinging sound wave*

3.3.1 Sound absorption

Low density and highly porous materials with medium airflow resistance can be sound absorptive. The network of interconnected nanostructures in monolithic aerogels generally satisfies this criterion. However, the absorption depends on the ratio between the mean pore diameter and the mean free path of air. If the mean pore diameter is smaller than the mean free path of air, less sound will penetrate the pores and enter the structure of the aerogel (Ramamoorthy et al., 2018). If the mean pore diameter is larger than the mean free path of air, the material will allow moving particles (the sound wave) to enter through its pores instead of being reflected. When the air particle enters a pore of a granular material such as aerogel, a series of collisions with the pore wall is likely to occur. For every collision, vibrations in the pore walls will absorb some of the acoustic energy by thermal and viscous losses. Therefore, some of the acoustic energy is absorbed (Mazrouei-Sebdani et al., 2021).

3.3.2 Sound insulation

On the other hand, an effective sound insulation material layer is one that is airtight or holds a high airflow resistance. The effectiveness of such materials depends on the materials stiffness and mass. Higher area weight leads to more effective sound insulation. This is the case for one layer of sound insulation. Therefore, aerogel is not an effective sound insulator on its own. However, layered, solid, lightweight materials can be very effective sound insulators as a part of a composite. This requires that there are airgaps or soft materials between the multiple layers of the lightweight material. Porous materials can also be filled into the empty spaces. This contributes to increasing the damping and to decouple the solid layers (Mazrouei-Sebdani et al., 2021).|

3.3.3 Aerogels as sound insulation and absorbents

The effectiveness of aerogels acoustic properties is not understood fully. The main barrier for understanding the acoustical properties is a lack of accurate data on the aerogels pore size distribution and pore connectivity. For a low-density aerogel such as silica aerogel, the sound wave will propagate in the fluid of the pores and in the solid frame (Mazrouei-Sebdani et al., 2021). Silica aerogel has been shown to obtain a very low velocity of sound at around 100 m/s (Akimov, 2002). Therefore, an impinging sound wave will be decelerated and weakened due to a wide variety of physical phenomena. Moreover, properties such as geometry and distribution of pores will be decisive to which phenomenon that dominates. These properties will vary depending on the many different material preparation methods. Experimental results in the literature vary depending on the thickness of each layer and which experimental setup is used (Mazrouei-Sebdani et al., 2021). Therefore, they are not yet fully understood. For more data on the experimental results of acoustics in aerogel products, look up table 2 in (Mazrouei-Sebdani et al., 2021).

3.4 Fire properties

For a fire to occur, heat, oxygen and a combustible material must be present. It is important to have control over fire and fire development. To have manageable control over fire and fire development it is important to know the fire properties of all the products and materials used in buildings and means of transport. Therefore, the fire resistance of a material is an important property. The most common type of insulation is mineral wool. Both are non-combustible. In this context, non-combustible means that the products have such a high melting point that they will not burn.

Aerogel is claimed to have high fire resistance (Yu et al., 2018). This property comes from the addition of well-distributed inorganic substances such as silica. The structure of the binary network microstructure endows the aerogel its fire resistance. As mentioned earlier, aerogel contains up to 99.8 % air by volume, meaning the remaining mass is very small. With a mass this small, very little heat that can by conducted from the aerogel. The aerogel with the most air by volume will have the best fire resistance due to the limitation of the radiative transport. Commercialized silica aerogel has an application range as high as 1000 ^{o}C (Aerogel felt - DY10 series). Due to the chemical structure of the silica aerogel no toxic gasses are being released during fire (Calisesi, 2017).

3.4.1 Aerogel blankets as fire insulators

Aerogel blankets are one of the aerogel-based products of which there are most variants in the commercial marked. In 2021 an investigation of the fire resistance levels (FRL) of load-bearing light gauge steel framed (LSF) walls insulated with silica aerogel fiberglass blankets was done. The study showed that the aerogel blankets, used as a form of external insulation, had an enhanced fire resistance compared to cavity insulated LSF walls. The fire resistance was enhanced by a delayed stud temperature development by about 20 min and a reduced flange temperature difference up to 200 ^{o}C (Tao & Mahendran, 2021).

3.4.2 Comparison of heat release rate for silica aerogel composite and a composite of rock wool with a water resisting barrier

An experiment was carried out in 2017, investigating the fire properties of silica aerogel (Li et al., 2017). The experiment was carried out in accordance with the standard ISO 5660, and investigated composites consisting of glass fiber and aerogel when exposed to heat radiation.

Traditional thermal insulation materials combustion behavior has previously been tested extensively by using cone calorimetry (Scudamore et al., 1991). This method is justified by the oxygen consumption principle, and is amongst other things, measuring the heat release rate (HRR) and peak heat release rate (PHRR). These two parameters describe the fire intensity of a material or composite, which is a critical factor to obtain in pursuance of controlling fire related dangers. An estimate for heat release rate (HRR) (kW) is given by:

$$HRR = E\,(m^{0}_{O2} - m_{02}) \tag{3.6}$$

where E is Huggetts' average value of 13.1 ± 5% (MJ/kgO_2), m^0_{O2} and m_{02} is the amount of mass of oxygen that enters and leaves the reaction per second, respectively (Li et al., 2017). PHRR is the largest value of HRR that is achieved during the reaction. Other important factors to consider are time to ignition (TTI) and total heat release (THR).

When an incident heat flux of 35kW/m^2 was applied to the experimental aerogel composites, THR was measured to be in the range of 7.049 to 7.825 MJ/kg. PHRR varied from 40.829 to 54.072 kW/m^2. TTI was between from 9 to 3 seconds (Li et al., 2017). In another experiment, the same heat flux was applied to a composite of stone wool with a water resisting barrier. The PHRR in this experiment reached 105 kW/m^2 (Černoša, 2020). When an incident heat flux of 60kW/m^2 was applied to the aerogel composite PHRR varied from 58.028 to 79.294 (Li et al., 2017). This is nearly a 50% increase from what was reached by applying 35 kW/m^2. For the stone wool composite, the PHRR reached 144 kW/m^2, when a heat flux of 50 kW/m^2 was applied (Černoša, 2020). The aerogel composite has a lower PHRR than the rock wool composite when the same heat flux is applied.

3.5 Mechanical properties

Aerogel has a low thermal conductivity due to the low thermal conductivity of silica and the nanometer pore size. Concurrent as these properties make aerogel a good insulator, they also make the material fragile and brittle. It is typical for brittle materials to have low tensile strength in relation to compressive and shear strength. This also applies for aerogel. Consequently, aerogel is challenging to use in load-bearing applications.

Aerogel is sensitive to moisture absorption from storage and handling, and has shown a tendency to become more brittle with aging. Additionally, stress relaxation (known as creep) may occur under certain conditions (Parmenter & Milstein, 1998).

In pursuit of improving the tensile strength of aerogel, efforts have been made to incorporating fiber matrix and producing fiber-reinforced aerogel composites. The goal is to empower the compoites as load-bearing parts without affecting the thermal conductivity substantially, as well as the aerogel having elasticity when subjected to a load. The indicated has proven to be a challenge (Yang et al., 2011).

There is a correlation between the hardness and compressive strength for both fiber-reinforced and unreinforced silica aerogels. There is generally a lower compressive strength and a decreased elastic modulus for aerogel with reinforced fibers. Higher matrix densities have been observed for unreinforced and slightly reinforced aerogels than for reinforced aerogels. This is due to the fibers supporting the matrix, reducing the shrinkage during the supercritical drying. This implies that the material shrinks more the less fiber it contains, causing the matrix density to increase. This leads to an increase in hardness and compressive strength, but a decrease in the strain at fracture (Parmenter & Milstein, 1998).

4 State-of-the-art review: Aerogels for building applications

4.1 Aerogels

Aerogel is a good alternative to traditional insulation, such as mineral wool and rock wool, due to its low thermal conductivity. However, aerogel is an expensive material, and the high costs are considered challenging for implementing the material in the building industry. The costs must be reduced substantially for aerogels to become a widespread thermal insulating material. Despite this, aerogel may be considered as beneficial in the cases where space is an important aspect, as it is not space consuming.

This chapter addresses the current state of aerogel, both existing and potential applications of different aerogel types. This includes opaque, translucent, and transparent aerogel products, covering a wide range of building applications (Sletnes et al., 2017).

4.1.1 Opaque aerogels

Opaque aerogel does not let any visible light through the material and is therefore used as insulation in walls and other components that does not require an outdoor view. There are currently several aerogel-based insulation materials on the market with remarkably lower thermal conductivities than traditional insulation materials. One can find opaque aerogel products such as panels, plasters, blankets and internal wall insulation systems (IWI).

For opaque aerogel products, the thermal conductivities range between 0.011 W/(mK) at 20 ^{o}C and 0.056 W/(mK). This applies for the products “Skogar ultra-fine super-insulating sheets” from Enersens and “Airloy X103” from Aerogel Technologies, respectively. Note that for the latter product, the temperature is not given for the measurement of thermal conductivity. The thermal conductivity of thermal insulation materials is dependent of the operating temperature. For most materials, the thermal conductivity has shown to rise with the increase of influencing temperature (Khoukhi, 2018). This also applies for aerogel. Due to the lack of data, it is therefore difficult to fully compare the products. Note that also other parameters, especially moisture, is likely to influence the thermal conductivity of insulation materials, especially if the temperature differences are considerable (Khoukhi, 2018). Additionally, the method of measurement is also a parameter that can influence the thermal conductivity.

The former product is available in a thickness of 0.5 - 2.5 mm and is hydrophobic. The fire property (A1, s1, d0) indicates that it’s non-combustible, generate small amounts of smoke and no burning drops. This also make it the aerogel product with the least reaction to fire of all the products with reported fire properties.

4.1.2 Translucent aerogels

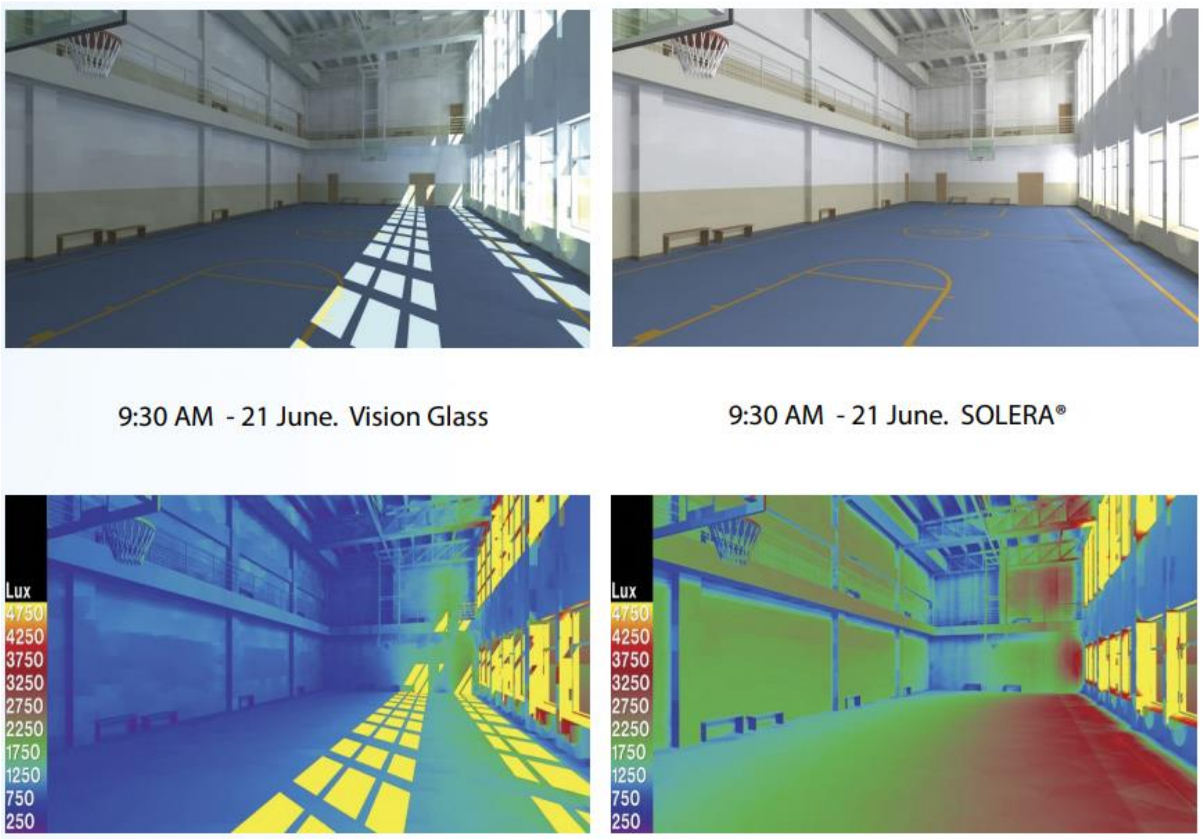

Figure 4.1: *Daylight simulation comparing diffusion of natural light for traditional (left) and translucent aerogel windows (right) (Solera, 2012).*

Translucent aerogels are considered interesting because of its concurrent low thermal conductivity and high transmittance of solar energy, especially daylight (Baetens et al., 2011). Due to these properties, translucent aerogels are suited for fenestration. The material is not transparent, which is caused by the granules making the material diffusive. This makes the material applicable for use where the user does not require an outdoor view (e.g. roof, grand facades) (Buratti et al., 2021).

It is also possible to use the material inside components (e.g as insulation in walls). In this case, there is no requirements for light transmittance, making opaque aerogel the preferred alternative as it is usually cheaper.

Different climates require different properties to optimize the indoor environment. In areas with cold climates there is a need to retain heat to reduce energy consumption from heating. It is considered a plus if the building is well insulated simultaneously as an external heat source can warm up the building. Therefore, it is preferable with a high SHGC for buildings in these areas to exploit the heat from the sun.

On the other hand, in warm climates it is important to keep the heat outside of the building to avoid overheating and a high energy consumption caused by cooling. Therefore, it is desirable with a SHGC that is as low as possible. Nonetheless, there are tradeoffs between the different properties.

For example, Kalwall has several translucent products with a U-value ranging between 0.28 - 3.01 W/(m^2 K). These products include windows for roofs and facades. The thickness for most of the glasses are not stated, making it difficult to compare the components. It is however normal for the U-value of windows to increase when the thickness decreases. Note that a U-value of 3.01 W/(m^2 K) is very high, which is not desirable.

"Lumira aerogel panel" by Pilkington Profilit is the translucent product with the lowest U-value in table B. The reported U-value is 0.19 W/(m^2 K) for the component with a thickness of 25mm. The reported U-value is 0.19 W/(m^2 K) for the component with a thickness of 25 mm. The visible light transmission (VLT) for this product is 38 %. If a higher or lower VLT is desirable, other products are better suited.

"Solera L" from Solera has the highest VLT–range, varying from 12 % to 62 %. The SHGC for this product lies within the range of 0.11–0.58. However, the U-value is 2.65 W/(m^2 K), which is a high value.

The product with the compact VLT-range in the lower area is "Solera plus Lumira R25-T" from Solera, varying from 5 - 20 %. This product has a U-value of 0.22 W/(m^2 K) and SHGC between 0.05 and 0.19.

Sound transmission class (STC) is explained in section 4.2.2. In table B, Solera reported the highest STC-values for some of their translucent window products. The STC-values were in the vicinity of 52.

There is a market for translucent aerogels as particle products. These particle products can be used for building applications. One example is in high performance aerogel concrete (HPAC), which is discussed in section 4.2.5. The main reason for using aerogel particle products for building applications is the low thermal conductivity.

The product «Aerogel powder particles» from JINNA is the one with the lowest reported thermal conductivity in table C. The reported value lies between 0.008 and 0.015 W/(m K). The granule size, which affects the radiative transmittance, is not reported for this product. As mentioned in section 3.2.3, the light transmittance will increase with an increasing granule size, and vice versa. In the table, Cabot's "Enova MT"-series reported the lowest granule size of 2 - 24 µm. The thermal conductivity is not specified for this product. Cabot is also providing the products with the highest granule size. "Lumira LA1000" and "P300 particles" has granules ranging from 1.2 – 4 mm. The products have thermal conductivities of 0.012 and 0.130 W/(m K), respectively.

4.1.3 Transparent aerogels

Monolithic aerogel can be transparent, making it useable in conventional windows. Similar to translucent aerogel, transparent aerogel has both low thermal conductivity and high transmittance of solar energy (Baetens et al., 2011). It seems to be a lack of transparent aerogel products on the market today. Therefore, only two products are listed in table D.

The first product is "SUFA" by Tiem Factory Incorporation. The thermal conductivity lies between 0.012 - 0.014 W/(m K). It has a mass density of 0.11 - 0.12 g/(cm^3). This is considerably lighter than for traditional glass panes. The compressive strength of "SUFA" is 9.22 MPa. It has a contact angle with water at 140^o, which means that it is water repellent.

The second product is "Airloy X56" by Aerogel Technologies. The thermal conductivity is 0.03 W/(m K). It has a mass density of 0.30 ± 0.05 g/(cm^3). The compressive strength is 0.65 MPa, which is substantially lower than for "SUFA". For "Airloy X56" the contact angle with water is not specified.

4.2 Constructing with aerogels

4.2.1 Walls and coatings

When insulating new or existing buildings, there are many types of insulations to choose from. In Europe, around half of all existing buildings were constructed before the insulation requirements came in the 1970s (Fantucci et al., 2019). Therefore, a large portion of European buildings are poorly insulated. Many companies have tried to solve this problem by providing easy-to-use products to increase the thermal comfort.

Aerogel incorporated products like blankets, boards and coatings/plasters are designed for installation in or application on exterior walls. The products are opaque, which is not a problem where visibility is not required. Blankets and boards are often placed in the cavities between the studwork of exterior walls, to insulate the building. The studwork itself has a relatively high thermal conductivity. Therefore, thermal bridges can become a problem which must be taken into consideration.

Blankets fit into narrow cavities and are slightly malleable, while hard panels are more difficult to mold and install in tight spaces. Both products can be cut and shaped using standard craftsman equipment. Cabot's "Thermal Wrap Blanket"-series has one of the lowest thermal conductivities in the commercial marked by 0.013 W/(m K).

Coatings/plasters are used on interior walls. Application of aerogel-based plasters is an efficient way to protect the inside from external cold or heat. It is easy to apply and therefore suitable for upgrading old buildings. Core Conservation has developed a plaster named "Termo Rasante Aerogel thermal finishing plaster" with a thermal conductivity as low as 0.016 W/(m K). By applying a layer of the plaster on the inner walls, a higher heat reflectance is achieved.

4.2.2 Windows

Windows are meant to provide sufficient daylight, which is important for the circadian rhythm and wellbeing of humans. It also improves the work performance. From a thermal point of view, windows have a substantially higher thermal transmittance compared to other building envelope components. In fact, windows can contribute with a total energy loss up to 45 % (Gao et al., 2015). This applies for conventional, clear glass windows, and is considered a substantial drawback. Therefore, it has been of great interest to improve the thermal insulation of windows.

Monolithic silica aerogel panes have a low mechanical strength. Therefore, glazing units (Gao, Jelle, Ihara, et al., 2014) assembled with granular aerogel is preferred as it has a stronger mechanical strength. Aerogel glazing units (AGU) are double glazing units (DGU) containing aerogel granules in the air cavity and are translucent. Since the windows can provide diffuse lighting, the daylight management in buildings can be enhanced, contributing to the wellbeing and comfort of the user as it prevents solar overheating and glare. However, where there is a desire for an outdoor view, monolithic aerogel glazing units must be applied (Gao et al., 2015). For this reason, the translucent glazing units are more suited as facades and roofing in commercial buildings than residential windows, where an outdoor view often is a requirement (Jelle et al., 2011).

Studies have shown that incorporating aerogel granules into the DGUs reduces the thermal transmission. The explanation as to why the granules contribute to a smaller heat transfer through the glazing unit is clarified in section 3.1. Increasing the layer thickness of granules enhances the U-value of the window. In addition, the thermal conductivity may be reduced by applying aerogel granules with lower thermal conductivity. The latter is preferred when taking the economy into account, since the material consumption and costs are reduced (Gao et al., 2015).

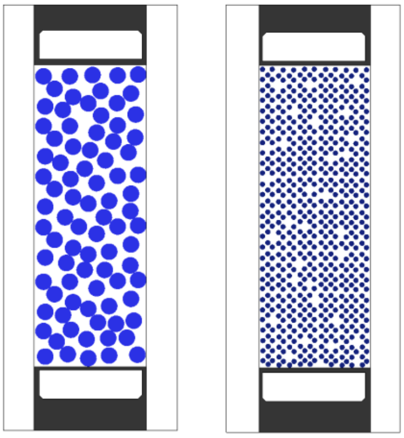

Figure 4.2: *Aerogel glazing units (AGU) with granules of different particle sizes, where the AGU to the left has large granules and the AGU to the right has small granules.*

Over time gradual subsidence of the aerogel granules will occur. This results in visible air pockets in the top of the pane, decreasing the performance of AGUs. To prevent this, a honeycomb structure is implemented into the gap of the aerogel glazing system. This decreases the subsidence potential to each cell, which in turn reduces the overall effect of the subsidence (Gao et al., 2016). This is applied to glazing systems with granules.

If aerogel is exposed to water, the aerogel structure gets destroyed. Therefore, aerogel granules are often made with a hydrophobic surface to avoid water absorption. Over time the granules may partially or fully lose their hydrophobicity. This is considered an issue.

Applying AGUs rather than common DGUs may reduce the total thermal transmission through the building envelope. For this reason, AGUs may be favorable for both retrofitting and new constructions, as they will contribute to a smaller energy demand for heating and cooling.

Regardless, it is necessary to evaluate other aspects than energy efficiency, such as economics and environmental impact of AGUs. Incorporating granules into the DGU increases the manufacturing costs. However, the energy savings of AGUs during the service time might compensate for this, but that must be calculated for the specific project.

Production of AGUs may cause a large environmental impact due to the high embodied emissions and CO_2 emissions. It is therefore important to evaluate this up against the potential energy gain of using AGUs over DGUs, when evaluating the total benefit of AGUs. The potential health risks are also important to evaluate for the nanoporous material (Gao et al., 2015).

Evacuated aerogel glazings are double-pane glazing units with monolithic silica aerogel inside the gap. Monolithic aerogel is often transparent, but when exposed to direct sunlight some haze appears due to scattering in the aerogel. For this reason, evacuated aerogel glazings are suitable for use when not exposed to direct sunlight, for example towards north. This results in pleasant daylight and a net energy gain. A slight haze may still appear when the glazing unit is faced towards north. The evacuated aerogel glazings have an excellent combination of high solar and light transmittance and low thermal conductivity (Schultz & Jensen, 2007).

Figure 4.3*: Example of an evacuated aerogel glazing consisting of monolithic aerogel. The view through is clear, although some haziness is present. The window is not exposed to direct sunlight (Schultz & Jensen, 2007).*

Sound transmission class (STC) is used for rating the sound insulation of different building components, including windows, doors, interior partitions, ceilings and floors. The STC rating is measured in dB and reflects the decibel reduction of noise that an assembly can provide. A higher STC rating indicates a better sound insulation achievement for the given component (Chiu et al., 2015).

The STC rating for windows is dependent of several factors, including the glass thickness, the mass, the interior air space depth, lamination of panes, and how and what the frame is constructed of. The assembly of windows, whether the windows are fixed or openable, affects the STC rating. A fixed window will most commonly have a higher STC rating than an openable window. Furthermore, the material of the frame alters the STC rating, with aluminum having a lower STC rating than wood. Increasing the interior air space depth between the glazings gives a higher STC rating. In general, an air space depth of less than 19 mm is not effective when using thin double-paned windows. Increasing the weight of the glass may also improve the STC rating (Long, 2014).

As late as 2020, it was stated that only granular aerogel glazing systems were available on the market at the time. This seems to still apply, as the authors’ has not found any monolithic/transparent aerogel glazing products on the market today (Buratti et al., 2021). Table B lists the translucent aerogel window products that were found on the market. Amongst other, different windows from Solera having STC ratings ranging between STC40 to STC52. STC52 is the highest STC rating and therefore the most sound insulating out of all the window products listed in table B.

The U-value for the translucent aerogel glazing products found on the market, ranges between 0.19 - 2.65 W/(m^2K), where “Lumira aerogel panel 25 mm” has the lowest U-value. KALWALL has several products with U-values ranging between 0.28 - 3.01 W/(m^2K), for example “Thermally broken wall systems”, “Skylights, Geo-roofs”, “Skylights, S-lines”, “Skylights, Standard pyramids” and “Kalcurve 180^o vaults”. The large range in U-values are determined by various pane thicknesses and differences in the granule size.

4.2.3 Roofs and skylights

It is important for roofs to be airtight and well insulated. Airtight roofs are desirable to prevent warm air from leaking through. Since warm air ascents, the roof must also be properly insulated to avoid wasting energy. The need for daylight and fire evacuation routes is often solved by incorporating skylights in the roof. Skylights may cause larger thermal losses. Aerogel-based insulation products is well adapted for use in roofs, both as re-insulation and insulation in new buildings. Most aerogel-based products are claimed to withstand fire and be sound insulating. Simultaneously, the thermal conductivity is low (Meliță & Croitoru, 2019). This reduces the energy demand for heating and cooling. However, the disadvantages of using aerogel are the high costs and the dust that develops from the fabrication process (Meliță & Croitoru, 2019).

The most typical aerogel-based products used for roofs, are opaque blankets and boards. These are usually installed underneath the roof tiles. Compared to traditional windows, aerogel enables larger window panes as they can satisfy the maximal requirements for energy loss. To meet both daylight and energy efficiency requirements simultaneously, aerogel glazed skylights might be an attractive solution. KALWALL delivers different types of skylights containing aerogel granules in the cavity. These granules make the windows translucent, but lowers the U-value considerably compared to traditional windows. KALWALL "skylights", "Geo-roofs", "S-lines" and "standard pyramids" has U-values as low as 0.28 W/(m^{2}K). By having well-insulated skylights in the roof, three important problems are solved simultaneously. The requirement for daylight, insulation and reduced energy consumption from electrical lighting (Zheng et al., 2020).

4.2.4 Floors

Floors in buildings comes in several formats with different constructions. Floors are usually built out of wood-joists or concrete. A mix of the two is also used in many instances. When addressing the concept of flooring in commercial buildings, one usually talks about ground floor and floor dividers. Cold surfaces and poor sound insulation between floors are well known problems. Therefore, requirements for thermal insulation, sound insu(Cuce et al., 2014)lation and fire resistance have tightened across Europe in recent years. With stricter requirements the costs increase. Aerogel is expensive compared to traditional insulation, but to meet the energy requirements in a more space efficient way, it might be a good investment. Using aerogel instead of traditional insulation can reduce the space requirement by up to 67.1 % (Cuce et al., 2014).

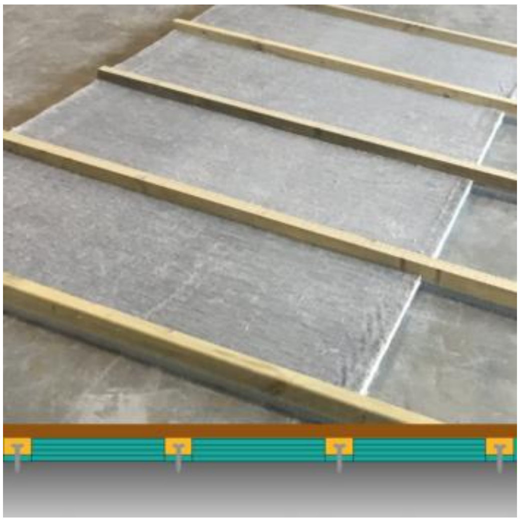

Figure 4.4: *Thermablok insulation slab system for internal floor systems λ = 0.015 W/(mK) (Thermablok, n.d.-d)*

There are several companies that supply aerogel insulation that is specifically designed for floors and walls. Opaque blankets and boards are easy to fit in these construction elements.

The main differences between the products are the maximum allowable temperature, and the thermal conductivity that varies from 0.025 W/(mK) all the way down to 0.011 W/(mK). A suitable product for floor insulation can be “Thermablok Aerogel Thermaslim Board” from Thermablok. The insulation boards can be purchased in thicknesses from 10 mm all the way up to 50 mm and all of the thicknesses has a thermal conductivity of 0.015 W/(mK). The installation process is relatively simple, and the boards can easily fit into cavities during renovation of old floors. When rehabilitating, 30 mm aerogel blankets can reduce the energy consumption considerably. By using an aerogel blanket, the existing room height can also be maintained. This allows the building`s characteristic features to persist.

4.2.5 Aerogel incorporated concrete, mortar, and plasters

By embedding silica aerogel granules in a high strength cement matrix, the heat transfer through the concrete is drastically reduced. Concurrently, the compressive strength is also reduced. However, it has been reported to have a compressive strength of up to 25 MPa. There is an almost linear correlation between the compressive strength and the thermal conductivity in HPAC. According to this correlation, an HPAC with a compressive strength of 25 MPa has a thermal conductivity of 0.26 W/(mK) (Schnellenbach-Held & Welsch, 2016). This is substantially lower than for traditional concrete. However, attempts of finding aerogel incorporated concrete for commercial use has been unsuccessful. This also applies for aerogel incorporated mortar (AIM).

For AIM, a review was published in 2021 listing four mortar products from the literature (Adhikary et al., 2021). In the first experiment, different mortars consisting of between 0 – 80 vol % aerogel, cement and silica fume was reported to have a compressive strength of from 55.3 MPa to less than 0.1 MPa, and thermal conductivities ranging between 0.18 - 0.97 W/(mK), respectively, for the different percentages of aerogel incorporated in the mortar (Ng, Jelle, & Stæhli, 2016). In the second experiment, different compositions of aerogel and cement was tested with between 0.5 to 2.0 wt%. Compressive strength was 13.1 - 5.9 MPa, and thermal conductivity 0.41 - 0.12 W/(mK) (Kim et al., 2013). In the third experiment, 0 – 64 vol % aerogel, cement and silica fume sand were mixed. The compressive strength was 91.9 - 1.4 MPa and thermal conductivity was 1.70 - 0.17 W/(mK) (Zhu et al., 2019). In the last experiment the same composition was used as in the latter, consisting of between 0 - 60 vol % aerogel with smaller granules. The mortar shows a compressive strength of 2.15 MPa and the thermal conductivity was 0.1524 W/(mK) with 60 vol % aerogel (Liu et al., 2016).

Aerogel incorporated plasters (AIP) may be purchased in the commercial market. The two commercially available products are listed in table E. Out of these two, Core Conservation provides the plaster with the lowest thermal conductivity of 0.016 W/(mK), named “ThermoRasante AeroGel Thermal Lime Finishing Plaster”. The recommended layer thickness is between 4 - 10 mm. For the product “FIXIT 222” from Fixit, the recommended layer thickness is between 30 - 150 mm. However, the thermal conductivity is higher than for the former product, ranging between 0.026 - 0.028 W/(mK). Nonetheless, by applying the recommended layer thickness, “FIXIT 222” will provide the lowest U-value.

4.3 Retrofitting and rehabilitation examples

Rehabilitation is the process of returning a dilapidated building to its original state. Retrofitting is an upgrade from the original performance characteristics of a building to a more functional unit. Both are usually expensive processes. More than 30 % of the total energy consumption and greens house gasses comes from the building sector (Orsini et al., 2020). Therefore, aerogel can become one of many required solutions for saving energy and limiting greenhouse gas emissions. The properties of aerogel are well suited for use in rehabilitation and retrofitting. This is mainly due to the low thermal conductivity and density, but also due to its resistance to high temperatures and ability to let light through.

Traditional insulation materials like mineral wool are often used during rehabilitation. The materials have a thermal conductivity of between 0.035 - 0.040 W/(mK). Traditional insulators cover over 85 % of the marked demand (Orsini et al., 2020). By replacing the traditional types of insulation with aerogel, you can achieve a much better insulation ability, both in walls, floors ceilings and windows. There are aerogel-based products that are sold with a thermal conductivity as low as 0.011 W/(mK).

There are many different possibilities when it comes to insulation during rehabilitation or retrofitting. Opaque aerogel products are most applicable in walls, roofs, and floors. These are usually placed inside the wall between the studwork. There are also ready-made panels that can easily be mounted on the outside or inside of walls or in the ceiling. This depends on what the user/owner prefers. Applying aerogel on the inside of walls reduces the usable area to some degree, but not significantly. A 20 mm aerogel panel can be equivalent to a 110 mm layer of rock wool (Orsini et al., 2020).

Replacement of windows and doors is also common during rehabilitation. Depending on the need for visibility through the glass, translucent or transparent aerogel windows can be applicable. This can reduce the heat flux from the building significantly compared to traditional windows.

Figure 4.5: *Installation of 20 mm aerogel blankets during rehabilitation (OldBuilders, n.d.)*

A product that differs from others when it comes to retrofitting is Thermablok's "Aerogel Thermaslim Reveal Board" shown in figure 4.5. It stands out by having a finished chipboard mount on the outside of the insulation material. This makes the product very useful not only for walls and jamb lining, but also for ceilings. The surface is paintable and can also be wallpapered.

Figure 4.6: Aerogel thermaslim reveal board from Thermablok λ = 0.015 W/(mK) *(Thermablok, 2017d).*

Aerogel-based plasters are promising for improving the energy efficiency (Del Curto & Cinieri, 2020). Plasters can be applied to walls, ceilings, and partitions to increase the thermal performance. However, the additional cost for using aerogel instead of conventional insulation is approximately 10 times higher (Cuce et al., 2014).

4.4 New construction examples

Silica aerogel is an insulation product that is suitable for new constructions. Its transparent, translucent, and opaque appearance makes it very useful and very versatile. Due to these three different states of visibility, the aerogel can be used inside walls, outside walls, ceilings, floors and windows. Aerogel is often implemented in various products and can be purchased in many different forms. The most common building products are: glass, boards, blankets, wall paintings, aerogel-incorporated vacuum insulation panel (VIP), wallpapers, reinforced concrete, mortars and plasters (Del Curto & Cinieri, 2020).

There are many modern construction examples using translucent aerogel. By using a translucent aerogel as an insulator, requirements for daylight and thermal conductivity can be met simultaneously. However, the costs are many times higher than for traditional windows.

Figure 4.7: *Double-glazed glass panel from Lumira Aerogel (ArchiExpo, n.d.).*

Opaque aerogel is the most available category in the commercial market. For floors, roofs and walls, blankets are most often used. This is due to the flexibility in the blankets that allows application in areas that require shape-customization. The craftsperson can cut the blanket into a desired shape without damaging the thermal conductivity of the product. Alison Aerogel's "Aerogel felt DRT02" is one example of such a product. It has a Thermal conductivity of 0.017 W/(mK) at 25^{o}C.

To sum up, aerogel may substantially increase the performance characteristics of a building. It is space efficient, energy efficient and can let daylight into a building. However, the costs are much higher than for traditional insulation and windows.

5 Future research pathways

The current cost of producing silica aerogel (Stojanovic & Koebel, 2015) is probably too high to spread across the commercial market to any meaningful degree. The prices of HMDZ, TEOS and NH_4OH are the main reasons for the high costs of producing silica aerogel (Garrido et al., 2019). It seems like the synthesis of silica aerogel using ambient pressure drying costs much less than the raw materials that go into the process (Garrido et al., 2019). A reduction in the raw material costs could also contribute to more transparent aerogel products on the market, which in turn could be important for increasing the demand due to visibility through the glazing systems. Therefore, research on reducing the costs of the mentioned raw materials could be a vital step towards increasing the commercial availability. Depending on the method for synthesizing aerogel, the energy expenditure can be quite significant. More energy effective ways of synthesizing aerogel could also be important to research further in pursuance of reducing the costs.

Information about the fire properties of a material can be relevant when deciding where to place the material in a building. Specific information on fire properties is absent in many of the products listed in the appendices. More research into the fire resistance of composites containing silica aerogel could be relevant information to provide. Cone calorimetry experiments would be most useful because the ISO 5660 standard uses this experiment for certification. Aerogel mixed composites may among other things increase space efficiency, which can be a useful fire insulator for load-bearing systems.

It is important that the aerogel is hydrophobic to avoid moisture problems. If water is absorbed, the wooden parts of the construction can be damaged. Most of the products listed in this article's appendices are reported to be hydrophobic. However, there are no mentions on the durability of this property. Over time, the hydrophobicity may gradually diminish. This can possibly make the aerogel harmful for the construction due to moisture. Therefore, researching the durability of hydrophobicity would be interesting.

Some aerogel properties are difficult to measure and calculate. This is partly due to aerogels complex pore size distributions and pore connectivity. More accurate measurements of the distribution and connectivity could become useful for measuring and calculating other properties. For example, acoustic properties are not yet fully understood due to the lack of this data as discussed in the acoustic properties section.

Aerogel is one nanomaterial with interesting properties for building applications, but there are other insulation materials that are also promising ((Baetens et al., 2011), (Jelle et al., 2014), (Jelle, 2011)). Vacuum insulation panels have thermal conductivities from 3 to 4 mW/(mK). However, they become useless if punctured. The same applies for gas-filled panels that has a thermal conductivity of 40 mW/(mK). The gas-filled panels have low emissivity surfaces which reduces the radiative heat transfer. Phase change materials are also interesting in this context. During changes in temperature, the material will change phase from solid to liquid or vice versa. This will absorb or emit energy accordingly, and can contribute to stabilizing the temperature in a building. Gas insulation materials are porous materials filled with gas. These materials can have thermal conductivities as low as 4 mW/(mK).

6 Conclusions

Aerogel may become an important material in the construction industry to decelerate future energy consumption. This is due to its low thermal conductivity and wide range of applications. Many opaque and translucent aerogel products are commercially available. However, to the authors’ knowledge, there is a scarce supply of transparent aerogel products in the market. This is probably caused by the high costs of the raw materials.

Opaque aerogel products come in the form of blankets, sheets and different composites. The blankets and sheets can easily be customized to fit into demanding spaces and then be applied in walls, floors and ceilings during construction, retrofitting or rehabilitation. The composites are prefabricated and can be placed directly into a new construction. The thermal conductivity of these products is reported to be in the range of between 0.010 - 0.056 W/(mK). The lower part of the range is considered very low compared to traditional insulation materials. Therefore, it can increase the thermal comfort in a building relatively space efficiently. However, these products cannot be used where solar radiation and daylight transmission is required.

The translucent aerogel products that are commercially available are both glazing systems and granulates. The lowest reported U-value for a glazing system was 0.19 W/(m^2K). There is no visibility through the glass, but solar radiation can pass through. This can contribute to meeting the requirements for sufficient daylight and energy efficiency simultaneously. Depending on the chosen product, visible light transmission (VLT) ranges from 3 – 62 %. Moreover, heat from the sun can be exploited because the solar heat gain coefficient (SHGC) is ranging from 0.04 – 0.65. If solar heat is not desirable, it can also be obstructed by choosing a product in the lower part of the range.

Aerogel particle products are also translucent. They can be applied in miscellaneous mixtures with for example mortars, plasters and concrete. They can also be filled into different cavities between for example window panes or be mixed into painting and tape. This can reduce the thermal conductivity substantially. Some of the mentioned mixtures are available in the commercial market. Due to the brittleness of aerogels, it has been hard to satisfy the compressive strength requirements for aerogel incorporated-concrete (AIC). Fortunately, the research on AIC is currently on the verge of becoming usable, and a compressive strength of up to 25 MPa has been reported by researchers. The reported thermal conductivities for pure aerogel particles in the tables ranges from 0.008 – 0.023 W/(mK). The reported bulk and particle densities are less than 200 kg/m^3 for all the products. They are also claimed to be hydrophobic, but there are no mentions of the durability of this property.

Transparent aerogel products are scarce in the commercial market. Currently it seems that there are only two transparent aerogel products that are commercially available. These products can be used in glazing systems where visibility is required. Tiem Factory Incorporation reported a thermal conductivity of 0.012 – 0.014 W/(mK) and a compressive strength of 9.22 MPa for their product SUFA as stated in table D. This is a low thermal conductivity compared to traditional windows.

The raw material costs for producing aerogel are too high to compete with traditional construction materials on price. The production process itself has become much more effective by using new technologies for drying, but the raw materials are still very expensive. Therefore, research into lowering the cost of the raw materials has been suggested as an important future research pathway. If the costs are lowered to a reasonable level so the price can decrease, aerogel products can probably spread across the commercial market and subjugate large market shares. This will likely result in a substantial reduction of the energy consumption from heating and cooling of buildings.

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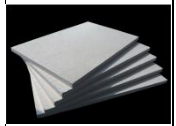
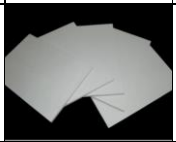
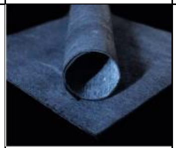
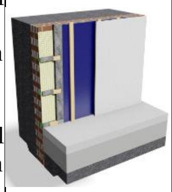
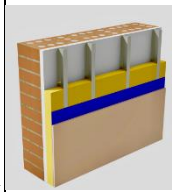
Appendices

Appendix A – Opaque aerogel products

Manufacturer	Product	Illustration	Standard dimensions (L x W) (mm x mm)	Thickness (mm)	Thermal conductivity (W/ (m K))	Mass denisty (kg/m^3)	Color	Hydrophobic	Compression strength (kPa)	Tensile Strength perpendicular (Per) and parallell (Par) to faces (kPa)	Operating/ application temperature range (℃)	Flame spread index (Flame), smoke developed index (smoke) and reaction to fire (Fire)	Additional information	Reference
Alison Aerogel	Aerogel board - DY06 series		1000 x 500	10	0.023 at 25℃	250 ± 10 %	White	≥99 %			650		Easy to cut, unorganic material and easy to dispose	(AlisonAerogel)
	Aerogel felt – DY10 series		1000 x 500	10	0.023 at 25℃	300 ± 10 %	White	≥99 %			1000		Easy to operate	(AlisonAerogel, n.d.-b)
	Aerogel felt DRT02 series		W = 1500	5 and 10 or as requested	≤ 0.017 at 25℃	160 ± 20	White	≥ 99 %			-200 to 125		Excellent stability at ultra-low temperature, reusable, and easy to shape, cut and sew	(AlisonAerogel, n.d)

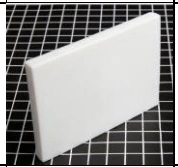
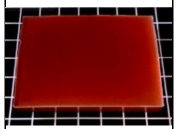
Manufacturer	Product	Illustration	Standard dimensions (L x W) (mm x mm)	Thickness (mm)	Thermal conductivity (W/ (m K))	Mass denisty (kg/m^3)	Color	Hydrophobic	Compression strength (kPa)	Tensile Strength perpendicular (Per) and parallell (Par) to faces (kPa)	Operating/ application temperature range (℃)	Flame spread index (Flame), smoke developed index (smoke) and reaction to fire (Fire)	Additional information	Reference
	Aerogel felt DRT03 series		W = 1480	2 - 3	0.022 at 25℃	200 ± 20	Grey	≥ 99 %			350		Easy to shape, cut and sew.	(AlisonAerogel, n.d.-c)
	Aerogel felt DRT06 series		W = 1500	3, 5, 6 and 10	0.021 at 25℃	200 ± 30	White	≥ 99 %			650		Prevent moisture from penetrating	(AlisonAerogel, n.d.-e)
	Aerogel felt DRT05 series		W = 1200	1.2, 1.8 or as requested	0.021 at 25℃	200 ± 20	White	≥ 99 %			500		Easy to shape, cut and sew.	(AlisonAerogel, n.d.-d)
	Aerogel felt DRT10 series		600 x 1200	10	0.023 at 25℃	200 ± 20	White				800		Easy to shape, cut and sew.	(AlisonAerogel, n.d.-f)
Thermablok	SLENTEX/Spaceloft A2 fibre reinforced aerogel blanket		No limit x 25	10	0.019 at 10 ℃	190 - 200		Yes	3,9 at 10 % compression	16 Per and 1085 Par			Intended for use in walls, floors and ceilings	(Thermablok, n.d.-a)

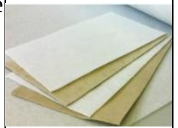
Manufacturer	Product	Illustration	Standard dimensions (L x W) (mm x mm)	Thickness (mm)	Thermal conductivity (W/ (m K))	Mass denisty (kg/m^3)	Color	Hydrophobic	Compression strength (kPa)	Tensile Strength perpendicular (Per) and parallell (Par) to faces (kPa)	Operating/ application temperature range (℃)	Flame spread index (Flame), smoke developed index (smoke) and reaction to fire (Fire)	Additional information	Reference
	Aerogel Isolation Strips		No limit x 25	5 and 10	0.019 at 10 ℃	190 - 200	Blue/Grey	Yes	3,9 at 10 % compression	16 Per and 1085 Par			Suitable for use in narrow cavities	(Thermablok, 2017a)
	Thermablok Aerogel Thermaslim IWI Board (wall)		2400 x 1200	10, 20, 30, 40 and 50	0.015	150 ± 20	Blue/Grey	Yes					Easy installation and clean surface	(Thermablok, 2017b)
	Aerogel Thermaslim IWI Board (Door/window)		2400 x 1200	26	0.015	150	Blue/Grey	Yes					Easy to assemble and paintable surface	(Thermablok, 2017c)
	Aerogel Thermaslim Reveal Board		2400 x 1200	16	0.014	150	Blue/Grey	Yes					Easy to assemble and paintable surface	(Thermablok, 2017d)

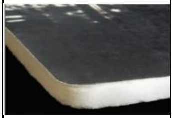
Manufacturer	Product	Illustration	Standard dimensions (L x W) (mm x mm)	Thickness (mm)	Thermal conductivity (W/ (m K))	Mass denisty (kg/m^3)	Color	Hydrophobic	Compression strength (kPa)	Tensile Strength perpendicular (Per) and parallell (Par) to faces (kPa)	Operating/ application temperature range (℃)	Flame spread index (Flame), smoke developed index (smoke) and reaction to fire (Fire)	Additional information	Reference
	Aerogel Thermaslim Basement Rail IWI Stud/Rail Basement System			30, 40, 50	0.015	150	Blue/Grey	Yes	80				GWP less than 5. Expected to last for 60 years.	(Thermablok, n.d.-c)
	Aerogel Insulation Slab and Frame Internal wall insulation system (IWI)				0.015	150 ± 20 %	White		3.9	16 Per and 1085 Par	-200 to 200			(Thermablok, n.d.-b)
	Internal floor insulation (IFI) impact panel		1220 x 605	5, 10	0.15							C, s1, d0		(Thermablok, n.d.-d)

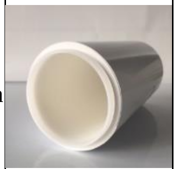
Manufacturer	Product	Illustration	Standard dimensions (L x W) (mm x mm)	Thickness (mm)	Thermal conductivity (W/ (m K))	Mass denisty (kg/m^3)	Color	Hydrophobic	Compression strength (kPa)	Tensile Strength perpendicular (Per) and parallell (Par) to faces (kPa)	Operating/ application temperature range (℃)	Flame spread index (Flame), smoke developed index (smoke) and reaction to fire (Fire)	Additional information	Reference
Aspen Aerogels	Spaceloft		Width 1.475m	5 and 10	15.0 mW/ (m K)		Grey	Yes					Flexible high performance insulation for building envelopes & equipment	(AspenAerogels, 2016)
	Pyrogel XTE			5 mm, 10 mm	20 mW/ (m K) at 0 ℃	12.5 lb/ft^3	Maroon	Yes	Stess at 10 % strain = 78.3 Stress at 25 % strain = 255.2		650	0 (Flame) and 0 (Smoke)	Flexible thermal insulation for high-temperature applications	(AspenAerogels, 2012)
	Pyrogel HPS			10	0.15 at 25 ℃		Grey				650		High pressure steam gas and steam turbines delayed coking	(AspenAerogels, 2020)
	Pyrogel XTF			10	0.15 at 25 ℃		Grey				650		High pressure steam gas and steam turbines delayed coking	(AspenAerogels, 2021)

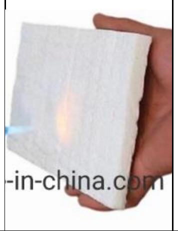
Manufacturer	Product	Illustration	Standard dimensions (L x W) (mm x mm)	Thickness (mm)	Thermal conductivity (W/ (m K))	Mass denisty (kg/m^3)	Color	Hydrophobic	Compression strength (kPa)	Tensile Strength perpendicular (Per) and parallell (Par) to faces (kPa)	Operating/ application temperature range (℃)	Flame spread index (Flame), smoke developed index (smoke) and reaction to fire (Fire)	Additional information	Reference
Cabot	Thermal Wrap TW250		160000 x 757	2.5	0.013 at 25 ℃	70	White				-200 to 125 (peaks at 160)		Highly-breathable, but water repellent	(Cabot, 2020c)
	Thermal Wrap TW350		120000 x 762	3.5	0.013 at 25 ℃	70	White				-200 to 125 (peaks at 160)		Flexible, bendable and wrappable	(Cabot, 2020d)
	Thermal Wrap TW600		85000 x 762	6	0.013 at 25 ℃	70	White				-200 to 125 (peaks at 160)		Highly-breathable, but water repellent	(Cabot, 2020e)
	Thermal Wrap TW800		110000 x 762	8	0.013 at 25 ℃	70	White			517 Par	-200 to 125 (peaks at 160)		Low-dusting and low powering when cutt	(Cabot, 2020f)

Manufacturer	Product	Illustration	Standard dimensions (L x W) (mm x mm)	Thickness (mm)	Thermal conductivity (W/ (m K))	Mass denisty (kg/m^3)	Color	Hydrophobic	Compression strength (kPa)	Tensile Strength perpendicular (Per) and parallell (Par) to faces (kPa)	Operating/ application temperature range (℃)	Flame spread index (Flame), smoke developed index (smoke) and reaction to fire (Fire)	Additional information	Reference
Aerogel Technologies	Airloy X103		50 x 75	7	0.023 - 0.056	0.1 to 0.55 ± 0.02 g/cc	White		600 to 13000		80		Strong compression strength	(AerogelTechnologies, n.d.-b)
	Airloy X114		46 x 64	7	0.032	0.4 ± 0.02 g/cc	Red-brown		3000	167000 Par	300		High operating temperature	(AerogelTechnologies, n.d.-c)
	AirloyX 116		50 x 75	10	0.029	0.09 ± 0.02 g/cc	Yellow		400	11000 Par	400		Non-flammable strong aerogel	(AerogelTechnologies, n.d.-d)
Armacell	ArmaGel HT		1500 x (4000-65000)	5, 10, 15 and 20	0.021 at 24 °C	160 - 240	Grey		20.7 at 10 % compression		650	B-s1, d0 (Fire)	Flexible aerogel blanket for elevated temperature	(Armacell, 2022)

Manufacturer	Product	Illustration	Standard dimensions (L x W) (mm x mm)	Thickness (mm)	Thermal conductivity (W/ (m K))	Mass denisty (kg/m^3)	Color	Hydrophobic	Compression strength (kPa)	Tensile Strength perpendicular (Per) and parallell (Par) to faces (kPa)	Operating/ application temperature range (℃)	Flame spread index (Flame), smoke developed index (smoke) and reaction to fire (Fire)	Additional information	Reference
	ArmaGel DT		1500 x (4000-65000)	5, 10, 15 and 21	0.021 at 24 °C	160 - 240	Grey		34.5 at 10 % compression		250	≤25 (Flame) and ≤50 (Smoke)	Thermal insulation of pipes, vessels and ducts	(Armacell, 2021)
Enersens	Skogar ultra-fine super-insulating sheets			0.5 - 2.5	0.011 - 0.013 at 20 °C	175 ± 15	Multiple	Yes			-160 to 400	A1, s1, d0 (Fire)	Very good accoustic properties and is sustainable. Utilisable for many applications	(Skogar, 2015)
Ama Aerogel	Aerogel HT650		Roll x 1500	3, 6 and 10	0.021 at 25 °C	200 ± 30	White	Yes			-50 to 650		Well suitable for industrial applications	(AmaAerogel, n.d.-c)
	Aerogel HT450			3, 6 and 10										(AmaAerogel, n.d.-d)

Manufacturer	Product	Illustration	Standard dimensions (L x W) (mm x mm)	Thickness (mm)	Thermal conductivity (W/ (m K))	Mass denisty (kg/m^3)	Color	Hydrophobic	Compression strength (kPa)	Tensile Strength perpendicular (Per) and parallell (Par) to faces (kPa)	Operating/ application temperature range (℃)	Flame spread index (Flame), smoke developed index (smoke) and reaction to fire (Fire)	Additional information	Reference
	Aerogel LT200ALU		Roll x 1500	3, 6 and 10	0.010 at - 200 ℃	200 ± 30		Yes			-200 to 100		Pipelines and equipment in cold insulation	(AmaAerogel, n.d.-e)
	Aeropan		1400 x 720	10, 20, 30, 40	0.015	230 ± 10 %			80		-200 to 200	C, s1, d0 (Fire)	Ideal for application on outside perimeter walls and inside walls.	(AmaAerogel, n.d.-b)
	AeroGips		1400 x 720	5, 10, 20, 30, 40	0.015				80		-90 to 90	A2, s1, d0 (Fire)	Good heat-acoustic comfort	(AmaAerogel, n.d.-a)
JINNA	JN80-C				0.0145 at 0 ℃	160 ± 20		Yes			-200			(HebeiJinnaTechnologyCo., n.d.-c)
	JN200				0.016 at 0 ℃	160 ± 20		Yes						(HebeiJinnaTechnologyCo., n.d.-d)
	JN450				0.017 at 100 ℃	180 ± 20		Yes			650			(HebeiJinnaTechnologyCo., n.d.-e)

Manufacturer	Product	Illustration	Standard dimensions (L x W) (mm x mm)	Thickness (mm)	Thermal conductivity (W/ (m K))	Mass denisty (kg/m^3)	Color	Hydrophobic	Compression strength (kPa)	Tensile Strength perpendicular (Per) and parallell (Par) to faces (kPa)	Operating/ application temperature range (℃)	Flame spread index (Flame), smoke developed index (smoke) and reaction to fire (Fire)	Additional information	Reference
	JN650				0.021 at 200 ℃	180 ± 20		Yes			650			(HebeiJinnaTechnologyCo., n.d.-a)
	JN850					180 ± 20		Yes			800			(HebeiJinnaTechnologyCo., n.d.-b)
Aerchs	KZ903 Aerogel ultra-thin		Customized	0.1 - 0.3	0.02		White, Black				-40 to 120		Protection for weak heat-resistant components.	(Aerchs, n.d.)
GBS	Nano Aerogel felt		Customized x 1500	0.1 - 10	0.014 - 0.028	200	White, light yellow	Yes		1700 Par	100 to 500		High tensile strenght	(GBS, n.d.)

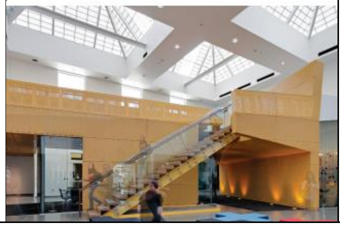
Manufacturer	Product	Illustration	Standard dimensions (L x W) (mm x mm)	Thickness (mm)	Thermal conductivity (W/ (m K))	Mass denisty (kg/m^3)	Color	Hydrophobic	Compression strength (kPa)	Tensile Strength perpendicular (Per) and parallell (Par) to faces (kPa)	Operating/ application temperature range (℃)	Flame spread index (Flame), smoke developed index (smoke) and reaction to fire (Fire)	Additional information	Reference
O-BASF	Slentite			15	0.018	110 - 135	White	Yes	300	100 Par		Class E (Fire)	Stable low thermal conductivity.	(Günther et al., 2020)
	Slentex			10	0.019	190 - 200	White	Yes	30	16 Par		A2-s1, d0 (Fire)	High degree of design freedom and anables very slim constructions.	(Günther et al., 2020)
Zhejiang UGOO Technology Co., Ltd	Fma650		36000 x 1500	10	0.02	180 - 210	White	Yes		200 Par	100 to 650		Flexible, fireproof and waterproof	(Zhejiang UGOOTechnologyCo., n.d.-a)
	SNF350			2, 3, 5	0.02	220	White				-180 to 350		Blanket for Fire Protection of Energy Storage Batteries	(Zhejiang UGOOTechnologyCo., n.d.-b)

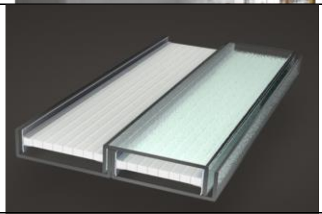
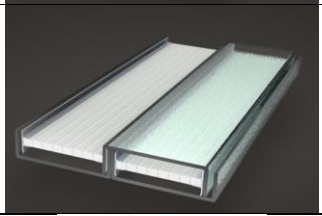
Manufacturer	Product	Illustration	Standard dimensions (L x W) (mm x mm)	Thickness (mm)	Thermal conductivity (W/ (m K))	Mass denisty (kg/m^3)	Color	Hydrophobic	Compression strength (kPa)	Tensile Strength perpendicular (Per) and parallell (Par) to faces (kPa)	Operating/ application temperature range (℃)	Flame spread index (Flame), smoke developed index (smoke) and reaction to fire (Fire)	Additional information	Reference
	UG450		36000 x 1500	10	0.02	180 - 210	White	Yes		200 Par	-100 to 450	Class A (fire)		(Zhejiang UGOOTechnologyCo., n.d.-c)

Table A: *Opaque aerogel products*

Appendix B – Translucent aerogel products

Manufacturer	Product	Illustration	Thickness (mm)	U-value (W/(m²K))	Color	Visible light transmisson (VLT) (%)	Solar heat gain coefficient (SHGC)	Wind load	Snow load (kPa)	Sound transmission class (STC)	Reference
KALWALL	Standard wall systems		70	1.02 - 3.01		3 - 58	0.1 - 0.65				(Kalwall, 2020a)
	Thermally broken wall systems		70	0.28 - 1.31		3 - 35	0.04 - 0.36				(Kalwall, 2020a)
	Specialty applicatio ns		70	0.28 - 3.01							(Kalwall, 2020a)
	Self supporting ridge roofs			0.28 - 3.01	White	3 - 58	0.04 - 0.65				(Kalwall, 2020b)

Manufacturer	Product	Illustration	Thickness (mm)	U-value (W/(m^{2}K))	Color	Visible light transmisson (VLT) (%)	Solar heat gain coefficient (SHGC)	Wind load	Snow load (kPa)	Sound transmission class (STC)	Reference
	Kalcurve 90° low profile vaults			0.28 - 3.01	White	3 - 58	0.04 - 0.65				(Kalwall, 2020b)
	Kalcurve 180° vaults			0.28 - 3.01	White	3 - 58	0.04 - 0.65				(Kalwall, 2020b)
	Skylights, Geo-roofs			0.28 - 3.01	White	3 - 50	0.04 - 0.65	1.197	0.958 - 1.915		(Kalwall, 2019)
	Skylights, Standard pyramids			0.28 - 3.01	White	3 - 50	0.04 - 0.65	1.197	1.915		(Kalwall, 2019)

Manufacturer	Product	Illustration	Thickness (mm)	U-value (W/(m²K))	Color	Visible light transmisson (VLT) (%)	Solar heat gain coefficient (SHGC)	Wind load	Snow load (kPa)	Sound transmission class (STC)	Reference
	Skylights, S-lines		70 and 100	0.28 - 3.01	White	3 - 50	0.04 - 0.65		1.915		(Kalwall, 2019)
Pilkington Profilit	Lumira aerogel Panel 16 mm		16	0.21	White	50	0.42			44	(Pilkington Profilit, n.d.)
	Lumira aerogel Panel 25 mm		25	0.19	White	38	0.31			44	(Pilkington Profilit, n.d.)
Solera	Solera plus Lumira R25-T		102	0.22		5 - 20	0.05 - 0.19			May exceed 52	(Solera, n.d.-b)

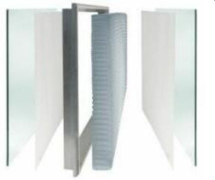
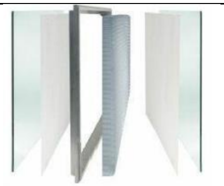
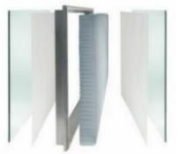
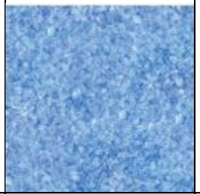
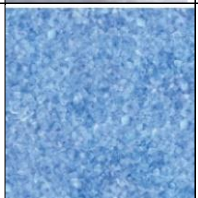
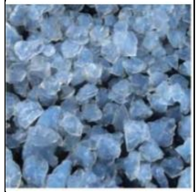
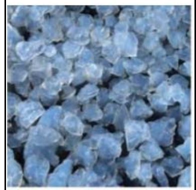
Manufacturer	Product	Illustration	Thickness (mm)	U-value (W/(m²K))	Color	Visible light transmisson (VLT) (%)	Solar heat gain coefficient (SHGC)	Wind load	Snow load (kPa)	Sound transmission class (STC)	Reference
	Solera T R18+Aerogel		76	0.31		7 - 32	0.07 - 0.30			May exceed 52	(Solera, n.d.-f)
	Solera T R9+Aerogel		44	0.61		9 - 40	0.09 - 0.37			May exceed 52	(Solera, n.d.-e)
	Solera S R5+Aerogel		25.4	1.14		10 - 45	0.10 - 0.42			May exceed 52	(Solera, n.d.-c)
	Solera T R5		76.2	1.14		10 - 55	0.09 - 0.51			Up to 52	(Solera, n.d.-d)
	Solera L		25.4	2.65		12 - 62	0.11 - 0.58			Up to 40	(Solera, n.d.-a)

Table B: *Translucent aerogel products*

Appendix C – Translucent aerogel as particle products

Manufacturer	Product	Illustration	Thermal conductivity (W/(mK))	Color	Particle denisty (kg/m^3)	Bulk density (kg/m^3)	Porosity (%)	Hydrophobic	Particle size (mm)	Application range (℃)	Additional information	Reference
Cabot	P150 aerogel particles		0.13 at 25℃		120 - 180	80 - 100	> 90	Yes	0.1 0.5		Can be used in a variety of end-use bulk applications. Performance benefits: sound absorption, non-combustible, UV-stability and inert	(Cabot, 2020b)
	P250F aerogel particles		0.13 at 25℃		120 - 180	65 - 85	> 90	Yes	0.5 - 4.0		Can be used in a variety of end-use bulk applications	(Cabot, 2020b)
	ENOVA IC3100		0.13 at 25℃		120 - 150	80 - 100	> 90	Yes	2.0 - 40.0μm		Utra-low thermal conductivity and exstrem resistance to shear	(Cabot, 2021b)
	ENOVA IC3105		0.13 at 25℃		120 - 180	80 - 100	> 90	Yes	0.1 0.5		UV stability and sound absorpstion	(Cabot, 2021e)
	ENOVA IC3110		0.12 at 25℃		120 - 150			Yes	0.1 0.7		Safe touch performance for personnel protection	(Cabot, 2021c)

Manufacturer	Product	Illustration	Thermal conductivity (W/(mK))	Color	Particle denisty (kg/m^3)	Bulk density (kg/m^3)	Porosity (%)	Hydrophobic	Particle size (mm)	Application range (℃)	Additional information	Reference
	ENOVA IC3120		0.012 at 25℃		120 - 150			Yes	0.1 1.2		Benefits: Insulation performance unaffected by shear, high single pass DFT, safe touch performance for personnel protection and complete hydrophobicity	(Cabot, 2021d)
	ENOVA MT1100 ;MT1200					25 - 50		Yes	2.0 - 24.0μm		Ideal high performance matting additive due to extremely low viscosity build	(Cabot, 2021a)
	LUMIRA LA1000		For Particle: 0.012, for Bulk: 0.017-0.022		120 - 150	68	> 90	Yes	1.2 - 4.0		Performance benefits: UV stability, sound absorption, high light transmission, lightweight, non-combustible and inert.	(Cabot, 2021f)
	LUMIRA LA2000		For Particle: 0.012, for Bulk: 0.017-0.023		120 - 150	75	> 90	Yes	0.7 - 1.2		Performance benefits: UV stability, sound absorption, high light transmission, lightweight, non-combustible and inert.	(Cabot, 2021f)

Manufacturer	Product	Illustration	Thermal conductivity (W/(mK))	Color	Particle denisty (kg/m^3)	Bulk density (kg/m^3)	Porosity (%)	Hydrophobic	Particle size (mm)	Application range (°C)	Additional information	Reference
	P100 Particles		0.13 at 25°C		120 - 180	80 - 100	> 90	Yes	0.1 - 4.0		Thermally insulative materials that can be used in a variety of end-use bulk insulation applications	(Cabot, 2020a)
	P200 Particles		0.13 at 25°C		120 - 180	75 - 95	> 90	Yes	0.1 - 1.2		Thermally insulative materials that can be used in a variety of end-use bulk insulation applications	(Cabot, 2020a)
	P300 Particles		0.13 at 25°C		120 - 180	65 - 85	> 90	Yes	1.2 - 4.0		Thermally insulative materials that can be used in a variety of end-use bulk insulation applications	(Cabot, 2020a)
JIOS AeroVa	Aerogel powder (D20 Grade)		0.017 to 0.022	White		30 - 100	> 90	Superhydrophobic	0.02	-200 to 1600	Can be used in markets such as building and construction, aerospace, energy, cosmetics, performance textiles and general industrial applications.	(JiosAeroVa, 2015)

Manufacturer	Product	Illustration	Thermal conductivity (W/(mK))	Color	Particle denisty (kg/m^3)	Bulk density (kg/m^3)	Porosity (%)	Hydrophobic	Particle size (mm)	Application range (°C)	Additional information	Reference
Enersens	Kwark		0.018 - 0.022			75		Yes	0.01 - 3.5	-195 to 450	Stable in front og all external conditions	Kwark
Aerogel+	Aerowder: Ecological silica aerogel powder		0.015 - 0.022			90 - 100		Yes		-200 to 1200		(Aerogel+, n.d.)
JINNA	Aerogel powder Particles		0.008 - 0.015			40 - 180	90 – 98	Yes			Widely applied as the interlayer, stuffed layer, multi-layer to insulated equipment	(Jinna, n.d.)

Table C: *Translucent aerogel as particle products*

Appendix D – Transparent aerogel products

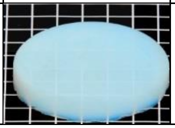
Manufacturer	**Product**	**Illustration**	**Thermal conductivity (W/(mK))**	**Mass denisty (kg/m^3)**	**Standard dimensions (L x W) (mm x mm)**	**Thickness (mm)**	**Compressive strength**	**Bending strength (MPa)**	**Contact angle water**	**Application range (ºC)**	**Reference**
Tiem Factory Inc.	SUFA		0.012 - 0.014	0.11 - 0.12 g/cm^3			9.22MPa	0.05 - 0.4	140 degrees Super water repellency	up to 467	(TiemFactoryInc., n.d.)
Aerogel Technologies	Airloy X56		0.023	0.30 ± 0.05 g/cm^3	5 cm diameter	5	0.65MPa			80	(AerogelTechnologies, n.d.-a)

Table D: *Transparent aerogel products*

Appendix E – Miscellaneous aerogel mixtures

Manufacturer	Product	Illustration	Thermal conductivity (W/(mK))	Color	Bulk density (kg/m^3)	Mass density (g/cm^3)	Standard dimensions (L x W) (mm x mm)	Thickness (mm)	Tensile strength (N/mm^2)	Application range (ºC)	Light transmission (t_vis) (%)	Reference
FIXIT	FIXIT 222 Aerogel High Performanse Insulation Plaster		0.026 - 0.028	Grey	220			min. 30 - max. 150		5 to 30		(Fixit, 2022)
Core Conservation	TermoRasante AeroGel Thermal Lime Finishing Plaster		0.016	White				min. 4 - max. 10		5 to 35		(CoreConservation, n.d.)
Rova Corporation	Rova shield black - Aerogel insulation coating		0.040 - 0.045	White		0.5 - 0.6		0.5		10 to 35		(RovaCorporation, 2019c)
	Rova shield - Solar reflective aerogel insulation coating			White		0.64 - 0.68		0.3		10 to 35		(RovaCorporation, 2019d)
	Rova flex - Aerogel insulation tape		0.040 - 0.050	White			500 mm x 500 mm x 1 mm		0.1 - 0.12			(RovaCorporation, 2019a)

***Table E:** Miscellaneous aerogel mixtures*