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Innovation in thermal insulation materials, a step toward sustainable buildings

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Abstract

The continual increase in energy needs that results from developing technology, depletion of natural sources needed for life, and environmental pollution all give cause to environmental issues on local and global scales. Sustainable design principles which emerge as a consequence of attempts to minimize negative effects aim for health and comfort conditions which are required both for human life and the protection of ecological balance. In this sense, so that the abovementioned conditions may be fulfilled, the use of ecological materials in the construction of sustainable buildings is of capital importance. When insulation materials, of indisputable importance in terms of energy conservation, are considered in ecological terms, it may be underscored that no insulation material has all the necessary features. With technological developments and the application of ecological and green principles, insulation materials have gained different features. These materials, prominent in the process of energy-efficient building design, continue to develop not only in heat, fire, and sound insulation but also, İn the scope of sustainable structural design, İn causing no harm to human health and the environment, and in addition to the function of heat insulation as a component of passive design featuring solar radiation conductivity providing for heat gain and natural lighting of the design space. In addition to organic insulation materials such as aerogel with low embodied energy and that are sensitive to the environment, innovative materials with high heat resistance and recycled insulation materials such as cellulose are also among the outstanding examples of this period of change. The paper presents also an analytical application demonstrates that it is supposed to be an expensive method initially but is more advantageous, considering the low costs afterwards, mainly, because of reduced energy consumption. It talks about chemical adaptation of Aerogels for optical applications, chemical adaptation of Aerogels to thermal insulation and its various applications in Building Industry.

Keywords: thermal insulation, aerogel, sustainability, architecture, material

۱. Introduction

Thermal insulation materials are materials with a high degree of thermal resistance, used to minimize heat transfer. In order to provide these, insulation materials must have the heat transfer coefficient below the European Standards of ۰,۰٦- ۰,۱۰ W/m۲K. The application of insulation materials are varied for the types of buildings and structures and also climatic conditions. Because of this variety, choosing the expedient materials is vital not only for building's energy performance but also reducing its impact on the environment. It is important that materials be chosen that are long-lasting, sufficiently durable, minimally polluting, use a minimum of natural resources, and achieve the necessary outcomes in thermal performance [۱], [۲], [۳].

In addition to the performance criteria based on physical properties (density, durability, thermal resistance, sound insulation, resistance to fire and humidity, etc.) widely used to date, effects on the environment also play an important role in the classification of insulation materials. Based on analyses of embodied energy, gas emissions during production, use of additives as protection against biological impacts, and life cycle, materials can be ranked with respect to reusability, recyclability, and effects on human health. The examination of conventional and alternative insulation materials in the context of sustainability criteria is basic for determining their effects on the environment. [۱],[٤],[٥].

Classification of Insulation Materials

With the aim of examining insulation materials with respect to sustainability principles, this study evaluates "Conventional" (inorganic and organic insulation materials widely used in the present), "Organic" (materials developed as alternatives, derived from organic sources), "Innovative" (technologically advanced and new insulation materials), and "Recyclable" (derived from recycled materials) insulation materials. Under these headings, insulation materials will be evaluated in the context of sustainability. Figure ۱

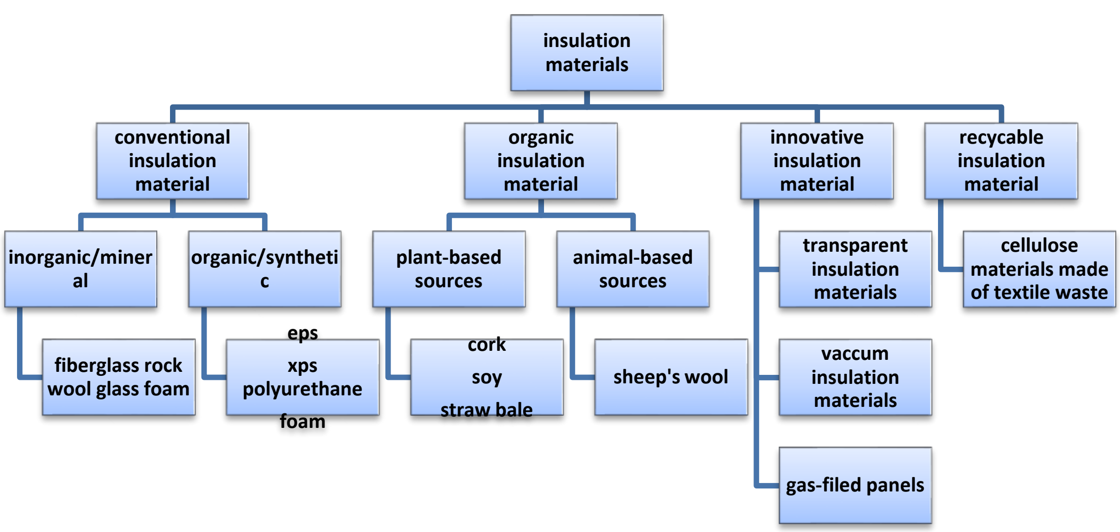

Figure ۱. Classification of Insulation Materials [۴, ۵،۶،۷،۸ ,۹]

۲. Innovative Insulation Materials

Innovative insulation materials, developed with the full potential of technology as alternatives to conventional insulation materials and their effects on the environment, have a quite low thermal conductivity. Unfavorable qualities of innovative materials include their still being in development, lack of widespread use, and high cost, but it is nonetheless expected that these materials will enter the insulation sector in the near future. (cf. table ۲)

Opaque insulation materials applied to a building's shell, usually on the exterior, eliminate the potential to harness solar heat. Energy conservation is made possible through the minimization of heat loss through the application of transparent insulation materials (TIM) in low-energy building shell applications, and additionally the provision of passive solar gains through the storage of solar heat, and the provision of hot water through either the wall functioning as a thermal mass or through hybrid systems. High thermal resistance and solar radiation transmittance are the most important features of transparent insulation; these features, however, are inversely correlated with one another [٦].

In light of these specifications, the simplest example of transparent insulation is that of glass; in spite of its low thermal resistance, glass both permits the transmittance of radiation and prevents the loss of harnessed solar energy. Though glass is resistant to fires and environmental factors, its density and high degree of heat conductivity are among its unfavorable qualities. Applications of evacuated glazing, which eliminates these unfavorable characteristics, are in development now, with laboratory testing in progress. Thermoplastic and silica aerogels, transparent insulation materials that present an alternative to glass, are in use now [٦]. figure ۲

The energy performance of wall components made of transparent insulation materials depends on the insulation material's structural construction and organization. Transparent insulation materials are permeable to short-wavelength infrared radiation but are opaque to long-wavelength infrared radiation. Short-wavelength infrared radiation that passes through the insulation is absorbed by the absorbing surface and converted to heat in the wall mass, and said heat energy is transferred to the indoor space through convection-radiation [٦].

Transparent insulation materials are categorized by ٤ types according to their geometric structure. The types are as follows: Absorber – parallel; Absorber – perpendicular; Cavity structure; and Quasi-homogeneous [٦,٧]. Absorbing-parallel structures are single- or multi-layered components whose layers are parallel to the absorbing structure. The effectiveness of the system depends on reflection and absorption rates; increasing the number of layers improves heat insulation at a detriment to radiation transmittance. In multi-layered structures, the use of argon, krypton or xenon as filler material can increase thermal resistance [٦]. Absorbing-perpendicular structures, such as capillary tubes and honeycomb structures, are arranged perpendicular to the absorbing surface and assure that the sun's rays reach the wall's surface rather than being reflected. Depending on the sun's angle of incidence, in the summer months the sun's rays enter the tubules with the vertical surface creating an acute angle, while in the winter months they enter nearly horizontally at an oblique angle and reach the absorbing surface by reflecting off the tubules' walls. Thermal energy stored in solid walls is thus transferred to the interiors by way of conduction and radiation [٦].

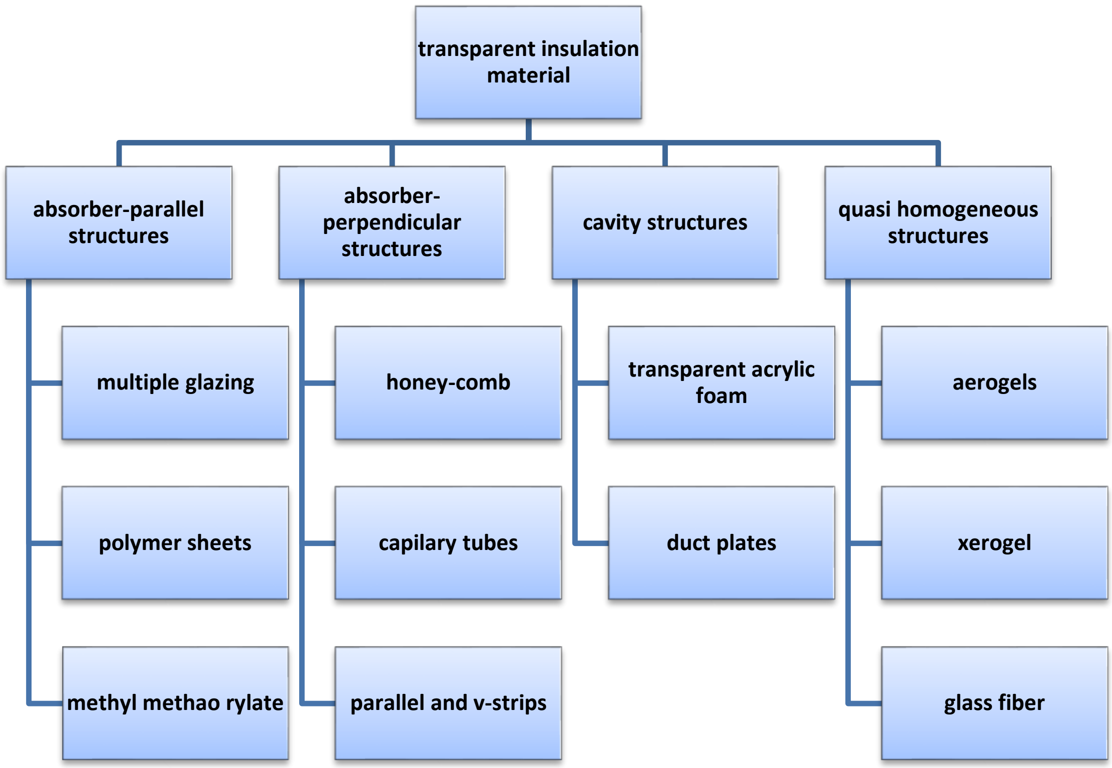

Figure ۲. Classification of transparent insulation materials

Aerogels are a diverse class of porous, solid materials that exhibit an uncanny array of extreme materials properties. Most notably aerogels are known for their extreme low densities (which range from ۰,۰۰۱۱ to ~۰,۵ g cm-۳). In fact, the lowest density solid materials that have ever been produced are all aerogels, including a silica aerogel that as produced was only three times heavier than air, and could be made lighter than air by evacuating the air out of its pores. That said, aerogels usually have densities of ۰,۰۲۰ g cm-۳ or higher (about ۱۵ times heavier than air). But even at those densities, it would take ۱۵۰ brick-sized pieces of aerogel to weigh as much as a single gallon of water[٦].

Essentially an aerogel is the dry, low-density, porous, solid framework of a gel (the part of a gel that gives the gel its solid-like cohesiveness) isolated in-tact from the gel's liquid component (the part that makes up most of the volume of the gel)[۵]. Aerogels are open-porous (that is, the gas in the aerogel is not trapped inside solid pockets) and have pores in the range of <۱ to ۱۰۰ nanometers (billionths of a meter) in diameter and usually <۲۰ nm. Aerogels are dry that refer to the fact they are derived from gels–effectively the solid structure of a wet gel, only with a gas or vacuum in its pores instead of liquid.

The term aerogel does not refer to a particular substance, but rather to a geometry which a substance can take on–the same way a sculpture can be made out of clay, plastic, papier-mâché, etc., aerogels can be made of a wide variety of substances, including: Silica, Most of the transition metal oxides (for example, iron oxide), Most of the lanthanide and actinide metal oxides (for example, praseodymium oxide), Several main group metal oxides (for example, tin oxide), Organic polymers (such as resorcinol-formaldehyde, phenol-formaldehyde, polyacrylates, polystyrenes, polyurethanes, and epoxies), Biological polymers (such as gelatin, pectin, and agar agar), Semiconductor nanostructures (such as cadmium selenide quantum dots), Carbon, Carbon nanotubes and Metals (such as copper and gold). Aerogel composites, for example aerogels reinforced with polymer coatings or aerogels embedded with magnetic nanoparticles, are also routinely prepared.

۳. Special Properties of Aerogels

Many aerogels boast a combination of impressive materials properties that no other materials possess simultaneously. Specific formulations of aerogels hold records for the lowest bulk density of any known material (as low as ۰,۰۰۱۱ g cm-۳), the lowest mean free path of diffusion of any solid material, the highest specific surface area of any monolithic (non-powder) material (up to ۳۲۰۰ m۲ g-۱), the lowest dielectric constant of any solid material, and the slowest speed of sound through any solid material. It is important to note that not all aerogels have record properties[۱].

Aerogels of all sorts hold records for different properties. Here are some: Records held by some specially-formulated silica aerogels: Lowest density solid (۰,۰۰۱۱ g cm-۳), Lowest optical index of refraction (۱,۰۰۲), Lowest thermal conductivity (۰,۰۱٦ W m-۱ K-۱), Lowest speed of sound through a material (۷۰ m s-۱), Lowest dielectric constant from ۳-٤۰ GHz (۱,۰۰۸)[۹].

۳-۱- Historical Background

Aerogel was created by Steven Kistler in ۱۹۳۱ and it has become a material of interest to scientists in recent decades due to its light weight. Aerogel is a synthetic porous ultra light material derived from a gel, in which the liquid component of the gel has been replaced with a gas. It is an advanced material which holds ۱٥ entries in the Guinness Book of Records for properties such as lowest density solid and best insulator. It is a silica-based substance, consisting of a loose dendritic network of the atom silicon.

Production of Aerogels: Preparation : Aerogels can be prepared by using Alumina, Chromium, Tin oxide and Carbon. But apart from these materials used for making of aerogel, silica based aerogel is preparation is easier and reliable.

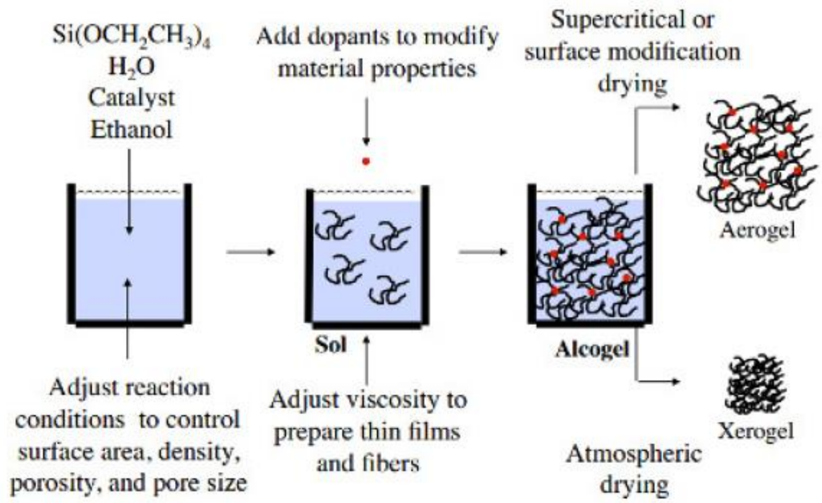

Figure ۳. Aerogel preparation method

٤ to ۳۰ times more water is added to Tetraethylorthosilicate (TEOS) in the presence of ethanol it leads to the further chemical reaction

Si (OCH۲CH۳) ٤ (liq.) + ۲(H۲O) (liq.)¨ SiO۲ (solid) + ٤(HOCH۲CH۳) (liq.)

Final product density is mainly depends on the concentration of silicon alkoxide monomers in the solution. After gelification, the gel is left undisturbed in the solvent for ٤٨ hours to complete the reaction. Once reaction will complete the alcogel product will form. Inorganic aerogels can be prepared via sol-gel processing, a technique which requires alcoxides or metal salts in alcoholic or aqueous solutions. The alcogel is then submitted to supercritical drying. The final products formed in this reaction are[٥]:

. Aerogel

. Xerogel

After mixing, a dispersion of colloidal particles is generated (hydrolysis and condensation polymerisation) which form a three-dimensional network (gelation). The particle size depends on the catalyst and varies between nanometer and micrometer scale. After the gelation process the enclosed pore liquid has to be carefully removed to preserve the nanostructure of the aerogel. Figure ۳

۳-۲- Cellulosic aerogels

Aerogels, materials with extreme porosity and very low bulk density, can be made using the so called 'Critical Point Drying'- technique.In a recent study aerogels were prepared from cellulose, xylan, lignin, their mixtures and from spruce wood, Figure ٤. The procedure was:

• Dissolution of the lignocellulose material in an ionic liquid[٤].
• Creating a hydrogel by precipitating the dissolved polymeric material with aqueous ethanol.
• Exchanging the aqueous precipitant to pure ethanol.
• Exchanging ethanol to liquid carbon dioxide.
• Increasing the temperature to above the Tc of carbon dioxide .

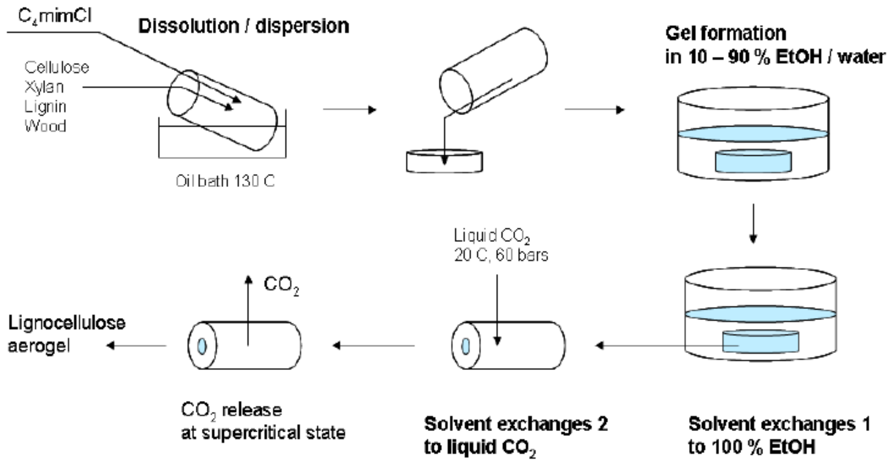

Figure ۴. lignocelulose Aerogel.

۳-۳- Carbon aerogels

• Carbon aerogels provide high specific surface areas combined with a fully tunable three-dimensional
structure.

• They have tunable performance for specific applications by the addition of dopants that can enhance the
electrical, thermal, and mechanical properties of the composite material.

• They are excellent thermal insulators because their gaseous components greatly reduces heat transfer by
conduction, convection, and radiation.

• They improve electric double-layer super capacitors—very low impedance compared to conventional super capacitors, yet can absorb or produce very high peak currents.

٤. Potential Applications

• Energy storage in batteries and super capacitors are an ideal use of carbon aerogels. Tunable porosities can be used to minimize diffusion resistance while maintaining constant surface area.

• Hydrogen generated from water by solar energy, and electric energy from sustainable sources, are anticipated fuels of the future. These technologies incorporate CAs as functional nano materials.

• CAs as nano catalysts can assist in electro-catalysis as electrode materials and by providing catalyst support in proton-exchange-membrane fuel cells.

• CAs offer considerable potential to significantly improve desalination efficiency through a technique known as capacitive deionization. This can increase the world's fresh water supply through capacitive desalination of sea water and brackish water[۲].

• CAs are extremely "black" in the infrared, making them efficient in solar-energy collectors.

٤. Properties of Aerogel : They possesses following properties:

• Low thermal conductivity

• Hardness
• Heat resistance
• Transparency
• Elasticity
• Insulation
• Durability
• Flexibility

۵. Use of Aerogel for Sustainable Building Construction

Roof : Aerogel insulation can insulate roof cavities or be used to reduce thermal bridging in roof rafters[۵]. It can be used for highly insulated homes that are sealed from the outside, both over masonry and under shingles and it has high insulatin value. In ood frame homes, thin strips of aerogel can be applied to studs to prevent what's called thermal bridging, where heat escapes through the walls'framing. Aspen provides this chart for for the R-value-philes (Spaceloft being Aspen's brand name for their building insulation aerogel): figure ۵

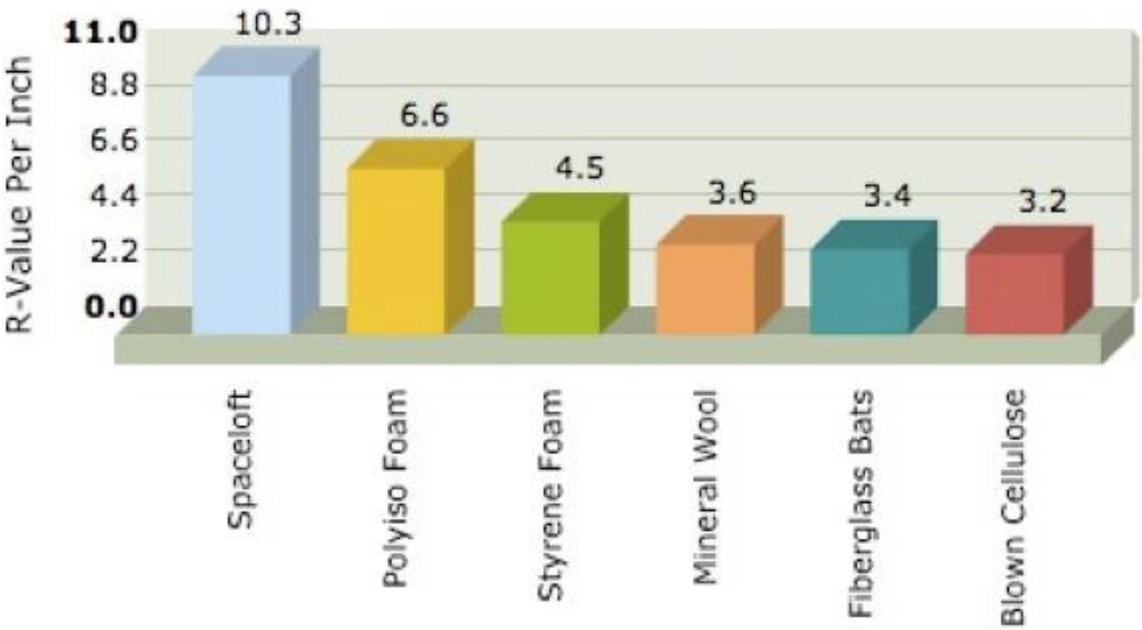

Figure ۵. R-value of Aerogel.

Framing : In a typical building, the framing (۲۵٪ of the building envelope) is un-insulated, resulting in heat loss through the studs. The insulation stops this "thermal bridging" and improves thermal performance up to ٤٠٪ in steel studs and up to ۱۵٪ in wood studs.

The development of the super insulating glazing would lead to significant energy savings in both existing and new residential and commercial buildings. The light transmittance and U-value of aerogel-glazed windows, ٤٠٪ and ۰,۸۵ W/m۲K, respectively, present new opportunities for the use of day lighting in buildings and the architectural design of building façades. In addition to glazing, aerogels have also been used in solar collector covers[۳].

Floor : Aerogel insulation's thermal efficiency, good compression strength, and thin profile make it attractive as an under floor insulating layer where height is an issue. It installs fast in under floor applications without disrupting door fittings, while providing substantial energy savings. Aerogel insulation is a fast, cost-effective solution for basement renovations, easy to install, improves thermal comfort, and does not disrupt door fittings because it is so thin. It installs quickly and can improve the thermal comfort of a house. If used with radiant floors it saves energy and enables a fast heating cycle.

Aerogel as a Super-insulator: Aerogel is a transparent material with interesting optical properties, such as high light and solar transmittance but, differently from the normally used transparent materials such as glass, it has also very good thermal insulation properties; it is in fact used as transparent wall in solar collectors and in office buildings[۲].

Aerogel is available as panes and as granules. Glazing systems with monolithic aerogel are not yet used in mass production , but during the year ۲۰۰۵ many types of translucent granular aerogel appeared on the market for day lighting systems . The different systems found in the Literature polycarbonate panels, structural panels, insulated glasses) are able to offer excellent thermal performance, high quality of the diffused light, a good solar heat gain and good sound insulation characteristics. One of the most important examples of aerogel uses to date is the application of silica aerogels as super insulation. An inch-thick pane of a low-density silica aerogel is as effective of an insulator as a stack of ۳۰ panes of window glass, and thanks in part to this impressive insulating ability, the electronics on the twin Mars Exploration Rovers have managed to survive the extreme thermal cycling experienced on Mars (from - ۱٤۰°C to ۲۰°C) well beyond design lifetime. Aspen Aerogels has even recently commercialized a family of superinsulating blankets based on silica aerogel for terrestrial use. One major advantage to silica aerogel as a terrestrial thermal insulation is the enhanced energy efficiency it can bring to industrial plants. Energy-intensive refineries, for example, predominantly use mineral wool as an insulating medium. Silica aerogel materials are now poised to displace mineral wool as a superior insulation in the next decade, resulting in greater efficiency that translates into reduced emissions in what amounts to ۱۵٪ of all industrial CO۲ emissions in the United States. Furthermore, unlike polyurethane and polystyrene insulations, no chlorofluorocarbon (CFC) blowing agents are required to manufacture aerogel insulation[۱].

٦. Highly energy-efficient windows

In addition to the low thermal conductivity of silica aerogel, a high solar energy and daylight transmittance is achieved. In fact, by using the passive solar energy through windows, it is possible to reduce the annual energy consumption for space-heating in cold climates, such as in the northern European Countries or in highlands. Double-pane windows, sealed sandwiches of glass with rarefied gas like Ar or Kr trapped inside, are a way to address this problem, however lose their insulating ability over the course of about ۱۰ years. It has been proposed that silica aerogel, which is usually transparent, could be a revolutionary window insulation material. Unfortunately, due to nanostructural variations in the aerogel’s substructure, silica aerogels

Rayleigh scatter the short wavelengths of visible light, which makes them appear blue. For practical commercial applications in windows, this effect would need to be significantly reduced, and in order to do so, a better understanding of the origins of these nano-structural variations and how to control them must be established[٦,٧].

۷. Conclusion

The unique properties of aerogels offer many new applications in buildings. The extraordinary low thermal insulation and optical transparency of aerogels allow its applications in window panes and solar collector covers. Due to their low thermal conductivity and acoustic property for noise abatement, aerogels could be used in buildings, as well as for adsorption and catalysis in indoor air purification, photocatalysis in environmental clean-up, noncombustibility (inorganic aerogels) in fire retardation boards in kitchens. Aerogel materials may also be applied to a building's walls, attics, grounds and appliances. The unusual properties of aerogels open the way to a new range of opportunities for their application in buildings. Their main benefits include excellent insulating properties provide energy and cost savings due to reduced loss of heated or conditioned indoor air, healthier indoor environment due to removal of airborne contaminants, heat- and sound-retarding properties due to the non-combustibility and acoustic properties of the aerogel. Above all they are user-friendly, recyclable and reusable.

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