International Journal of Engineering Applied Sciences and Technology, 2022
Vol. 7, Issue 6, ISSN No. 2455-2143, Pages 194-200
Published Online October 2022 in IJEAST (http://www.ijeast.com)

IMPLEMENTATION OF AN AEROGEL IN CIVIL ENGINEERING - A REVIEW

Samruddhi M. Vibhute
Department of Civil Engineering
Sinhagad Academy of Engineering, Pune, Maharashtra, India.

Abstract— **Recent climate change has already indicated the need to reduce high-energy materials and increase the implementation of eco-friendly materials. As climate change can affect building structures, the construction industry must have to concerned about its contribution to greenhouse emissions and reduction in the use of high-energy materials. This paper studies the building materials made up of aerogel, a nanoporous solid with ~99% of air, which could help civil engineering to achieve minimum emission and energy-efficient structures. This review concluded that the implementation and application of aerogel-based construction materials can benefit both civil engineering and the environment.**

Keywords— **Energy efficient buildings, Aerogel, Construction materials, nanotechnology, thermal insulation, lightweight construction materials, wastewater treatment, towards zero-emission construction, Building retrofitting and repairing**

I. INTRODUCTION

It has become a need of the hour to reduce greenhouse emissions and global warming as the globe is facing heat waves, floods, the melting of Antarctica, and the terrible effects of climate change. The urgency of discovery and utilization of eco-friendly substances is increasing day by day since global warming and climate change are the factors affecting infrastructure, the country's development, economy, health, and many industries including the construction industry. It is miserable and remarkable how human beings are capable of contributing to global warming and the way global warming affects back human health. In the same manner, various industries have also contributed and found themselves affected. According to global status reports on buildings and construction, the construction industry contributes 38-39% of total CO2 emissions and 35% of total energy consumption [44], [45]. Climate changes and temperature variations lead to problems like a creep in structures, infrastructure damages, etc. Some of the conventional building materials have high ozone-depleting potentials such as cement, steel, and other high-energy materials. They must have to be replaced with sustainable and eco-friendly materials.

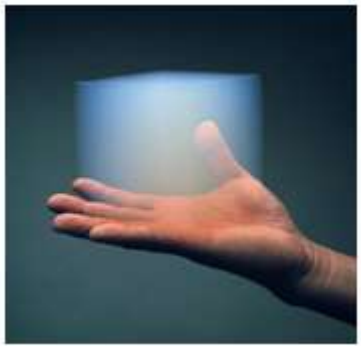

Fig. 1. Picture of hand holding cube of aerogel: Image source [47]

This paper studies various types of eco-friendly and energy-efficient materials made up of aerogel, a nanoporous, lightest known solid with 99.8% of air, which can help in minimum emission and a further improvement in civil engineering. With its lowest thermal conductivity, it reduces the energy consumption of buildings. This study mainly focused on aerogel, its derived building materials and composites, their applications, and actually the need to implement them as it will be beneficial to both Civil Engineering and the environment too. Likewise, challenges in implementation and application are studied and a conclusion has been drawn that aerogel-based materials are preferable to use. However, the aerogel and some of its derivative materials have to be studied further and need to improve their properties more.

Aero gel [41]

Aerogels are produced synthetically by the process of extracting liquid components from the gel and replacing it with gas, without collapse of the gel structure, which is also called supercritical drying or freeze drying. Aerogel is a class of micro porous ultra light material that is classified into solids with extremely low density and extremely low conductivity. IUPAC (International Union of Pure and Applied Chemistry) defined aerogel as "Gel comprising a micro porous solid in which the dispersed phase is a gas." Micro porous silica, micro porous glass, and zeolites are some Aerogels. Aerogels can be made from a variety of chemical compounds. Samuel Stephens Kistler first invented an aerogel from silica gel and his later work involved aerogels based on alumina, chromium oxide, and tin dioxide.

International Journal of Engineering Applied Sciences and Technology, 2022
Vol. 7, Issue 6, ISSN No. 2455-2143, Pages 194-200
Published Online October 2022 in IJEAST (http://www.ijeast.com)

General properties

- Aerogel is nothing but 99.8% air, with a porous solid network that contains air pockets, which makes it almost substantially weightless [41].
- graphene aerogel can support more than 6,000 times its self-weight [41]
- Because of its hygroscopic nature, it is a very strong desiccant [41].
- Nanopores in aerogel make it excellent for thermal insulation. [42]
- They are very fragile but incorporated with a fibrous matrix to form an aerogel blanket [41].

Properties of aero gel that can be applied to civil engineering

1. **Anticorrosive** [4]

Aerogel paint has acid and alkaline resistance that is intact even when exposed to salt water for a long time. This paint is applicable for structures in coastal areas where they are highly exposed to calcium chloride as a preventive measure for the carbonation of concrete.

2. Fire resistance [5]

Aerogel Paint has a semi-nonflammable function as it greatly reduces heat flow due to the nano porosity properties of Aerogel, thus delaying combustion of the driven material as much as possible. Also, no toxic gas is emitted in the event of a fire because of the water-repellent material.

3. Low thermal conductivity

The thermal conductivity of a material is its ability to transfer heat. Aerogel and aerogel-based materials are excellent thermal resistors or insulators, according to various research and experimental studies performed. All the studies from the literature referred to show the lowest heat conductivity of aerogel [1]. It has lower thermal conductivity than the top insulating materials i.e. mineral wool [43]. Aerogel's Nano porosity structure maximizes cooling efficiency with superior thermal reflection (94%) and low thermal conductivity (0.034 ~ 0.058 w/mk) in summer and prevents the transfer of cooling air from outside surfaces and outside loss of internal warmth with low thermal conductivity in winter.[6]

4. Mold proof [7]

Aerogel Paint shows an excellent effect on condensation and mold problems. Any area such as a wet wall, basement wall, and warehouse well. Due to the excellent waterproofing and water repellent properties of Aerogel, molds are not easily absorbed even in small amounts of moisture. The testing result shows mold damage and the fungal-affected area can be easily removed without treatment.

5. Light weight

As aerogel is nothing but almost air, it is the lightest known solid in the world. Aerogel-based materials are easy to handle because of their lightweight. It also makes easy transportation and easy construction operations with a reduction in time consumption and manpower requirement. Henceforth, could be applicable for speedy construction work or projects.

II. AEROGEL-BASED CONSTRUCTION MATERIALS

1. Aerogel-based paints

A year before, in [39] researchers invented a silica aerogel micro powder which has a thermal conductivity of 0.025 W/mk, a high surface area of 786m² & porosity of 96.36%, from solid waste ashes gathered from waste to energy incineration plants. And mixed into water-based paint to develop it with improved thermal insulation properties.

Findings indicated that by incorporating aerogel in paints, the thermal conductivity and the thickness of coatings (in micrometers) can be reduced remarkably.

It has been observed that the properties of the paint varied according to the aerogel content present in it. An experimental Study of considered research gave the variation in workability of paints with different aerogel contents.

2. Aerogel blankets

Aerogel blankets are textile-like, flexible, and incorporate aerogel particles into ultra-thin nonwoven with superior insulating properties. This aerogel product is widely used in not only the construction sector but also in various sectors including the textile industry & footwear. [12]

These are made by adding fibers or a fibrous matrix to the pre-gel mixture which contains gel precursors, and then the gel can be dried [8]. "An aerogel blanket/ panel is a composite of silica aerogel and fibrous reinforcement that turns the brittle aerogel into a durable, flexible/ solid, and hydrophobic material, useful in building envelopes, inside or outside" [9]. They can be applicable for roofs, floors, and external and internal insulation in the construction sector. [9]

But according to the thesis by [8] the aerogel blanket catches fire within a short time, and it should be prevented from fire exposure.

3. Aero bricks

Researchers at Empa, have produced an insulating building material using aero gel called "Aero bricks"—bricks with internal cavities filled with aerogel granules. [11]

Adding aerogel into air-filled (hollow) brick fillings can improve the brick's insulating abilities. Jannis developed a paste of aerogel granules to use as a filling material in hollow brick, which would bind with the clay of the brick by achieving adhesion and normal handling would be allowed. This research made by using a guarded hot plate setup and substituting perlite filling in insulating bricks with a compound made from aerogel granules shows a strong decrease in thermal conductivity of those bricks of about 30% without considering mortar between them i.e. U value for perlite filling and aerogel filling is measured as $0.502W/(m^2.k)$ and $0.337W/(m^2.k)$. Results showed thermal conductivity of 3/7 bricks with perlite filling

International Journal of Engineering Applied Sciences and Technology, 2022
Vol. 7, Issue 6, ISSN No. 2455-2143, Pages 194-200
Published Online October 2022 in IJEAST (http://www.ijeast.com)

and aerogel filling is 91mW/(m·K) and 59mW/(m·K) respectively. In the end, the researcher concluded, "Full-sized aerobrick has excellent thermal properties with U value of 0.157W/(m^2.k)."[11]

4. Aerogel plaster

Aerogel plaster is a high-energy efficient wall finish with extremely low thermal conductivity. It is plaster with incorporated aerogel granules in which aggregate (sand) is replaced by aerogel granules resulting in improved thermal performance as compared to thermal conductivities of conventional plaster and conventional thermal insulation plaster of 0.2mW/(m·K) say 0.5mW/(m·K) and 0.1-0.2mW/(m·K) respectively and 0.026 to 0.1mW/(m·K) is that of Aerogel plaster.[14]

Fixit 222 Aerogel High-Performance Insulating Plaster prevents the growth of algae and hinders fungal attacks. [13] The procedure of application of AP on the surface as described in[14].

- First, AP is mixed with water at the time of application.
- Before one week of applying AP, an undercoat layer of 5mm thickness is applied on the surface where AP is to be applied. This must be done to increase or maintain the adhesion between AP and the existing surface.
- Apply the AP with the help of a spraying machine having a normally limited thickness of 60 to 80mm.
- The AP layer should be smoothed.
- The curing period is three weeks or can vary depending upon site conditions, climatic conditions, and AP layer thickness. Keep it safe from temperature stresses by keeping it moist to prevent risks of cracks.
- After AP's hardening, apply a layer of surface stabilizer.
- Then, a layer of reinforcement plaster is added to protect the AP from external mechanical stresses and impact.
- The external plastering system can be covered by various types of coatings and paints as per the required or desired external appearance.

5. Cementitious composition of aerogels

As from literature, aerogel cementitious composites are characterized as below,

- **Aerogel incorporated concrete**

[17] incorporated silica aerogel particles in a mortar or cement-based material resulted in AIC (aerogel incorporated concrete). In this experiment, conventional aggregate is replaced by silica aerogel particles. Here, concrete is prepared by adding 60% of silica aerogel particles, which resulted in thermal conductivity of ~0.26W/mk, and compressive strength of ~8.3MPa. These values varied corresponding to that of aerogel content.

The study performed in [16] on the development of HPAC (High-performance aerogel concrete), embedding 60% of Silica aerogel granules with a mixture of a few of the components i.e. concrete liquefier, micro silica, Portland cement, etc. concluded the appropriate and convenient mixture with compressive strength of 10MPa, the density of 860kg/m^3 and thermal conductivity of 0.17W/(mk).

In the experimental study [15] on Ultra High-performance aerogel incorporated concrete (UHPAC), it is observed that the compressive strength of concrete (in MPa) decreases as the percentage of silica aerogel content increases.

An increase in macro pores of cementitious composites caused a decrease in thermal conductivity. [15]

In [18], 15% of cement composites are replaced by aerogel particles, resulting in a reduction in the compressive strength of concrete by more than 42%. Observations showed low adhesion or bonding of aerogel particles with the cementitious contents around them.

- **Aerogel incorporated mortar or cement paste**

[19] showed thermal conductivity decreased by 75% by adding silica aerogel.

[21] prepared aerogel incorporated mortars by partially replacing OPC with calcined clay as a binding material and concluded the result of a decrease in thermal conductivities with mechanical strength maintained.

[20] made samples consisting of OPC (Ordinary Portland Cement), free water, and different volumes of silica aerogel and cured for 3,7, and 28 days and tested accordingly. The study found that the lowest thermal conductivity is achieved by a sample of 20ml of silica aerogel with 93.58% and the highest permeability of 25.60%. But, the highest compressive strength of 54.33MPa is achieved by a sample of 10ml of silica aerogel. The research concluded that an increase in silica aerogel contents can reduce thermal conductivity but the compressive strength too.

- **Lightweight aerogel composites**

[23] produced a composite by replacing sand in aerogel incorporated cement-based composites with Silica aerogel (synthesized from rice husk) by 25, 50, 75, and 100% volume, resulting in better performance of aerogel synthesized from rice husk.

The study by [24] showed improvement in properties i.e. heat generation stability and heat-dependent electrical characteristics and enhanced electrical properties of cementitious composites by incorporation of CNT (Carbon Nanotube) and silica aerogel.

When aerogel is used with PCRAs (Paraffin Coated Recycled Concrete Aggregates)[25], it improved the thermal conductivity but reduced the durability and mechanical characteristics of the mixture or composite.

[26] concluded the low thermal conductivity of silica aerogel-based render with a mass reduction of 14.52% after the freeze or thaw cycle and indicated its suitability of it for heat insulation by suggesting further research on the interaction of aerogel with surrounding aggregates and binder matrix.

[22] developed a composite made of FAC (fly ash cenosphere), silica aerogel as lightweight aggregates, and polyvinyl alcohol fibers to improve the mechanical properties of cementitious

composites. It resulted in the formation of mechanically strong and thermal insulated lightweight composites.

III. IMPLEMENTATION OF AEROGEL-BASED MATERIALS IN CIVIL ENGINEERING

1. Energy-efficient buildings

An energy-efficient building is a building that consumes a minimum amount of energy as compared to a conventional building. Using aerogel-based material can reduce energy consumption in building, in turn contributing to making the building more energy efficient. The feasibility of using aerogel blankets as insulators has been experimentally verified by the reduction in energy consumption of 23% and 38% observed when using single (10mm) and double (20mm) layers of aerogel respectively for a year. [27]

2. Facade system and super-insulating glazing

Buildings can be made more energy efficient by using aerogel material as a facade system and even more by using aerogel window glazing and panels as super-insulating glazing. It will prevent the convectional transfer of heat from the building envelope. These materials can also be used as a transparent insulating material, to maximize daylight without adjusting energy efficiency. [28, 29]

3. Sound insulation

Aerogel has high porosity. Pores present in aerogel absorb sound waves significantly and attenuate. "Sound velocity through a Silica aerogel can be as low as 100m/s, compared with 332m/s in the air at 0°C. Aerogel-based materials can be used for offices, theatres, etc. where sound insulation is necessary. It is also found that aerogel possessed sound absorbing properties." [9]

But later, review research [30] studied that silica aerogel and its composite products often have good acoustic properties. However, it does not necessarily outstand conventional materials and products. According to [30], the knowledge about physics of sound propagation through silica aerogel is not well understood yet, but from available data, it is observed that combining aerogel with other ingredients, components or building materials can affect its acoustic performance either negatively or positively [31]. Improvement of acoustic properties was observed [32, 33] for aerogel-filled double glazing systems but no increase in sound absorption is observed.

4. Treatment of wastewater

Wastewater treatment is a very important part of water supply and sanitary, irrigation, and environmental engineering. It is necessary to remove the contaminants, human or biological wastes, or other harmful impurities from the water before using or discharging it into natural water bodies i.e. rivers, lakes, oceans, etc. Wastewater treatment is a process of removing those impurities and returning that water to the water cycle. Sand, gravel, etc. are commonly used in this process to remove pollutants. Here, the high surface area of aerogel offers it high adsorption capacity; hence they are also applicable in the treatment of wastewater.

Carbon aerogel is a good adsorbent for the removal of antibiotics from water resources [35] and CA electrodes are suitable for chromium removal (depending on pH) [34].

5. Retrofitting and renovation of buildings

All studied types of aerogel materials are applicable for retrofitting operations. [36] accomplished a retrofitting project of an educational building located in Toronto, utilizing an aerogel-based system. After the study, it was figured out that the energy efficiency of that building increased up to 34%, by achieving high thermal resistance values.

It is also found that aerogel-based insulating materials are convenient for the renewal of historic architecture of industrial heritage in controlled situations.

6. Construction in high-density areas

Aerogel-based products i.e. plaster, coatings, renders, etc. are found to increase inhabitable space [8, 29]. Aerogel coatings show better performance in minimum layer thickness as a thermal insulator as compared to that conventional materials, consequently, reduction in wall thickness and large space can be saved and used where there is less space available for building construction.

IV. THE NECESSITY OF IMPLEMENTATION OF AEROGEL

1. Recyclable

- Aerogels can be used repeatedly for water treatment or water purification [2].
- Carbon aerogels can be easily recovered and regenerated by burning pressure recycling or squeezing [1].
- "Translucent aerogel concrete can be used to construct sidewalks and speed bumps that light up at night to improve safety and pedestrians and road traffic." [3]
- Aerogel blankets are fully recyclable and they have been rated as Silver in Cradle to Cradle SM certification from McDonough Braungart Design Chemistry (certification process examines a product's manufacturing and impact in order to know if the product's wastes are eliminated with a healthy and sustainable society) (Cabot Corporation 2011) [8].

2. Air purification [9]

- Aerogel is a highly porous material with a large surface area.
- That porous structure makes it better adsorbent. It can be used for wastewater treatment and as well as for air purification.
- Aerogel blankets, paints, and many other materials adsorb harmful contaminants and pollutants present in the air, with the help of pores.
- Then contaminants and pollutants held by pores can be destroyed by catalytic processes.

- According to [9], "Aerogel prepared nanocrystals of MgO, CaO, and Al_2O_3, with high surface area/ gram of up to 500m^2/g, have shown the remarkably high capacity to destructively adsorb VOCs (Volatile Organic Compounds) rather than physisorb them under the atmospheric pressure and temperature."
- It could also significantly improve human health by decreasing the rate of diseases corresponding to respiratory systems.

3. Greenhouse emission

- Ozone layer depleting potential (ODP) of material is the amount of ozone layer degradation caused by that material. Aerogel blankets have zero ODP and have a global warming potential (GWP) of less than 5 [8].
- Thus, increased use of aerogel could lead to an overall decrease in greenhouse emissions and could affect the crucial problem of global warming and further climate change.

V. CHALLENGES

Recent studies show economically affordable aerogel-based materials and construction works assisted with them [35], [40], [39]. It depends on the process, the quantity of aerogel and composites used, etc. for the manufacturing of these materials. For example, [37] found silica aerogel paint cheaper than conventional paint, and [39] developed a method that reduced the cost of silica aerogel production by 50%. But, the cost of the aerogel is currently extremely expensive. The aerogel market size is estimated to be USD 638 million in 2020 and is expected to reach USD 1,045 million by 2025 [38]. Demand for aerogel in various industries like construction, textile, transportation, etc. is increasing day by day. According to NASA, an increase in the production of aerogel could reduce its cost.

On other hand, its cementitious composites are weak in adhesion and could not develop bonding properly with most of the surrounding composites. Subsequently, reducing the compressive strength of concrete. It is necessary to test the nature of aerogel with many other composites, admixtures, etc., and its effect on the overall construction project. But, the cost of aerogel could obstruct the studies and research based on its derivative materials.

VI. CONCLUSION

- Aerogel-based materials are preferable for thermal insulation and energy-efficient buildings. (Except, in the case of some of its cementitious composites could lead to an increase in macro pores, and can cause an increase in thermal conductivity [46].)
- These materials give an environment-friendly, affordable, advanced, and more improved structure as compared to the structure made up of conventional building materials.
- Increasing the use of aerogel blankets could reduce the contribution of the construction sector to global warming.
- Adsorption properties of these materials can be used for air purification and water purification can improve human health.
- Aerogel-based cementitious composites require more improvement and research. Sound insulation properties of aerogel and its derivative materials need to be studied more.
- Though the initial cost of aerogel is high, the materials made up of it were found to be given economical construction works.

VII. REFERENCES

[1] Lei E, Wei Li, Chunhui Ma, Shouxin Liu, " An ultra-lightweight recyclable carbon aerogel from bleached softwood kraft pulp for efficient oil and organic absorption," Materials Chemistry and Physics, -, vol. 214, pp. 291-296, 2018.

[2] R. Ganesamoorthy, V. Vadivel, R. Kumar, O. S. Kushwaha, H. Mamane, " Aerogels for water treatment: A review," Journal of Cleaner Production, vol. 329, pp. 129713, 2021.

[3] S. Thenappa, P. Nguyen, N. Do, D. Le, Q. Thai, P. Le, N. Phan-Thien, H. Duong, " Advanced fabrication and multi-properties of aluminium hydroxide aerogels from aluminium wastes," Journal of Material Cycles and Waste Management -, vol. 23, pp. 885-894, 2021.

[4] Commercial Website: https://www.aerogelpaints.com/post/anticorrosion

[5] Commercial Website : https://www.aerogelpaints.com/post/fire-resistant

[6] Commercial Website : https://www.aerogelpaints.com/post/insulation

[7] Commercial Website : https://www.aerogelpaints.com/post/mold-proof

[8] Olaya Pérez, "The behavior of aerogel blankets as insulation material in external walls at high temperatures", Semantic Scholar, 2011. https://www.semanticscholar.org/paper/The-behavior-of-aerogel-blankets-as-insulation-in-P%C3%A9rez/35f1c7abd7907c511a64a270cf68d3e555557e7a

[9] S. Riffat, G. Qiu, "A review of state-of-the-art aerogel applications in buildings," International Journal of Low-Carbon Technologies, vol. 8, pp. 1–6, March 2013.

[10] The American Ceramic Society, "Aerobricks combine aerogel with brick to form energy-saving, super insulating building material", 2018. https://ceramics.org/ceramic-tech-today/aerobricks-combine-aerogel-with-brick-to-form-energy-saving-super-insulating-building-material

[11] J. Wernery, A. Ben-Ishai, B. Binder, S. Brunner, " Aerobrick — An aerogel-filled insulating brick", Energy Procedia vol. 134, pp. 490-498, 2017.

[12] Commercial Website : https://www.cabotcorp.com/solutions/products-plus/aerogel/blanket
[13] Commercial Website : https://www.fixit-aerogel.com/en/application
[14] Ali Naman Karim, "Aerogel-based plasters for renovation of buildings in Sweden Identification of possibilities, informationi deficiencies and challenges", 2021. https://research.chalmers.se/publication/522409/file/522409_Fulltext.pdf
[15] S. Ng, B. Jelle, L. Ingunn, C. Sandberg, T. Gao, Ó. Wallevik, "Experimental investigations of aerogel-incorporated ultra-high performance concrete", Construction and Building Materials, Volume 77, 2015, Pages 307-316, 2015.
[16] S. Fickler, B. Milow, L. Ratke, M. Schnellenbach-Held, T. Welsch, " Development of High Performance Aerogel Concrete ", Energy Procedia, Vol. 78, pp. 406-411, 2015.
[17] T. Gao, B. Jelle, A. Gustavsen, S. Jacobsen, " Aerogel-incorporated concrete: An experimental study", Construction and Building Materials, Vol. 52, pp. 130-136, 2014.
[18] S. Adhikary, Ž. Rudžionis, D. Vaičiukynienė, " Development of flowable ultra-lightweight concrete using expanded glass aggregate, silica aerogel, and prefabricated plastic bubbles", Journal of Building Engineering, Vol. 3, pp. 101399, 2020.
[19] S. Kim, J. Seo, J. Cha, S. Kim, " Chemical retreating for gel-typed aerogel and insulation performance of cement containing aerogel", Construction and Building Materials, Vol. 40, pp. 501-505, 2013.
[20] Khamidi, Dr. Faris & Glover, C. & Farhan, S. Ahmad & Husna, Nadzhratul & Nuruddin, " Effect of silica aerogel on the thermal conductivity of cement paste for the construction of concrete buildings in sustainable cities ", WIT Transactions on the Built Environment, Vol. 137, pp. 665-674, 2014.
[21] S. Ng, B. Jelle, T. Stæhli, " Calcined clays as binder for thermal insulating and structural aerogel incorporated mortar ", Cement and Concrete Composites, Vol. 72, pp. 213-221, 2016.
[22] A. Hanif, S. Diao, Z. Lu, T. Fan, Z. Li, " Green lightweight cementitious composite incorporating aerogels and fly ash cenospheres", Mechanical and thermal insulating properties, Construction and Building Materials, Vol. 116, pp. 422-430, 2016.
[23] N. Abbas, H. Khalid, G. Ban, H. Kim, H. Lee, " Silica aerogel derived from rice husk: an aggregate replacer for lightweight and thermally insulating cement-based composites", Construction and Building Materials, Vol. 195, pp. 312-322, 2019.
[24] D. Jang, H. Yoon, J. Seo, H. Lee, G. Kim, " Effects of silica aerogel inclusion on the stability of heat generation and heat-dependent electrical characteristics of cementitious composites with CNT", Cement and Concrete Composites, Vol. 115, pp. 103861, 2021.
[25] J. Rostami, O. Khandel, R. Sedighardekani, A. Sahneh, S. Ghahari, " Enhanced workability, durability, and thermal properties of cement-based composites with aerogel and paraffin coated recycled aggregates", Journal of Cleaner Production, Vol. 297, pp. 126518, 2021.
[26] A. Morgado, A. Soares, I. Flores-Colen, M. Veiga, and M. Gomes, "Durability of Thermal Renders with Lightweight and Thermal Insulating Aggregates: Regranulated Expanded Cork, Silica Aerogel and Expanded Polystyrene", Gels, Vol. 7, pp. 35, 2021.
[27] M. Elshazli, M. Mudaqiq, T. Xing, A. Ibrahim, B. Johnson & J. Yuan, "Experimental study of using Aerogel insulation for residential buildings", Advances in Building Energy Research, Vol. 16, pp. 569-588, 2022.
[28] G. Kim, S. Hyun, "Synthesis of window glazing coated with silica aerogel films via ambient drying", Journal of Non-Crystalline Solids, Vol. 320, Pages 125-132, 2003,
[29] M. Koebel, A. Rigacci, P. Achard, "Aerogel-based thermal superinsulation: An Overview", Journal of Sol-Gel Science and Technology, Springer Verlag, Vol. 63, pp. 315-339, 2012.
[30] Z. Mazrouei-Sebdani, H. Begum, S. Schoenwald, K. Horoshenkov, W. Malfait, "A review on silica aerogel-based materials for acoustic applications", Journal of Non-Crystalline Solids, Vol. 562, pp. 120770, 2021.
[31] I. Preikšs, J. Skujāns, U. Iljins Possibilities of silica aerogel application for foam gypsum compositions 3rd International Scientific Conference. Proceedings (Latvia). Latvia University of Agriculture (2011)
[32] P.P. Narang, "A theoretical study of sound transmission through aerogel glazing systems", Applied Acoustics, Vol. 34, pp. 249-259, 1991.
[33] C. Buratti, E. Moretti, "Experimental performance evaluation of aerogel glazing systems", Applied Energy, Vol. 97, pp. 430-437, 2012.
[34] P. Rana, N. Mohan, C. Rajagopal, "Electrochemical removal of chromium from wastewater by using carbon aerogel electrodes", Water Research, Volume 38, pp. 2811-2820, 2004.
[35] G. Aylaz, M. Okan, M. Duman, H. Aydin, "Study on Cost-Efficient Carbon Aerogel to Remove Antibiotics from Water Resources", ACS Omega, vol. 5, pp. 16635-16644, 2020.
[36] U. Berardi, "Aerogel-enhanced systems for building energy retrofits: Insights from a case study", Energy and Buildings, Volume 159, Pages 370-381, 2018.
[37] Ratanachotinun, J., & Pairojn, P. , "The Study of Paint with Silica Aerogel for Thermal Insulation", EAU Heritage Journal Science and Technology , vol. 14 (1), pp. 85–97, 2020.

[38] Aerogel Market by Type (Silica, Polymer, and Carbon), Form (Blanket, Panel, Particle, and Monolith), Processing (Virgin, Composites, and Additives), Application (Oil & Gas, Construction, Transportation, and Performance Coating) - Global Forecast to 2025.

[39] Xiaodong Li, Yanru Lu, Xi Jiang Yin et al. Development of Water-Based Thermal Insulation Paints Using Silica Aerogel Made From Incineration Ash, 20 July 2021, PREPRINT (Version 1) available at Research Square https://doi.org/10.21203/rs.3.rs-656147/v1

[40] Utilization of aerogel in building construction -A Review Utilization of aerogel in building construction - A Review November 2020IOP Conference Series Materials Science and Engineering 955(1), DOI:10.1088/1757-899X/955/1/012032

[41] Wikipedia contributors. (2022, August 20). Aerogel. In Wikipedia, The Free Encyclopedia. Retrieved 10:55, August 25, 2022, from https://en.wikipedia.org/w/index.php?title=Aerogel&oldid=1105576036

[42] T. Woods, SGT Inc. NASA's Glenn Research Center, "Aerogels: Thinner, Lighter, Stronger", Aug 2017. https://www.nasa.gov/topics/technology/features/aerogels.html

[43] N. Vatin, S. Sultanov, A. Krupina, "Comparison of Thermal Insulation Characteristics of PIR, Mineral Wool, Carbon Fiber, and Aerogel", International Scientific Conference Energy Management of Municipal Facilities and Sustainable Energy Technologies EMMFT 2018. EMMFT-2018, Springer, vol 983, pp. 877-883, 2019.

[44] United Nations Environment Programme (2020). 2020 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi https://globalabc.org/sites/default/files/inline-files/2020%20Buildings%20GSR_FULL%20REPORT.pdf

[45] Global Alliance for Buildings and Construction, International Energy Agency and the United Nations Environment Programme (2019): 2019 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector. https://www.unep.org/resources/publication/2019-global-status-report-buildings-and-construction-sector

[46] Ślosarczyk A, Vashchuk A, Klapiszewski Ł. Research "Development in Silica Aerogel Incorporated Cementitious Composites-A Review", Polymers, vol. 14, pp. 1456, 2022.

[47] Scientists are exploring how aerogel, a translucent, Styrofoam-like material, could be used as a building material on Mars. Aerogel retains heat; structures built with it could raise temperatures enough to melt water ice on the Martian surface. CREDIT, NASA/JPL-Caltech, https://www.nasa.gov/sites/default/files/thumbnails/image/pia23343-1041.jpg