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Article

Mechanical and Thermal Properties of an Energy-Efficient Cement Composite Incorporating Silica Aerogel

Tatiana Aleksandrovna Koriakovtseva [1,*], Anna Evgenyevna Dontsova [1] and Darya Viktorovna Nemova [2]

[1] School of Hydrotechnical and Power Engineering, Institute of Civil Engineering, Peter the Great St. Petersburg Polytechnic University, 195251 Saint Petersburg, Russia; dontsova_ae@spbstu.ru
[2] Laboratory of Protected and Modular Structures, Peter the Great St. Petersburg Polytechnic University, 195251 Saint Petersburg, Russia; nemova_dv@spbstu.ru
* Correspondence: musorina_t@spbstu.ru

Abstract: The thermal performance of the building envelope is significant in energy-efficient construction. Because concrete is widely used in civil engineering, options to reduce its R-value should be considered. This study explores the thermal and structural properties of aerogel-enhanced concrete. Silica aerogel powder was mixed with fine-grained concrete at 15 vol.%. Two series of samples were prepared to identify the preferred technology. The first series of samples were mixed without isopropyl alcohol; for the second series, the alcohol was mixed with silica aerogel before mixing into the dry mix. The thermal conductivity, compressive strength, and bending resistance of the specimens were measured. The presence of silica aerogel admix resulted in a decrease in the compressive strength of the specimens by 30% compared with that of the reference samples and a reduction in the bending strength of the samples by 9% compared with that of the reference samples. For the first and second series of samples, the K-values of the aerogel-enhanced specimens varied in the range from 0.83 W/(m·K) to 1.13 W/(m·K), respectively. To further decrease the thermal conductivity, gypsum putty was then added to the specimens, resulting in the K-values further decreasing to 0.64 W/(m·K) and 0.84 W/(m·K), respectively. The calculation of heat losses through 1 m^2 of the aerogel-enhanced concrete wall was performed. It has been shown that energy expenses for heating can be lowered by 30%. The calculation of the greenhouse gas emissions from the combustion of fuel required for heating was also considered. The emissions decreased by 30.2% compared with the reference sample. Microscopic examination of the face and section surfaces of the sample revealed a significant number of pores compared with conventional fine-grain concrete.

Keywords: concrete; aerogel; experimental study; compressive strength; three-point bending test; thermal conductivity

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1. Introduction

Energy efficiency improvement is an important challenge in civil engineering. Heating systems consume the largest share of energy. It is necessary to use powerful heating equipment to maintain comfortable indoor climate parameters in colder regions. The main energy expense item is heat loss through the enclosing structures. Thus, the thermal insulation requirements are being toughened. Manufacturers are encouraged to improve insulating materials, which can be used in energy-efficient construction projects.

The multilayer wall structure allows for the improvement of heat resistance. However, minimizing the energy consumption of the building while providing a comfortable indoor climate remains a challenge. Energy-saving technologies, materials, and measures should not only lead to a reduction in energy consumption but also be cost-effective. Unfortunately, investment performance in energy-saving measures is rarely considered [1,2]. Nowadays, there is a growing interest and demand for energy savings, reducing the load on material resources, and reducing pollution. The important condition for solving these complex problems is the development of new building materials with high strength and durability that are safe for human health and the natural environment [3]. The central task of energy-efficient design is to reduce heating costs while maintaining the conditions for human comfort [4]. Although new energy-efficient materials and innovative technologies are constantly emerging in the construction industry, the search for even more promising solutions does not end. New ideas must first meet requirements such as practical significance, operability, economic rationality, and environmental and social safety.

An option to comply with the heat resistance requirements in civil engineering is to decrease the thermal conductivity of the most popular building materials. The use of additives to create heat-insulating concrete is considered. Traditionally, the thermal performance of concrete is improved with a lower density or higher porosity of the composite. For this purpose, plant-based or synthesized aggregates are used. Sometimes, processed raw materials can also serve this purpose. The resulting concrete composite is durable and strong, even though it is more porous.

One of the most promising and revolutionary insulating materials is a nanostructured aerogel based on silicon dioxide, which was first created by scientists in 1931. The first to obtain aerogels in Russia were the staff of the Federal Research Center Boreskov Institute of Catalysis (Novosibirsk, Russia) and the Joint Institute for Nuclear Research (Dubna, Russia) [5–7]. In this study, silica aerogel powder was used as an aggregate to reduce the thermal conductivity of concrete. Cement-based aerogel mixes were first presented in 2008 [8] as heat-resistant concrete. The properties of the novel composite have shown its potential in engineering [9–15]. The 'high-performance aerogel concrete' made of sand, concrete, and 70% silica aerogel granulate was presented. The material had an admirable mechanical strength and a K-value of 0.1 W/(m·K). A mix for lightweight concrete was described in [16]. The main challenge was to walk a line between the contradictory properties: low K-value, on the one hand, and workability for the concrete mix and the high strength of the resulting composite, on the other hand.

A side effect of the subcritical production process of aerogel is the complete hydrophobicity of the material. Thus, aerogels cannot absorb water despite their open pores. Hence, solvents (most often alcohols) are used to ensure the homogeneity of the mixture. These reactions are usually performed with ethanol or methanol [17]. Therefore, it is necessary to change the water–cement ratio [18,19].

A scanning electron microscopy investigation of cement hydration revealed that aerogel particles are stable during the process [20], indicating the potential of aerogel admix for cementitious materials. The weaknesses of mixing silica aerogel into a high-strength cement matrix are given in [21]. These include the lack of adhesion at the boundary of the aerogel–cement binder, increased porosity of the composite, high water absorption capacity, and a significant decrease in compressive strength with large volumes of silica aerogel. Moreover, the gaps between the aerogel particles and the cement matrix can serve as capillaries for airflow. The gaps between the aerogel particles and the cement binder appear due to the hydrophobicity of the aerogel. The presence of the capillaries, as well as the fragility of the silica aerogel itself and the increased porosity of the cement matrix, determine the mechanical properties of the composite. Table 1 presents a review of the amount of aerogel mixed into cementitious composites [22].

The review data shows that the presence of granulated silica aerogel in a concrete mix results in a dramatic reduction in the compressive strength of the composite.

Another modification of concrete using aerogel was created in [23]. At first, silica sand was gradually replaced with aerogel. When all the sand was replaced with aerogel, the amount of the cement matrix used was proportionally reduced with increasing aerogel content, thus maintaining a constant cement matrix. The results showed a decrease in the compressive and flexural strength of the composite, as shown in Figure 1.

Table 1. A review of the amount of aerogel used for cementitious composites [22].

Type of Cementitious Composite	Scientific Name of Cementitious Composites with Silica Aerogel	Silica Aerogel Volume (%)
Concretes	Ultra-high-performance aerogel concrete	20–80
	High-performance aerogel concrete	45–70
	Aerogel-incorporated concrete	10–60
	Ultra-lightweight concrete	15–60
Mortars	Silica aerogel-incorporated mortar	20–80
Lightweight composites	Green lightweight composite	1–5
	Lightweight cement-based composite	15–100
	Ultra-lightweight cement composite	-
	Silica aerogel-incorporated concrete	2–8
	Thermal renders with silica aerogel	0–20

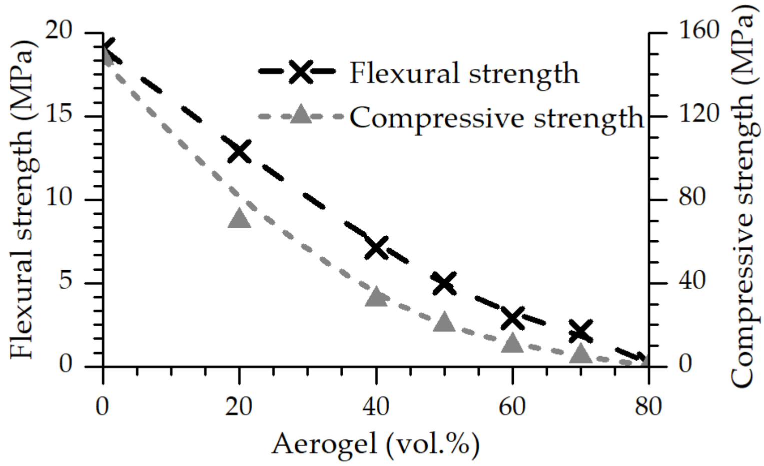


Figure 1. Mechanical properties of concrete depending on the silica aerogel content in the composite. Adapted with permission from Ref. [23]; published by Elsevier, 2015.

The effect of small amounts of aerogel and silica fume was studied in [24]. The samples were exposed to the curing process in water, the wetting–drying effect, and the $MgSO_4$ effect. Silica fume admix enhanced the compressive strength of samples cured with the wetting–drying and $MgSO_4$ effects and decreased the compressive strength of samples cured in water. For different curing conditions, the largest reduction in thermal conductivity of 31.2% was obtained for the water-cured sample containing 0.25% aerogel additive and 10% silica fume. Based on the data collected, it can be concluded that silica fume is not a suitable additive for enhancing insulation properties.

Recent scientific and technological advances allow researchers to assume that the mass application of aerogel as a thermal insulating material in civil engineering will soon be possible. Therefore, it is necessary to investigate the possibilities and prospects of using aerogel as a heat-insulating material in different engineering fields. Thus far, research on the properties of cementitious composites with an aerogel admix has been limited. Attempts have already been made to construct a correlation between the amount of aerogel and the final mechanical and thermal properties of the composite [25–28]; however, there is still insufficient data for a complete review evaluating the feasibility and possibilities of using silica aerogel as a heat-protective additive for dry concrete mixtures.

This study aimed to create a cementitious material that can perform both thermal insulation and bear loads. Two series of composite concrete samples and reference samples were manufactured, and their properties were examined to achieve this goal. The technology for adding the aerogel powder to the mixture was different. In one case, aerogel powder was poured into the dry mix. In the other case, the aerogel was first mixed with isopropyl alcohol and then poured into the dry mix. The thermal conductivity, compressive strength, and bending resistance of the specimens were measured. The surfaces of the samples were examined under a microscope to evaluate the microstructure of the composite. The calculation of heat losses through 1 m^2 of the aerogel-enhanced concrete wall was performed. The calculation of the greenhouse gas emissions from the combustion of fuel required for heating was also considered.

2. Materials and Methods

Figure 2 presents the experimental research program in general.

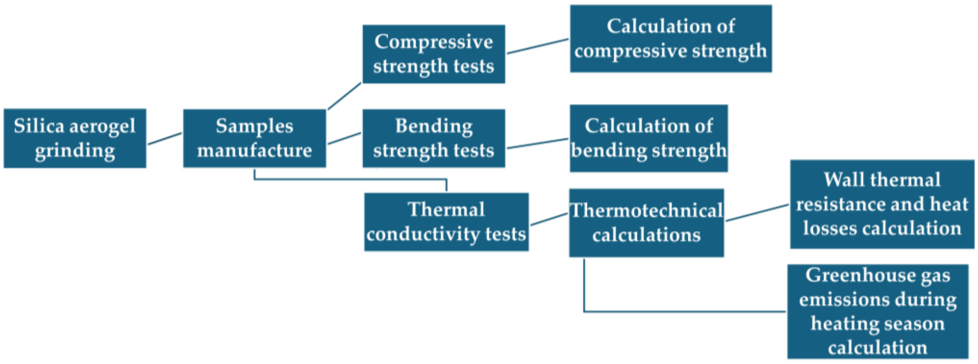


Figure 2. Flowchart for studying the properties of a cementitious composite containing 15 vol.% silica aerogel admix.

2.1. Grinder Choice and Silica Aerogel Admix Grinding

The general advantages of aerogel materials are as follows: environmental safety, fire resistance [29], incombustibility [30], low density (40–150 kg/m^3), hydrophobicity, high reflectivity, extremely low thermal conductivity (0.016 W/(m·K) at 10 °C), ease of installation, durable sheets, wide range of operation temperature [31], and long life [32,33]. However, the material is expensive because of its complex fabrication technique. Silica aerogel is widely used for thermal insulation [29–31]. In this study, silica aerogel granules (manufactured by Guangdong Alison Hi-Tech Co., Ltd., Yingde, China) were crushed to powder. The basic properties of the aerogel granules were provided by the manufacturer as follows: bulk density 40–150 kg/m^3; particle size > 0.5 mm; surface area 500–650 m^2/g; porosity > 90%; pore diameter 20–100 µm. The size of the graded particles was comparable to the concrete powder fraction size, which equals 40 µm or less. The size of the silica aerogel powder was determined using a sieve analyzer. The grinder was set with the minimum possible grinding gap. A JC 6 jaw crusher (Vibrotechnik, LLC, Saint-Petersburg, Russia) was used for grinding. The measured bulk density of the power was 110 kg/m^3. Figure 3 shows the initial and final conditions of the silica aerogel.

(**a**) (**b**)

Figure 3. The initial and final condition of silica aerogel: (**a**) granules before grinding; (**b**) grinded powder.

2.2. Concrete Mix Proportion

The composition of the fine-grain concrete mix for 1 L of the mix is presented in Table 2. Grinded aerogel was added to the mix in an amount of 15% by volume.

Table 2. Composition of the fine-grained concrete mix for the reference samples for 1 L.

Portland Cement M400 [g]	Silica Sand [g]	Plasticizer [g]	Water [mL]	Total Volume [L]
687	1253	7	253	1

The properties of the silica sand used for the concrete mix were provided by the manufacturer (REMIX manufacturer LLC, Saint-Petersburg, Russia) as follows: particle size 0–0.63 mm; clay bond amount < 5%; silica amount > 82%. The sand is claimed to be dedusted and thermally treated at 700 °C. The sand complied with Russian state standard GOST 8736-2014 [34] specifications for sand for use in construction works.

The first series of samples that were manufactured and tested are presented in Table 3. In this series, silica aerogel powder was mixed with a dry mix. Then, water was added to the mix. All samples in this study were cured in a humid environment for 28 days after manufacturing [35].

Table 3. The first series of samples, where aerogel was added directly to the concrete mix.

Sample No.	Amount of Mix Used [L]	Amount of Silica Aerogel [%]	Amount of Silica Aerogel [g]
K1–K4	4	0 (reference samples)	0
A1–A3	3	15	66

During the study, it was found that the technology for adding aerogel to the admix should be modified. The causes of technology modification are mentioned in the literature review [17]. In the second series of samples, the aerogel was first mixed with isopropyl alcohol and then added to the dry concrete mix. Information about the samples from the second series is presented in Table 4.

Table 4. The second series of samples, where aerogel was mixed with isopropyl alcohol and then added to the concrete mix.

Sample No.	Amount of Mix Used [L]	Amount of Silica Aerogel [%]	Amount of Silica Aerogel [g]
K2.1–K2.3	3	0 (reference samples)	0
A2.1–A2.3	3	15	66

2.3. Gypsum Putty

The properties of the gypsum putty used in the study were provided by the manufacturer (VOLMA conglomerate, Volgograd, Russia) as follows: drying time (at 20 °C) 24 h; adhesion strength $\geq$ 0.4 MPa; working life: 2 h. The putty complied with Russian standard GOST R 58278-2018 [36]. The mix proportions were chosen in accordance with the manufacturers' recommendations as follows: 0.5 L of water per 1 kg of putty.

2.4. Compressive Strength Tests

The samples for compressive strength tests were manufactured in metal forms. The forms were lubricated with mineral oil, and the concrete mix was poured into the forms. Cubes with side dimensions of 100 mm were made. Figure 4 shows the samples in the wet environment after manufacture.

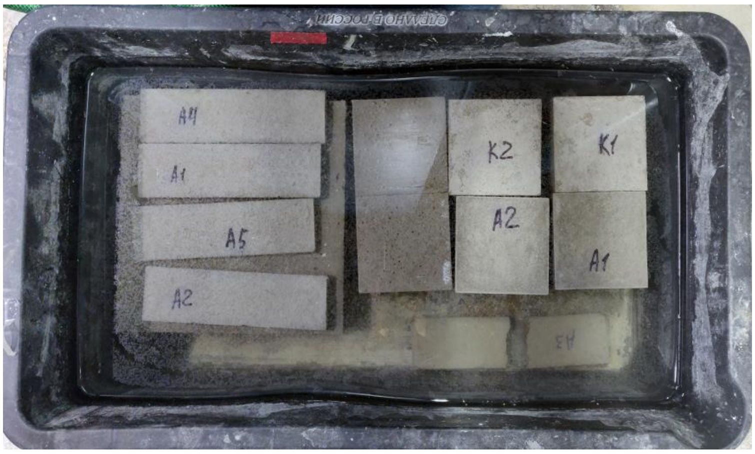


Figure 4. Curing of manufactured samples in water.

After 28 days of curing in a wet environment, the samples were dried. Every sample was measured and weighed before the tests to quantify the average density of the sample. Compressive strength tests were carried out using a hydraulic press. Figure 5 shows the general view of the machine.

Figure 5. Compressive strength testing.

The analog scale of the press spans 50 tons of load and has 300 divisions. The initial result of the test is the number of divisions on the scale. This number was then converted into MPa to obtain the compression strength of the sample and the average compression strength of the series.

2.5. Three-Point Bending Tests

Three-point bending tests were performed in the Institute of Civil Engineering of Peter the Great St. Petersburg Polytechnic University. An Instron 5965 system (Instron, Norwood, MA, USA) was used. The dual-column model can perform tensile, compression, flexure/bend, peel, tear, shear, and cyclic tests [37]. The operations were controlled from a computer using software that allows automatic measurements and the recording of the measurement results in a graphical form. The beam samples were manufactured for the bending test. A 20 cm-long specimen was placed on two supports. The span between the supports was 15 cm. The moving part of the universal testing machine was placed in the center of the span. The loading of the element continued until the element lost stability, i.e., until the formation of a destructive crack. The stress was calculated as follows:

$$\sigma = (3^* \times F \times l)/(2 \times b \times h^2), \tag{1}$$

where F is the breaking force; l is the length of the span; b is the width of the beam; and h is the height of the beam. Figure 6 shows the general view of the test.

Figure 6. Three-point bending test: the sample in the machine.

2.6. Thermal Conductivity Measurements

The thermal conductivity of the samples was evaluated using a PIT-2.1 thermal conductivity meter (Iztech, Kazan, Russia). The machine creates a stationary heat flow through a flat sample. The heat flow is perpendicular to the front faces of the sample. The power required to create the heat flow and the temperature of the faces was measured. The machine contains refrigerators that are designed to ensure the operation of PIT-2.1 at average sample temperatures below the ambient temperature. The refrigerators are made using Peltier elements [38]. The machine is able to plot the measured parameters during the experiment. The size of the samples was 250 × 250 × 30 mm. The ambient temperature was 21 °C. Figure 7 presents the general view of the machine.

Figure 7. PIT-2.1 thermal conductivity meter.

3. Results

3.1. Compressive Strength Tests

Table 5 presents the calculation of the compression strength of the samples. The results were compared to State Standard (GOST) 26633-2015 [39] to grade the concrete.

Table 5. Compressive strength of manufactured concrete samples.

Sample No.	Weight [kg]	Volume [cm^3]	Average Density [kg/m^3]	Number of Divisions	Load [t]	Compressive Strength [MPa]	Average Compressive Strength [MPa]	Concrete Grade
K1	2.003	1001.6	1983.28	116	19.33	18.93	19.37	B15 (M200)
K2	2.010	1006.7		117	19.50	19.12		
K3	1.994	1004.4		123	20.50	20.10		
K4	2.007	1027.9		118	19.67	19.32		
A1	1.899	1036.4	1861.09	76	12.67	12.42	12.09	B10 (M150)
A2	1.892	1018.3		71	11.83	11.60		
A3	1.923	1015.8		75	12.5	12.26		
K2.1	1.913	970.1	1973.35	128	21.33	20.92	21.08	B15 (M200)
K2.2	1.943	995		128	21.333	20.92		
K2.3	1.951	977.9		131	21.833	21.41		
A2.1	1.907	985.5	1931.64	88	14.67	14.38	14.44	B10 (M150)
A2.2	1.927	996.5		91	15.17	14.87		
A2.3	1.915	994.3		86	14.33	14.05		
A2.4	1.907	985.5		88	14.67	14.38		

Changing the aerogel mixing technology increased the average compressive strength of the samples by 19%. However, the overall reduction in compressive strength relative to the reference samples is 31.5%. Figure 8 illustrates the results of the compression strength tests in graphical form.

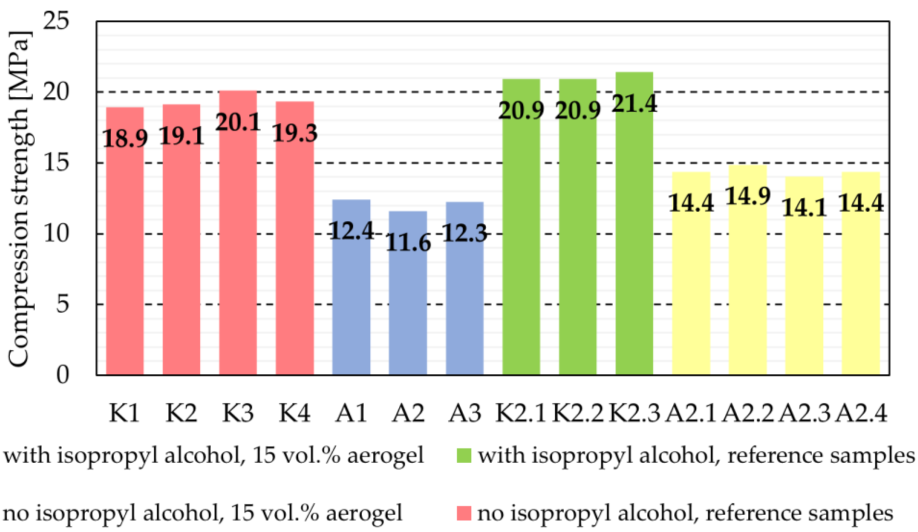


Figure 8. Compression strength of the specimens.

3.2. Three-Point Bending Tests

Bending tests were performed with the second series of samples. The results of the three-point bending tests are presented in Table 6.

Table 6. Bending strength of manufactured concrete samples.

Sample No.	Span [m]	Height of the Sample [m]	Width of the Sample [m]	Breaking Force [N]	Breaking Moment [N·m]	Bending Strength [MPa]	Average Bending Strength [MPa]
K2.1(b)	0.15	0.018	0.077	505.24	18.947	4.40	4.61
K2.2(b)		0.017	0.077	448.36	16.814	4.43	
K2.3(b)		0.020	0.077	681.68	25.563	5.01	
A2.1(b)	0.15	0.017	0.057	283.67	10.638	3.76	4.19
A2.2(b)		0.019	0.057	404.93	15.185	4.23	
A2.3(b)		0.016	0.057	259.2	9.720	3.10	
A2.4(b)		0.014	0.057	225.81	8.468	4.77	

The silica aerogel admix in an amount of 15% by volume decreased the bending strength of the samples by 9.19%. The results of the compression strength tests in graphical form are depicted in Figure 9.

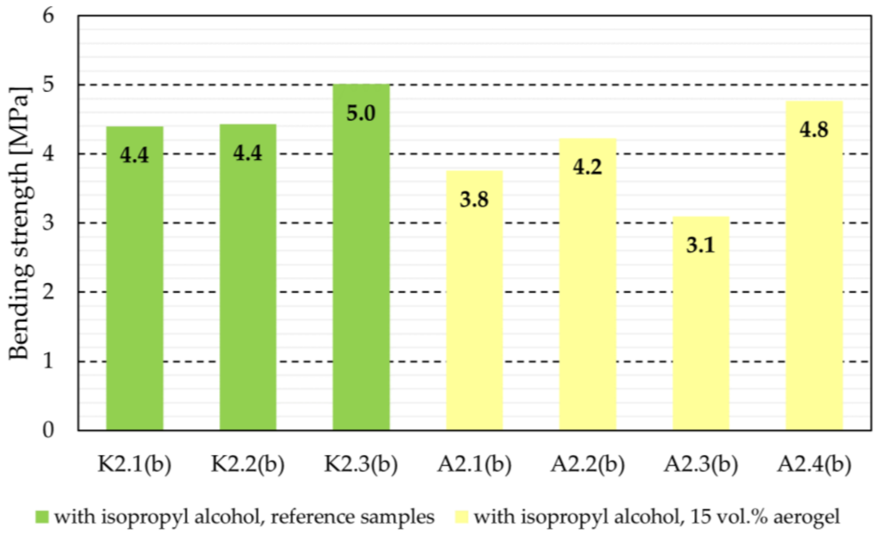


Figure 9. Bending strength of the specimens.

3.3. Thermal Conductivity Measurements

The thermal conductivity (K-values) of the aerogel-enhanced samples was measured twice. First, the bare sample was placed into the measuring machine. After the test, the faces of the samples were covered with a fine coat of gypsum putty. The samples were then dried, and the second set of measurements was performed. The second set of measurements was performed to evaluate the influence of the surface porosity on the measurements, as the aerogel admix increases the porosity of the material. The results of the measurements are presented in Table 7.

Table 7. Thermal conductivity of silica aerogel-enhanced concrete samples.

Sample no.	Weight [kg]	Average Density [kg/m^3]	Average K-Value of the Bare Sample [W/(m·K)]	Average K-Value of the Sample with Putty [W/(m·K)]
A1(K)	3709	1902	0.8295	0.642
A2(K)	3708.05	1921	1.1285	0.844

The thermal conductivity of the reference sample is 1.5 W/(m·K). The thermal conductivity of the puttied sample is lower by 45%, and the thermal conductivity of the untreated sample is lower by 25%. The decrease in the thermal conductivity of silica aerogel-enhanced samples compared to the reference sample thermal conductivity is illustrated in Figure 10.

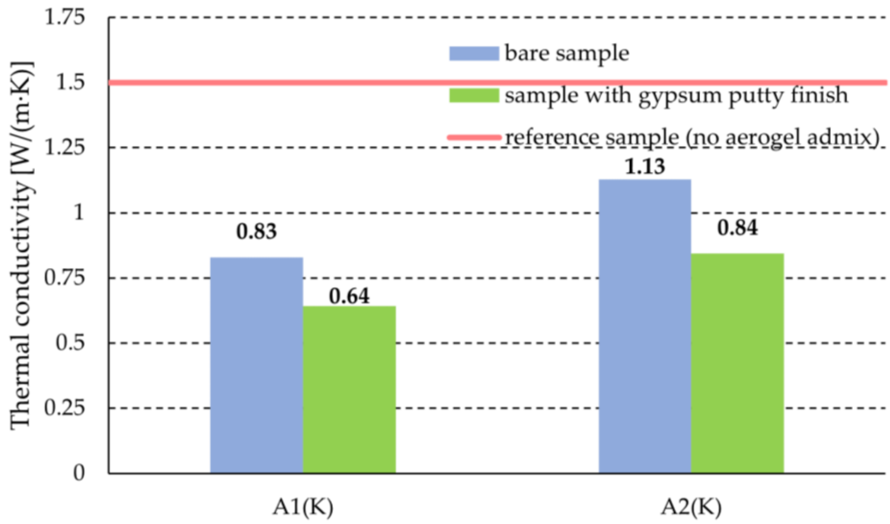


Figure 10. Thermal conductivity of aerogel-enhanced concrete samples.

3.4. Thermotechnical Calculations for Silica Aerogel-Enhanced Concrete

Heat-insulating concrete is used to manufacture structural thermal insulation elements. The high insulating properties of the concrete are achieved because of the low density and high porosity of the concrete mix in accordance with Russian Standard GOST 25820-2021 [40]. The thermal resistance of a regular concrete wall with a width δ = 0.3 m, a density of 2400 kg/m^3, and a K-value λ = 1.5 W/(m·K) is calculated using the following equation:

$$R = 1/\alpha_{int} + \delta/\lambda + 1/\alpha_{ext} = 1/8.7 + 0.3/1.5 + 1/23 = 0.358\ (m^2 \cdot K)/W. \quad (2)$$

where α_{int} is the heat transfer coefficient of the internal surface of the enclosing structure, α_{int} = 8.7; α_{ext} is the heat transfer coefficient on the outer surface of the enclosing structure, α_{ext} = 23. To determine the amount of heat required, the heat loss through the enclosing structures should be evaluated. In this particular case, only the heat loss through the external walls of the building is considered. According to Table 3 of the Russian state set of the construction rules, SP 131.13330.2020, "SNiP 23-01-99* Building climatology", Ministry of Construction, Housing and Utilities of the Russian Federation: Moscow, Russia, 2020, the temperature of the coldest five-day period with a probability of 0.92 in St. Petersburg (Russia) and the Leningrad region (Russia) is 249 K (−24 °C), and the heating period in region T is 211 days. In accordance with clause 4 of Russian Standard GOST 30494-2011 [41], the minimum temperature in a room is 291 K (+18 °C), and the maximum relative humidity is 55%. The amount of heat loss Q through an area S of 1 m^2 of a building envelope with thermal resistance R and a temperature difference Δt of 44 K during the heating period T [h] is calculated using the following formula:

$$Q = (S \cdot \times \Delta t \times \cdot T)/R = (1 \times (20 - (-24) \times (211 \times 24)))/0.41 = 543.45\ kWh. \quad (3)$$

The thermal conductivity of the aerogel-enhanced concrete was assumed from the experiments to be 0.844 W/(m·K) (Table 7). Natural gas was chosen as the fuel because it is the most popular type of fuel used for heating in Russia. The parameters of natural gas, such as its calorific value, density, and the amount of emissions per kg of gas used, are considered in the calculation of greenhouse gas emissions. The calculation is presented in Table 8.

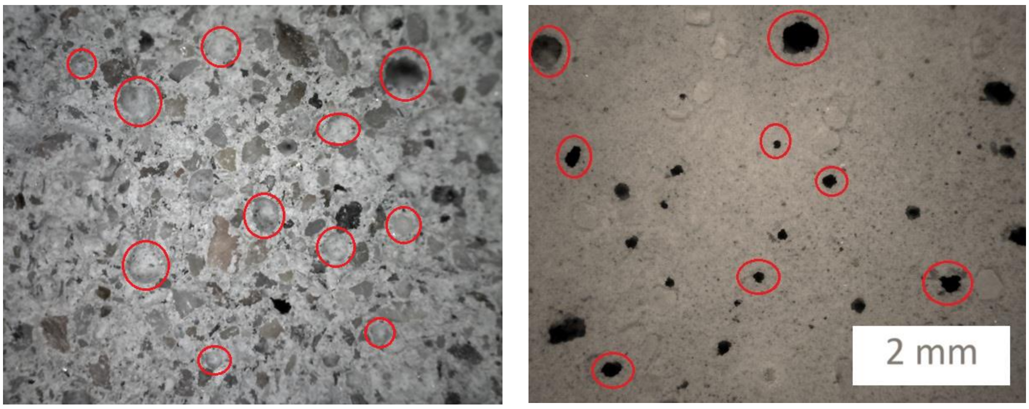
Table 8. Calculation of heat loss and greenhouse gas emissions.

Quantity Name	Value
K-value of the material [W/(m·K)]	0.844
R-value of the wall [(m^2·K)/W]	0.514
Façade area [m^2]	1
Temperature difference [K]	42
Heating season [h]	5064
Heat loss through external walls [W·h]	413,893.7
Heat loss through external walls [MJ]	1490
Calorific capacity of natural gas for 1 MJ/m^3	33.5
Natural gas consumption per year [m^3]	44.48
Natural gas density [kg/m^3]	0.68
Mass of consumed natural gas [kg]	30.25
Greenhouse gas emissions [kg CO_2e per 1 kg of consumed gas]	2.64
Total greenhouse gas emissions [kg CO_2e per year]	80
Heat loss through external walls [Gcal]	0.356

The calculations of heat loss through external walls and greenhouse gas emissions during the heating season show that the use of silica aerogel-enhanced concrete would reduce the consumption of natural gas by 30% compared to regular concrete.

3.5. Microscopical Analysis of the Samples

The microscopical analysis was performed using an electronic microscope, Dino-Lite, with a magnification range of 10× to 250×. The observations made with a magnification of 50× are shown in Figure 11. The pores on the section surface of the sample are shown in Figure 11a. The section surface was exposed after the breaking test. The pores on the face surface of the sample are shown in Figure 11b. The major pores are highlighted in red circles.



(**a**) (**b**)

Figure 11. Sample surfaces at 50× magnification: (**a**) section surface of the sample (after the bending test); (**b**) face surface of the sample. The major pores are highlighted in red circles.

Numerous pores were observed on the sample surfaces. The large number of pores decreases the thermal conductivity of the concrete. However, open pores observed on the surface of a concrete sample can negatively affect the properties of the material.

4. Discussion

The selection of the optimal aerogel-based concrete mix was presented in [42]. The amount of added silica aerogel varied from 50% to 75% by volume. The compressive strength of the samples varied between 3.0 and 23.6 MPa. The most interesting mix contained 60% aerogel granules by volume, and the thermal conductivity of the composite was 0.26 W/(m·K). The compressive strength of the samples was 8.3 MPa. The silica aerogel admix decreased the thermal conductivity of cement paste by 23.7%, 44.8%, and 68.75% as the amount of silica aerogel in the mix was increased from 0% to 20%, from 20% to 40%, and from 40% to 60% by volume, respectively [43]. The data obtained indicate that a large amount of silica aerogel in the mix leads to a decrease in thermal conductivity but has a negative effect on the compressive strength and permeable porosity of the cementitious composite.

Thus, it can be concluded that the nature, type, and quantity of the silica aerogel admix significantly influence the composite properties. A specific trend should be identified for silica aerogel-incorporating concrete composites. As mentioned, pre-treatment can enhance the adhesion between the hydrophobic aerogel and the cement matrix. Still, there are no detailed studies on such reaction mechanisms or the effect of pre-treated aerogel. The impact of pre-treatment on the mechanical and thermal properties of aerogel-based cementitious composites is also not yet clear. The stability of the aerogel particles in the cement matrix may be related to their hydrophobic properties. The particles repel the surrounding water and, therefore, prevent cement hydration [44].

The use of such enhanced concrete would reduce the thickness of the wall and lighten the weight of the structure, increasing cost efficiency and decreasing dead loads. Studying the stability of aerogel particles in concrete is also important because the alkaline environment can affect the aerogel through reactions similar to the well-known alkali-silica reaction. To achieve the indicated results, scientists varied the ratio of the components of the concrete mixture and the technological processes used to manufacture the composite samples.

The importance of passive design is highlighted in [45,46]. Efficient building envelopes, energy-efficient appliances, and renewable energy sources are required to reduce greenhouse gas emissions and the effects of global warming. It is necessary to evaluate the design and increase energy efficiency when choosing materials and additives for building envelopes [47–49]. Many innovations in high-performance construction materials have enabled the design and construction of sustainable and durable infrastructure. For instance, concrete is the most widely used building material in the world. Fibers are used worldwide to develop fiber-reinforced cementitious composites with high ductility to overcome the brittleness of concrete. In recent years, low-heat portland cement has been used to lower the cement hydration heat in an attempt to reduce the risk of thermal cracking. To improve the mechanical properties and microstructure of concrete, nanomaterials, such as silica fume, have been adopted [50]. In this study, a series of concrete composites with silica aerogel admix were manufactured and tested.

The compressive strength of the silica-aerogel-enhanced sample is 37.6% lower than that of the reference sample. Even with the modified technology for adding aerogel, the sample retains a relatively low compressive strength. The compressive strength of the second series of samples is 31.5% lower than that of the reference sample. Hence, silica aerogel admix significantly reduces the compressive strength of the concrete composite.

The bending strength of the silica aerogel-enhanced concrete samples was measured. The average bending strength of the composite was 4.19 MPa. These results are consistent with those presented in [20]. The authors of the abovementioned study used granulated aerogel. Because the results obtained are similar, it can be concluded that the fraction of the silica aerogel admix is not very relevant to the decrease in bending strength.

Aerogel has a low thermal conductivity of about 0.01–0.02 W/(m·K) [51,52]. It is apparent that the incorporation of aerogel particles into concrete will result in a thermally insulating composite since thermal conduction through the solid phase dominates the thermal conductivity of concrete materials [53]. However, the application of aerogel in thermally insulating concrete has not been widely studied, probably due to the high manufacturing cost of aerogel [54]. The grade of hydrophobicity turned out to have a major influence on the compressive and flexural strengths. It was found that the hardened concrete bulk density and the water-cement ratio were correlated with the compressive strength [55]. A high percentage of additive content in the concrete composite leads to an increase in porosity. Open pores form on the surface of the samples as well. The presence of the pores affects the thermal conductivity of the sample. The samples were covered with a fine coat of gypsum putty to close the surface pores. The thermal conductivity of the samples was measured before and after coating them with putty. The thermal conductivity of the reference sample was 1.5 W/(m·K). The thermal conductivity of the sample with putty was 50% lower than the reference value. The thermal conductivity of the sample without putty was 37.4% lower than that of the control sample.

The R-value of the wall made of silica aerogel-enhanced concrete was calculated in the study: R = 0.514 (m^2·K)/W. Annual heat loss through 1 m^2 of such a wall would equal 413.9 kWh. The use of concrete with aerogel admix reduced the weight of the structure and improved the thermal insulation properties. The heat transfer resistance of a silica aerogel-enhanced concrete wall is higher than that of conventional concrete, but it still does not meet the requirements of thermal protection. It is advisable to use this type of concrete in conjunction with a thin layer of insulation.

Further, silica-aerogel-enhanced concrete samples can be tested for weather resistance. Such composite material can be used as an outer layer of enclosing structures, especially during the reconstruction of historical buildings. The weather resistance of the silica aerogel-enhanced concrete was measured using a weatherometer. Based on the observed literature, standards for aerogel-enhanced concrete composites should be developed. In future research, it is planned to evaluate the life cycle of the concrete composite and its economic efficiency.

5. Conclusions

The novelty of this work is the creation of a fine-grain cementitious composite containing 15 vol.% silica aerogel admix. The mechanical and thermal properties of the composite were examined. The dry mix contained portland cement (M400) and silica sand (particle size 0–0.63 mm). Plasticizer was added to the concrete mix to improve the flow rate and rheology of the mix. The detailed properties of the concrete composite, the suggested manufacturing technology improvements, and the assessment of the use of the composite in the enclosing walls have practical significance for further research in aerogel-enhanced cementitious composites. The primary conclusions drawn from the results of the experiments and calculations are as follows:

- Samples of silica-aerogel-enhanced concrete were made. Two series of samples were manufactured. The technology was modified in the second series so that the mechanical properties of the composite were enhanced. For the second batch, the silica aerogel was first mixed with isopropyl alcohol and then added to the dry mix.
- The average compressive strength of the first series' samples was 12 MPa; of the second series' samples, 14 MPa; and for the reference samples, the average compressive strength was 20 MPa.
- The average bending strength of the first series' samples was 4.2 MPa, and the bending strength of the reference samples was 4.6 MPa.
- The average thermal conductivity (K-value) of the samples of the first series was 0.83 W/(m·K); of the samples of the second series, it was 1.13 W/(m·K). The samples were covered with a fine coat of gypsum putty. The average thermal conductivity of the coated samples was 0.64 for the first series and 0.84 for the second series.
- From the calculation of heat loss through external walls and greenhouse gas emissions during the heating season, it can be concluded that the use of silica aerogel-enhanced concrete for external walls would reduce the consumption of natural gas by 30% compared to regular concrete.
- The R-value of the wall made of silica aerogel-enhanced concrete was 0.514 (m^2·K)/W.
- The research can be expanded by manufacturing and testing more samples to specify the composite properties, develop the fabrication technique, and enhance the cost efficiency of the material.

This research will be expanded by investigating the relationship between the properties of the composite and the amount of silica aerogel added to the mixture. To reveal this correlation, a series of samples containing various amounts of silica aerogel will be manufactured and tested. The obtained experimental results will complement the existing data on this problem. Manufacturing plants can use the obtained results to produce aerogel-enhanced cementitious composites for the construction industry. The authors propose the use of such composites in the production of building panels for the construction of panel buildings.

The authors also plan to evaluate the deterioration of the properties of the silica-aerogel-enhanced composite as the material ages. For this purpose, the properties of the samples will be tested after accelerated material aging in a climatic chamber and a xenon weather aging chamber. An increase in the thermal conductivity of the composite during aging will result in an increase in heating expenses. Because not all manufacturers are willing to provide access to the environmental product declaration (EPD), calculations of greenhouse gas emissions have to be made based on available public data on the fuel burned.

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