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Performance evaluation of foamed materials based on cold-cured liquid glass

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ABSTRACT: Introduction. The current trend of transition to non-combustible and environmentally friendly thermal insulation and sound-absorbing materials involves development of research to obtain foamed silicate compositions, particularly those based on cold-cured liquid glass. The primary advantage of this material is its eco-friendliness throughout both its operational and production stages, facilitated by the employment of energy-efficient manufacturing technology. **Materials and methods.** Cold-cured liquid sodium glass and cullet-based foam glass were used as main raw materials. To determine optimal curing additive of liquid glass, Portland cement, slaked lime and sodium ethylsilicate were selected. The thermal conductivity of materials was evaluated with by means of appropriate coefficient, value of which depended on volume content of pores in material, nature of porosity and distribution of pores by size. The decrease in water absorption capacity was estimated by value of wetting edge angle. Sorption humidity was determined in accordance with GOST 24816-2014, and sound absorption coefficient was determined according to GOST 16297-80. **Results and discussion.** The prime objective of this study was to examine trends and provide explanations for the formation of specified performance indicators of thermal insulation and sound-absorbing materials, particularly those based on cold-cured foamed liquid glass. The issue of increasing water resistance of material by selecting effective additive-hardener was also investigated. **Conclusion.** The developed thermal insulation material based on cold-cured liquid glass is eco-friendly, with presence of large number of small and mainly open pores, giving it good sound-absorbing properties. The problem of high-water absorption of material was solved by introducing Portland cement as a curing additive.

KEYWORDS: non-combustible heat-insulating materials, silicate compositions, cold-cured foamed liquid glass, porosity parameters, thermal conductivity, water absorption, sorption moisture, sound absorption

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INTRODUCTION

Each passing year sees an increasing demand for non-combustible, environmentally friendly thermal insulation. This trend is accompanied by a steady drive towards reducing the thermal conductivity coefficient. The urgency of this problem is also confirmed by the introduction of the technical regulation of the Eurasian Economic Union "On the safety of building materials and products", which notes the need to comply with the criteria for fire safety of materials, including combustibility groups, flammability groups, smoke-generating ability groups, combustion products toxicity groups. Also, there is a need for rational use of natural resources.

Composite materials based on foamed silicate compounds are a group of materials that meet the requirements for modern thermal insulation. Such materials include foam glass, foam slag glass, glass pore, foam gypsum, as well as an innovative heat-insulating material based on cold-cured foamed liquid glass [1–7].

The design of any building material, possessing certain technical characteristics, is shaped by the intended use of the structure, and depends on several factors that influence its final performance attributes.

One of the primary advantages are the properties of raw materials – chemical composition, phase composition, structure parameters of raw materials.

The nature of the raw materials determines the chemical composition of the material, its chemical nature, reactivity to certain chemical interactions, as well as the features of the technological process of obtaining – physical and chemical effects on the raw materials (mechanical, temperature, temperature and humidity, electromagnetic effects, etc.).

At this stage, the formation of the phase composition of the material itself occurs due to the passage of the main chemical reactions occurring at the stage of mixing the components, exposure to high temperatures and electromagnetic radiation. The main part of structure formation occurs, which subsequently sets the parameters of the material structure: type of porosity, pore volume, pore size distribution, pore shape, etc.

Let us consider the influence of the above factors on the example of materials based on silicate compositions (more details on a heat-insulating material based on cold-cured foamed liquid glass) [8–12].

The material obtained after numerous impacts on raw materials has characteristics that were formed at the entire stage of the technological process of its production. The reasons for the appearance of certain characteristics of the material directly depend on the obtained parameters of the structure and composition.

Let us reveal in more detail the relationship between the obtained parameters of the material and its performance characteristics using the comparison of foamed silicate compositions as an example.

For the main performance indicators of a heat-insulating material based on foamed liquid glass, we take its thermal conductivity, water absorption, sorption activity and sound absorption.

MATERIALS AND METHODS

1. Formation of the thermal conductivity index of a material based on foamed liquid glass

As you know, the thermal conductivity of materials depends on several factors. They can be divided into the following groups:

– factors determined by the phase composition of the substance, the degree of crystallization and the size of the crystals, the characteristics of the porous structure, the anisotropy of the material and the direction of the heat flow;
– factors determined by the chemical composition and the presence of impurities;
– factors that make up the operating conditions of the material, depending on temperature, pressure and humidity.

In relatively small material pores, there is less gas convection and a reduced effect of the radiant energy of the heat transfer component.

Let us compare the thermal conductivity values of materials based on foamed silicate compositions similar in chemical composition, but having different structural parameters due to different production technologies and differing in the type of basic silicate raw material (cullet in the case of foam glass and liquid sodium glass in the case of a porous material based on cold-cured foamed liquid glass) (table 1).

At the same values of the average density, the materials have a different range of thermal conductivity due to different parameters of their structure (such as porosity and pore size distribution). So, at a density of 130 kg/m^3, foam glass has a thermal conductivity range of 0.043 ± 0.002 W/(m • K), and at a similar density, foamed liquid glass has different edge points of the thermal conductivity range due to the open type of porosity, but not to a large extent, due to due to the presence of a smaller pore size in the foam glass composition.

Convective heat transfer increases as the size of the pores and the air gaps connecting these pores grow. Therefore, a finely porous structure with the presence of a closed pore type is the most preferable for heat-insulating materials. Such a structure of the material slows down the convective heat transfer [13–15].

To reduce thermal conductivity, it is necessary to create an obstacle in the direction of heat transfer, for example, by creating a more finely porous material structure with a pore radius of not more than 1 mm.

The optimal structure of thermal insulation materials is obtained by creating a cellular structure with evenly distributed small pores, mostly closed. At the same time, a large number of micropores is not desirable, since due

Table 1
Thermal performance of porous silicate compositions

Material type	Porosity type	Average density, kg/m^3	Coefficient of thermal conductivity, W/(m • K)
Material based on cold-cured foamed liquid glass	Open Cellular	130–195	0.049–0.068
Foam glass	Closed cell	130–160	0.043–0.062

to their hygroscopicity, moisture sorption from the air is possible in them [16–22].

It should be noted that the open porosity of the heat-insulating material based on foamed liquid glass allows the material not to collapse when water freezes in an open cell, since the liquid can expand into neighboring pores.

The thermal conductivity of porous materials is affected not only by the size of the pores, but also by such parameters of their structure as the shape and location. Thus, the maximum volume of porosity with a dense cubic arrangement of spherical pores reaches 52.5%, and with a hexagonal arrangement it reaches 74%. Therefore, the goal is to obtain a structure with the most compact arrangement of pores, which is achieved with an optimal combination of large and small pores.

2. Formation of water absorption characteristics of material based on foamed liquid glass

Composite materials based on liquid glass have the ability to harden in air under normal conditions. At the same time, due to the evaporation of free water, the content of colloidal silica increases, which subsequently coagulates and compacts [23–27]. Sodium hydroxide in the composition of liquid glass prevents the precipitation of silicic acid, but carbon dioxide contained in the air neutralizes it, facilitating the transition of silicic acid into a colloidal solution. Such a scheme for curing liquid glass has a number of disadvantages. Among them are high water absorption due to the appearance of a surface film due to the action of carbon dioxide, as well as a low hardening rate [28–31].

The phase composition formed after physicochemical influences contains free cations of sodium liquid glass, which, without binding, form soluble compounds [32, 33].

Thus, it is necessary to select the optimal modifying additive that promotes accelerated and volumetric hardening of liquid glass.

A decrease in the water absorption of the material was considered by reducing the surface of its interaction with drip moisture due to hydrophilization. The comparison criterion was the wetting angle.

3. Formation of the characteristics of the sorption activity of a material based on foamed liquid glass

The sorption characteristics of the heat-insulating material based on foamed liquid glass were determined by experimental and computational-experimental methods. Experimental determination of sorption moisture was carried out according to GOST 24816-2014. In each desiccator with a relative humidity of 40, 60, 80, and 97%, containing an aqueous solution of sulfuric acid with a concentration of 47.13, 36.88, 25.23, 5.93, respectively, 3 bottles were placed.

As the material absorbs water vapor from the ambient air (sorption process), periodic weighing of the weighing bottles with samples was carried out.

The value of sorption moisture in percent was calculated using the following formula:

$$W_c = \frac{m_1 - m_2}{m_2 - m_3} \cdot 100, \qquad (1)$$

where m_1 is the weight of the bottle with the material sample after the end of the sorption process, g; m_2 is the weight of the bottle with the material sample after drying the sample to constant weight, g; m_3 – mass of bottle dried to constant weight, g.

Based on the obtained indicators of sorption activity, the specific surface area of the material was calculated based on the capacity of the monolayer. The calculation is based on the assumption that the sorption of water vapor by samples of foamed liquid glass proceeds exclusively by the mechanism of surface adsorption, that is, only a monolayer of adsorbed water is formed on their surface.

4. Formation of acoustic characteristics

The process of sound absorption can be represented in the form of two components – the surface layers of the acoustic material itself and sound waves in the form of a front of longitudinal vibrations with a certain kinetic energy, incident on this surface.

When a sound wave falls on a porous material in the air in the pores, an oscillatory process is initiated up to the coincidence of the oscillation frequency, that is, to the state of resonance. Due to the friction resistance and air viscosity, part of the sound energy is converted into heat, and due to the thermal conductivity of the pore walls, thermal energy is dissipated [34, 35].

The creation of effective porous sound-absorbing materials is based on some theoretical laws:

- patterns reflecting the propagation of sound waves in the air;
- regularities of wave energy transfer from air to absorbing material;
- patterns of assessment of the conditions for wave absorption in the thickness of the material and the relaxation conditions resulting from this heat fluxes in the material.

At a low density of a material having a fully or partially open communicating porosity, similar to the studied material based on foamed liquid glass, no excess pressure is formed behind the material layer. This phenomenon provides a decrease in the resonant nature of sound absorption. Resonant sound absorption is characteristic of low frequencies. With an increase in the frequency of

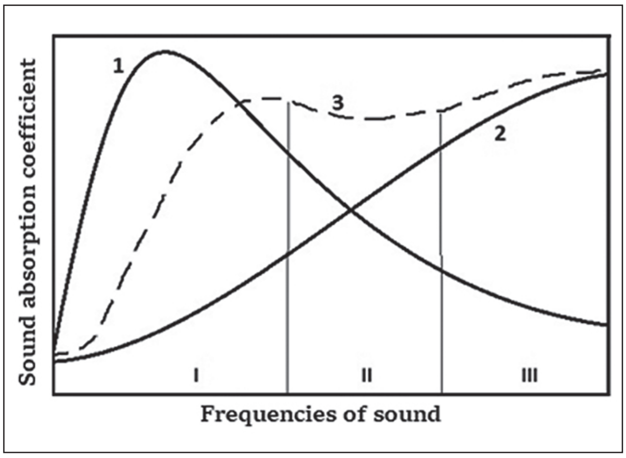

Fig. 1. **The mechanism of sound absorption:** I – resonant sound absorption; II – mixed sound absorption (transitional); III – sound absorption due to friction losses; 1 – sound absorption in the material, due to the characteristics of the matrix; 2 – sound absorption in the material, due to the parameters of its porosity; 3 – integral curve of sound absorption

sound, a transitional section takes place, after which the developed porosity becomes the determining factor in sound absorption.

Figure 1 schematically shows the mechanism of sound absorption depending on its frequency.

In section III, the sound absorption mechanism is as follows. The most effective sound absorption is possible if the dimensions of the wavelength of the incident air front and the dimensions of the pores and pore channels coincide. The pressure front of the sound wave that occurs on the surface of the material is transmitted inward, gradually weakening due to friction losses. The optimal porosity in this case will be one at which the pressure of the elementary wave will ensure the transfer of compressed air to a more distant pore or pores. In the process of moving the wave front inside the material, the change in pressure from pulsating near its surface will turn into an average excess near the back side. The damping of sound energy occurs due to two factors. Firstly, due to the deformation of the volume of air in the material, and secondly, as a result of friction losses during the passage of constrictions, channels and internal pores.

The absorption of sound waves of higher frequencies is provided by the presence of finer porosity. Such porosity is characteristic of porous materials based on silicate compositions, in particular, a material based on cold-cured foamed liquid glass. This is due to the fact that the energy of the sound wave must be commensurate with the mass of the volume of air in the pore, which must be sufficient to ensure the occurrence of excess pressure sufficient to move air into the next pore.

Porosity of sound-absorbing materials

The values of the sound-absorbing characteristics of porous materials directly depend on their porosity parameters: the presence of closed or open pores, the distribution of pores by size, and also their predominant shape [36–38]. The theoretical foundations associated with the identification of regularities in the formation of pore structures suggest the presence of the following types of porosity in materials: microporosity, capillary porosity, as well as contraction and gel porosity.

The sound-absorbing properties of highly porous cellular materials depend primarily on the type of pores in the surface layer of the material and the nature of the porosity of its inner layers. Highly porous and especially light materials are characterized by the presence of open and closed pores, as well as communicating and closed porosity.

According to the manifestation of acoustic properties, the pores are divided into acoustically active, acoustically passive and semi-passive.

Open pores, the dimensions of which are commensurate with the length of the sound wave, are referred to as acoustically active. This type of pores prevails in the material based on foamed liquid glass. Closed pores that do not have direct access to the surface of the material are referred to as acoustically passive. Through porosity with dead-end pores, as well as with open non-communicating pores, is classified as semi-passive. Such a closed or mixed type of pores is inherent in porous materials based on foam glass (Figure 2).

Among the open pores, hydraulically correct pores are distinguished, which are characterized by low values of the input resistance to air flows and the sound wave front. Such porosity is typical for materials with a granular structure, as well as for materials with special techniques for forming directional porosity. For classic highly porous materials with a cellular structure, it is not characteristic. Pores with constant resistance to the sound wave front are characteristic of materials with a fibrous structure. Materials with a cellular structure are characterized by hydraulically unstable (irregular) porosity, which has a high input resistance. This explains the fact that materials with a traditional cellular structure have obviously lower sound absorption values than granular or fibrous ones.

To assess the possibility of obtaining effective acoustic materials, porous materials of various structures were considered. Foam glass and material based on cold-cured foamed liquid glass were chosen for the study. As follows from the theoretical foundations of sound absorption outlined in the article, the pore size is closely related to the sound frequency. An increase in sound absorption at low frequencies can be achieved by relatively large pores, and at high frequencies by small pores. Sound absorption in a wide frequency range involves a combination of large and small pores in the acoustic material.

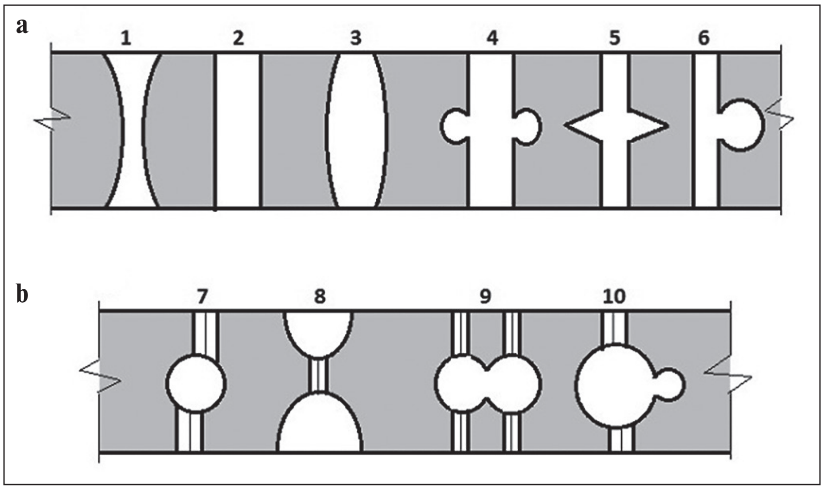

Fig. 2. **Types of pores:** a – open pores; b – closed pores; 1, 2, 3 – types of acoustically active pores; 4, 5, 6, 8 – types of acoustically semi-passive pores; 7, 9, 10 – passive porosity

Studies of the porosity of acoustic materials with high sound-absorbing properties showed that these materials are characterized by fine-grained, polyreaction porosity with pore sizes of 100–250 µm. The through porosity of these materials is in the range of 70–90%. A larger percentage of communicating porosity causes a decrease in the viscous friction of air in the material and, as a result, a decrease in the efficiency of sound absorption.

RESULTS AND DISCUSSION

1. Materials based on foam glass and foamed liquid glass have the following porosity parameters.

The total porosity, which refers to the entire volume of pores in the material, was determined by the experimental-calculation method according to the formula:

$$\mathrm{T_{otal}} = \left(1 - \frac{\rho_m}{\rho}\right), \qquad (2)$$

where ρ_m is the average density of the material, kg/m^3; ρ is the true density of the material, kg/m^3.

The true density of foam glass and on cold-cured foamed liquid glass was determined by the psychometric method.

Open porosity refers to pores that communicate with the external environment. The volume of these pores was obtained by water saturation of the material and calculated by the formula:

$$P_{op} = \left(\frac{m_2 - m_1}{V}\right)\left(\frac{1}{\rho_w}\right)100, \qquad (3)$$

where m_2 and m_1 are the mass of the sample, respectively, in the saturated and dry state, g; V is the volume of material, cm^3; ρw – water density, g/cm^3.

Closed porosity was calculated as the difference between total porosity and open porosity using the formula:

$$P_{cl} = P_{tot} - P_{op}. \qquad (4)$$

The results of determining the porosity parameters of materials based on foamed silicate compositions are shown in Table 2.

Thus, foam glass has a predominantly closed-pore structure, while a material based on foamed liquid glass has a predominantly open-pore structure.

Due to the dense smooth walls of the pores of heat-insulating materials based on foamed glass compositions, they have high strength characteristics.

Table 2
Porosity of materials based on foamed silicate compositions

Materials	Total Porosity, %	Open Porosity, %	Closed Porosity, %
Foam glass, ρ_m = 130 kg/m^3	92	1.62	90.38
Foam glass, ρ_m = 160 kg/m^3	87	1.17	85.83
Foamed liquid glass, ρ_m = 150 kg/m^3	91	56	35
Foamed liquid glass, ρ_m = 195 kg/m^3	84	61.6	22.4

In the studied material based on foamed liquid glass, the strength of the frame (the inner surface of the pores) is determined by the chemical nature of the raw materials themselves – amorphous silica, which creates a strong crystalline structure of the composite. The structure of porous materials, departing from the idealized model, is characterized by the presence of defects in the cellular structure that violate the closure of pores: these are cracks in the partitions and branched micropores, which increases the hygroscopicity and water absorption of the material. This is one of the arguments to explain the high-water absorption of the material based on foamed liquid glass; unreacted particles of soda glass form irregularities in the partitions.

Thus, the optimal porosity of the cellular material consists in a combination of open and closed pores, deformed into polyhedrons, with the thinnest and densest interpore partitions. In this case, the porosity of the cellular material can reach ≈ 98% [23, 39, 40].

2. To analyze the effect of modifying additives on liquid glass in order to reduce the water absorption of materials based on it, three compositions were studied. The sech for additives is aimed at replacing the common modifier-hardener of water glass Na_2SiF_6, since it is toxic.

Liquid glass with a density of 1.44 g/cm^3 and a silicate modulus of 2.7 was used for the study.

The additives chosen for the study can be divided into two categories:

1. Liquid water-soluble additive based on organosilicon (sodium ethyl siliconate ($C_2H_5Si(OH)_2ONa$)).
2. Dry mineral additives (calcium hydroxide $Ca(OH)_2$ (slaked lime) and Portland cement (main reactive phase $3CaO\ SiO_2$ (C_3S) (alite)).

The investigated compositions are presented in table 3.

The resulting compositions are inorganic polymers with a developed capillary-porous structure. Such a structure is characteristic of all porous silicate-based materials. Figure 3 shows various types of the porous structure of silicate compositions, differing in shape, size and distribution of pores over the volume of the material, depending on the characteristics of the production technology and raw material composition.

Composition No. 1.

The interaction of liquid glass with an organosilicon water-soluble water repellent causes the appearance of a hydrophobic crust. The additive does not interfere with the foaming process, resulting in a fibrous structure of the material (Figure 3d). When determining the contact angle of wetting, a drop on the material surface forms an angle greater than 110°, but this effect is achieved only on the formed hydrophobic crust, and when a drop is applied to the cut surface of a material sample, the drop is instantly absorbed.

Composition No. 2.

Curing the liquid-glass composition with calcium hydroxide (slaked lime) led to a slowdown in foaming, uneven dispersion of particles by volume during processing with electromagnetic waves, and as a result, a smaller increase in the foaming mass was obtained compared to other additives (Figure 3e). As a result of the primary check for a decrease in the water absorption of the material by the contact angle method, it was revealed that the drop penetrates into the thickness of the material after 5–7 s. after application.

Composition No. 3.

Portland cement turned out to be the best option for modifying the additive for curing the system. Portland cement in the indicated percentage, when reacting with liquid glass, acts as a hardener of the liquid glass matrix, lowering its water absorption performance (Figure 3c). The contact angle on the surface of this composition was more than 120°.

Table 3
Compositions of a porous material based on liquid glass with various modifying additives

Composition Number	Components	Content, % wt.
1	Liquid glass sodium $Na_2O \bullet 2,7SiO_2$	85
	Silicone water repellent sodium ethyl siliconate ($C_2H_5Si(OH)_2ONa$)	15
2	Liquid glass sodium $Na_2O \bullet 2,7SiO_2$	87
	Slaked lime $Ca(OH)_2$	13
3	Liquid glass sodium $Na_2O \bullet 2,7SiO_2$	90
	Portland cement (Main reactive phase – alit $3CaO \bullet SiO_2$ (C_3S))	10

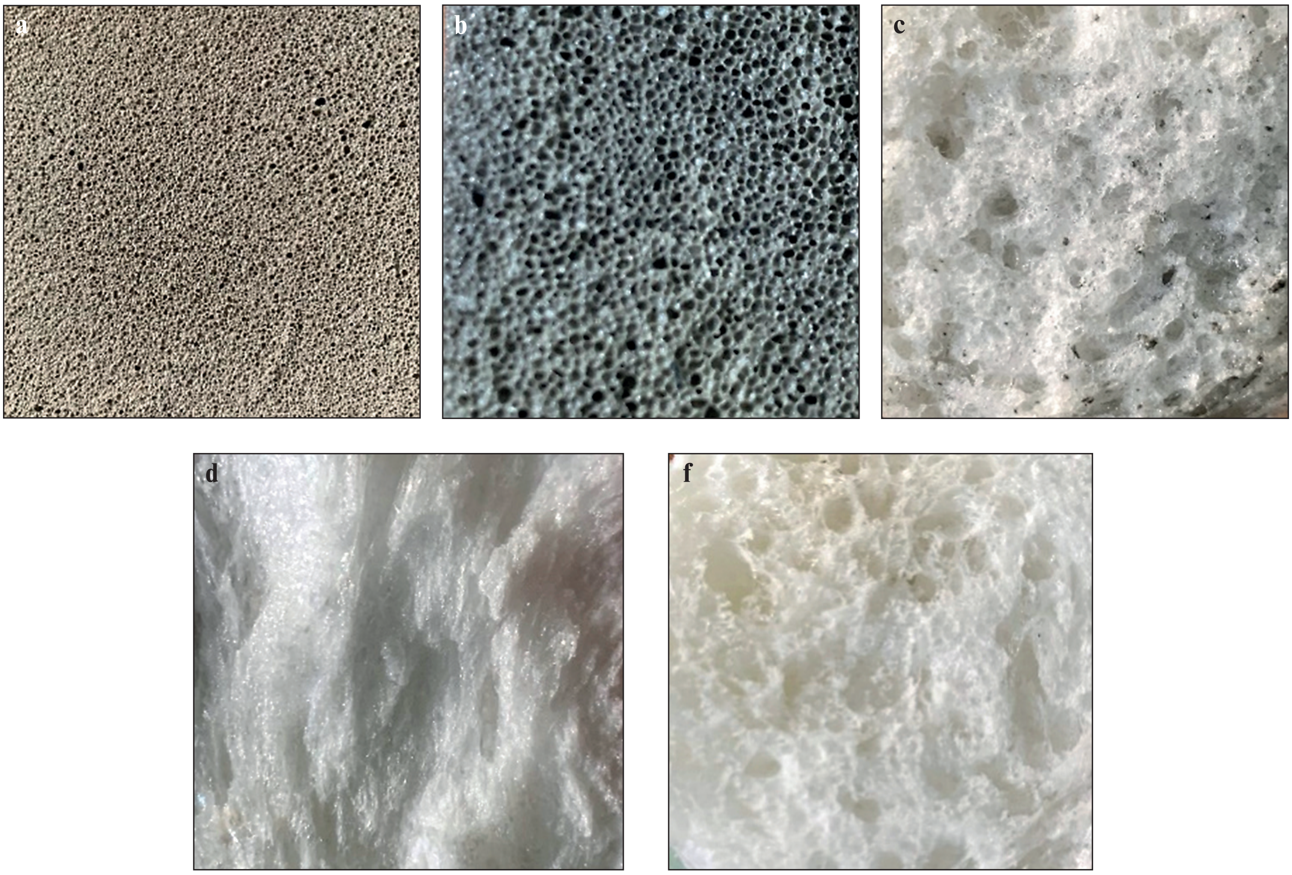

Fig. 3. **Structure of various silicate compositions of porous materials:** a – foam glass; b – foam glass crushed stone; c – material based on liquid glass with the addition of Portland cement; d – material based on liquid glass and organosilicon additive; f – material based on liquid glass and additives – calcium hydroxide

On the basis of experimental data, it turned out that the percentage of Portland cement additives indicated in Table 3 makes it possible to obtain optimal indicators for the wetting angle, in comparison with other compositions.

The reason for the decrease in water absorption in the "liquid glass – Portland cement" system can be described as follows: when the components interact (free water in liquid glass binds to Portland cement), low-basic calcium hydro silicates are formed, as well as calcium hydroxide, which subsequently binds free cations of sodium liquid glass into insoluble compounds. The reaction of the interaction of Portland cement tricalcium silicate and free water in liquid glass can be represented as follows:

$$2(3CaO \cdot SiO_2) + 6H_2O = \\ = 3CaO \cdot 2SiO_2 \cdot 3H_2O + 3CaOH_2. \quad (5)$$

In this case, Portland cement plays the role of not just a hardening activator of the silicate composition, but also participates in the formation of a decrease in the water absorption characteristics of the material due to the formation of a network of insoluble sodium-calcium compounds.

3. Sorption activity of the material based on cold curing foamed liquid glass is shown in Table 4.

The beginning of the graph of sorption moisture is accompanied by the filling of the first monolayer and the beginning of the formation of polymolecule films. The point of separation of the isotherm from the straight section of the polymolecule layer corresponds to the beginning of capillary condensation (Figure 4).

The different mechanism of the sorption and desorption processes of monolayer formation occurs due to different vapor pressure during its filling. The onset of capillary condensation, sorption and desorption also differ both in terms of moisture content and vapor pressure. In this case, the formation of a monolayer occurs at a sorption vapor pressure lower than the desorption vapor pressure, and the onset of capillary condensation occurs at values of a higher sorption vapor pressure. This is also explained by the different mechanism of filling the surface layers during sorption and desorption, which is the cause of the sorption hysteresis.

According to the type of hysteresis, based on the types of adsorption-desorption isotherms according to the IUPAC classification, which is compiled on the basis

Table 4
Indicators of sorption moisture content of the material based on foamed liquid glass of cold curing at a given relative humidity

Relative Humidity (φ), %	Sorption humidity (w_c), % wt
40	1.96
60	2.6
80	4
97	25

of the classical classification of adsorption-desorption isotherms of Brunauer, Deming, Deming and Teller (BDDT classification), this type of sorption of a material based on foamed liquid glass can be attributed to the fourth type. This type has a hysteresis loop, which reflects the process of capillary condensation in mesopores. The convex and concave nature of the initial section indicates, respectively, strong and weak interaction of the adsorbate-adsorbent.

Figure 5 shows different types of capillary-condensation hysteresis loops.

Each type of loop is associated with a certain type of porous structure of the substance. H1-type loops are typical for agglomerates that are uniformly packed and similar in size. For some globular systems, for example, silica gels, the H2 type is typical, however, in this case, the distribution and shape of the pores are ambiguous. H3 and H4 type loops were obtained for adsorbents having slit-like pores or, as in the case of H3, consisting of plane-parallel particles.

Type I isotherms with type H4 hysteresis indicate the presence of microporosity. Isotherm type IV is usually

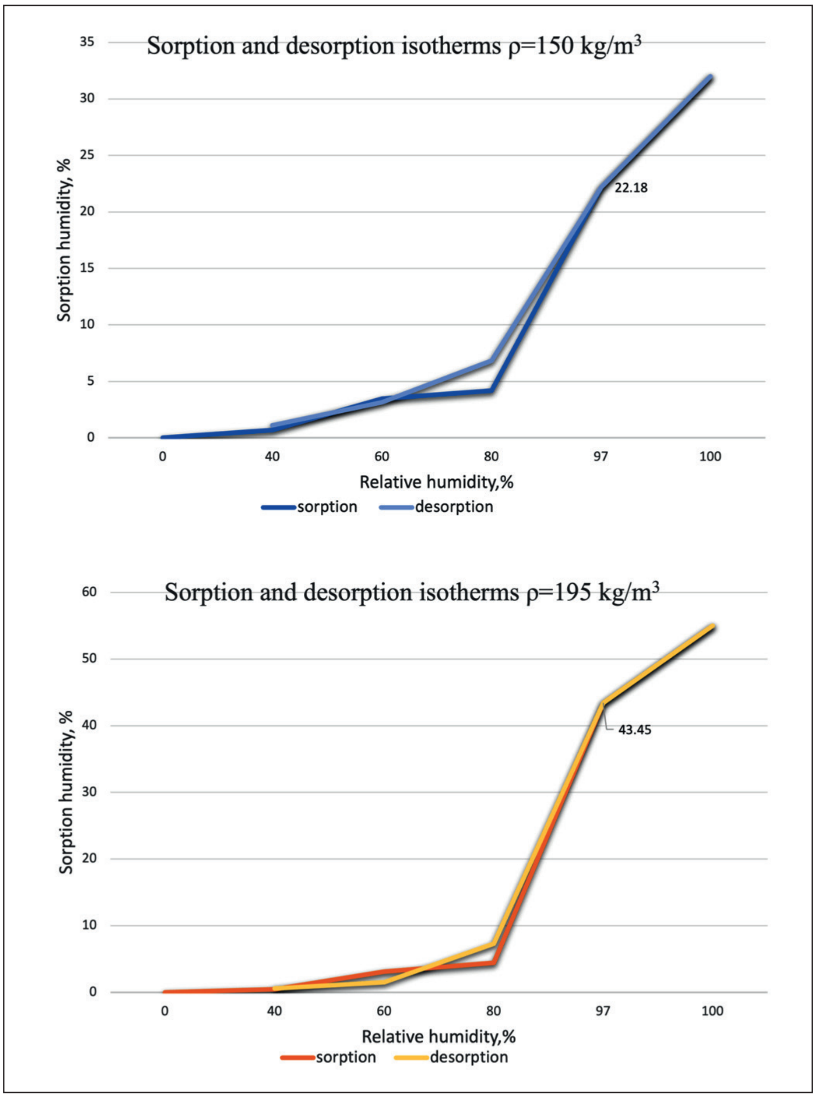

Fig. 4. **Graphs of the sorption and desorption activity of the material based on foamed liquid glass**

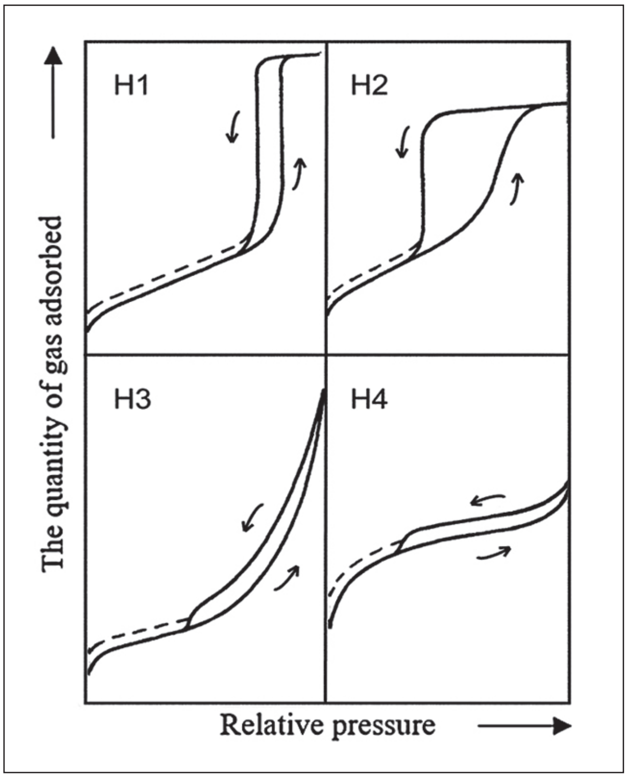

Fig. 5. **Types of hysteresis loops**

observed for substances containing mesopores or small macropores.

To calculate some parameters of the structure of a porous material based on foamed liquid glass, we introduce the assumption that the sorption of water vapor on the surface of foamed liquid glass proceeds exclusively by the surface adsorption mechanism, that is, only the monolayer is filled. Therefore, the sorption isotherm can be described by the equation (6):

$$w(\varphi) = w_m[-3.13/ln(\varphi/100)]^{1/2.55}, \quad (6)$$

where w_m is the parameter of the equation, which is the capacitance of the monolayer, %, which can be approximately calculated by the formula (7):

$$w_m = \frac{w(40)}{1.615} = \frac{1.96}{1.615} = 1.21\%. \quad (7)$$

An approximate calculation made it possible to determine w_m =1.21%. The obtained value of w_m, in turn, made it possible to estimate the specific surface of the material based on foamed glass according to the equation (8):

$$A = 35.5w_m \cdot 10^3\, m^2/kg = 35.5w_m\, m^2/g. \quad (8)$$

We got A = 42.9 m^2/g. This value of the specific surface makes it possible to make an assumption about the predominance of small pores in the material.

To calculate the specific surface area, the capacitance of the monolayer was calculated using the formula (9):

$$w_m = \frac{w_0}{n_0} = 1.35, \quad (9)$$

where w_0 is the sorption humidity at relative air humidity φ_0 = 40%; n_0 – was determined by the formula:

$$n_0 = \frac{c\varphi_0}{1+(c'-1)\varphi_0} N_0 = 1.45. \quad (10)$$

Here c' was determined by the formula:

$$c' = 6 + (1 + 5\varphi_0)/\varphi_0 = 13.5, \quad (11)$$

a N_0 corresponds to the value N at $\varphi = \varphi_0$, where N was calculated by the formula:

$$N = [-3{,}13/ln(\varphi)]^{0.39} = 1.615. \quad (12)$$

The specific surface area was calculated by the formula:

$$A = \frac{w_m N}{M} A_m = 5 \cdot 10^6\, m^2/g. \quad (13)$$

The high values of the specific surface area calculated by the calculation-analytical method provide an explanation for the obtained experimental data on the sorption activity.

4. Studies of the sound absorption coefficient of materials based on foamed liquid glass of cold curing and foam glass were carried out according to the method of GOST 16297-80. “Materials are sound-proof and sound-absorbing. Test Methods" on an interferometer (Knut’s tube). The test equipment consists of a low-frequency measuring generator, an electronic RMS voltmeter, a measuring microphone, a microphone amplifier, a loudspeaker, acoustic filters and an electronic frequency counter (Figure 6).

Testing steps:

– placing a sample of foamed liquid glass and foam glass into the interferometer holder so that not the front side is pressed by a rigid piston, but the front side is fixed on the edge of the holder, fixed in the pipe;
– determination of the voltage value at the output of the microphone amplifier, recorded by an electronic voltmeter, corresponding to the first maximum and minimum sound pressure level in the interferometer tube;
– testing in the frequency range from 100 to 2000 Hz;
– determination of the normal sound absorption coefficient.

Based on the test results, the average values of the sound absorption coefficients (SAC) αw at a frequency of 2000 Hz are shown in Table 5, and the results of the tests are presented in Figure 7.

Fig. 6. **Sound absorption test apparatus and test material samples**

The test results confirmed the assumption that materials of the same density, but differing in different degrees, types of porosity and pore size distribution, have excellent sound absorption coefficients. Thus, the material based on foamed liquid glass showed somewhat higher values of the sound absorption coefficient compared to foam glass, especially at higher frequencies due to the predominance of open porosity and the presence of small pores (Tables 5 and 6, Figure 7).

Comparison of technical characteristics of various porous silicate compositions is given in table 7.

Ecological factor in the design of heat-insulating material based on cold-cured foamed liquid glass.

Main advantages/disadvantages:

• at the raw material selection stage:

— renewable/non-renewable (mainly raw materials of the material under study are non-renewable or difficult to renew);
— the presence of components chemically harmful to humans (the material does not contain substances harmful to humans);
— use of waste (as a filler for a foam glass mixture, it is possible to use weed waste, including dried dispersed Sosnowsky's hogweed);

• technological process:

— energy spent on the entire technological process (the most energy-consuming technological unit is a mixer and auxiliary devices);
— high-temperature and high-frequency effects (high-temperature regimes are not required for production,

Table 5

Test results for determining the sound absorption coefficients

Materials	Foamed Liquid Glass		Foam Glass	
Average Density Pm, kg/m³	150	195	130	160
SAC (αw)	0.9	0.7	0.8	0.73

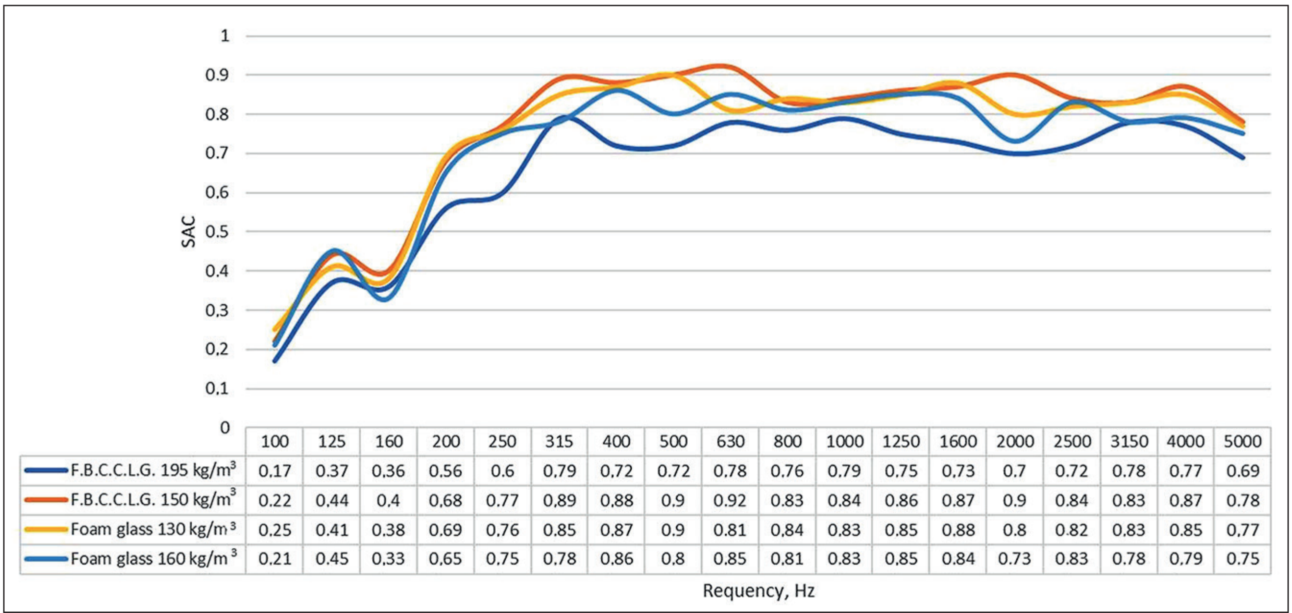

Fig. 7. **Test results for determining the sound absorption coefficients of foam glass and materials based on foamed liquid glass**

Table 6

Correlation between the values of porosity parameters and sound absorption coefficients of material samples

Materials	Average density, кg/m³	Porosity, %			Sound Absorption Coefficient
		Open	Closed	Total	
Foamed liquid glass	150	56	35	91	0.9
	195	61.6	22.4	84	0.7
Foam glass	130	1.62	90.38	92	0.8
	160	1.17	85.83	87	0.73

a temperature of 40°C is sufficient for processing the material in the cold curing mode);

• at the operational stage:

– the release of harmful substances or the ability to absorb them (due to the high rates of sorption activity, the material has the ability to absorb harmful substances from the air).

Based on the results of the analysis, it can be concluded that the developed heat-insulating material based on cold-cured foamed liquid glass is environmentally friendly, with a carbon footprint close to zero. The recommended temperature range of application of thermal insulation material based on foamed liquid glass of cold curing is from minus 70°C to plus 200°C.

CONCLUSION

The performance characteristics of a heat-insulating material based on cold-cured foamed liquid glass are formed due to the chemical and phase composition of the raw materials used, their structure parameters, as well as the features of the technological process that form the

Table 7

Free comparison table of technical characteristics of various porous silicate compositions

Materials	Structure	Compound	Main Technological Differences	Coefficient Of Thermal Conductivity, W/(m • °C)	Average Density, kg/m³	Sound absorption Coefficient	Vapor Permeability, mg/(m • h • Pa)	Sorption At Relative Humidity 97%, % Wt.
Foam Glass	Closed Porosity Prevails ≈ 98%	Cullet, Glycerin, Blowing Agent	Structure Formation Occurs Due To The Gas Formation Process Occurring In Furnaces At High Temperatures (of the Order 1200°C)	0.043–0.062	130–160	0.7–09	0.0019–0.0023	1.62–1.79
Cold-Cured Foamed Liquid Glass	Open Porosity Predominates ≈ 67%	Liquid Glass, Foaming Agent, Hardener, Filler	Structure Formation Occurs Due To The Process Of Foaming, Processing Takes Place In Low-Temperature Furnaces (About 40°C)	0.0556–0.068	150–195	0.73–0.8	0.1763–0.1788	19–25

structure of the material. The formation of the following performance characteristics was investigated: thermal conductivity, water absorption, sorption moisture and sound absorption. Based on the obtained experimental results, the following conclusions were drawn:

1. With a similar density, foamed liquid glass has different values of the edge points of the thermal conductivity range than foam glass due to the predominance of open porosity, but not to a large extent, due to the presence of a smaller pore size in the foam glass composition. Thus, foam glass has a predominantly closed-pore structure (≈ 98% closed porosity), while the material based on foamed liquid glass has a predominantly open-pore structure (≈ 67% open porosity).

2. The issue of excessive water absorption in cold-cured foamed liquid glass-based materials was resolved by incorporating an additive hardener, specifically Portland cement. This component not only serves as a hardening activator for the silicate composition but also considerably reduces its water permeability, but also participates in the mechanism of reducing the water absorption of the material due to the formation of a network of insoluble sodium-calcium connections.

3. High values of the specific surface area, calculated by the calculation-analytical method, provide an explanation for the experimental data obtained on the sorption activity (19–25 wt.%) of the developed heat-insulating material.

4. The results of tests to determine the sound absorption coefficient confirmed the assumption that materials of the same density, but differing in different degrees, types of porosity and pore size distribution, have excellent sound absorption coefficients. Thus, the material based on foamed liquid glass showed slightly higher sound absorption coefficients compared to foam glass, especially at higher frequencies due to the predominance of open porosity and the presence of small pores.

An analysis of the environmental factor showed that the developed heat-insulating material based on cold curing foamed liquid glass can be characterized as a comprehensively environmentally friendly material with a carbon footprint close to zero.

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