New functional materials for creating infrastructure facilities in the Arctic and Far North regions

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Abstract. The article presents aspects of the production of new functional building materials based on foam glass, reproducing the geological processes of formation of natural minerals and rocks. The creation of heat-insulating and structural glass composites (TCS) with increased strength requires the development of a new theoretical base that allows one to design various composites with an amorphous-crystal structure, which forms the specified properties. Two methods of amorphous matrix reinforcement are considered: physical and chemical (or thermochemical). Regularities of formation of porous glass composites are established. The values of technological parameters that are necessary for obtaining glass composites with the specified properties are determined. It is shown that the developed materials can be used for the construction of unique structures with reduced heat transfer. The resulting materials can be used to produce light prefabricated segments, which is important for transportation and installation in the Northern regions.

1. Introduction
For the Russian Federation, the development of the Northern territories rich in natural resources and energy carriers is a strategic goal and an important direction of scientific and technical breakthrough. The harsh conditions of these latitudes require the use of natural materials of various origins or the production of new high-performance building materials that reproduce the geological processes of formation of natural minerals and rocks, the creation of which can be based on modern advanced technologies, which in turn requires the development of a new theoretical base that allows one to design various composites with specified properties. This approach is used in geonics (geomimetics) - a scientific direction that consists in applying knowledge about natural processes to solve various engineering problems [1].

The amount of natural building materials is decreasing every day, and many deposits have been developed. An alternative is their man-made analogues, which may be inferior to prototypes in a number of properties, but the production of which can be established in the required volume [2].

For materials used in Northern latitudes, important characteristics are Thermophysics and strength characteristics, especially strength at sub-zero temperatures, when materials become brittle. Natural materials that meet these requirements include volcanic pumice and tuff, as the most effective inorganic thermal insulation and acoustic materials. However, as mentioned earlier, they cannot fully meet the needs of the construction industry. The use of traditional man-made analogues-aerated concrete, mineral wool, expanded polystyrene, etc., which have a number of disadvantages (low strength, high water saturation, combustibility, low environmental safety, etc.), deter designers.
Therefore, it is necessary to develop new high-performance composite materials that combine a whole range of necessary properties.

2. Scientific

Our research has shown that the basis of such composites can be made of foam glass. For the construction complex, the use of foam glass opens up new promising areas: the possibility of creating energy-saving objects easier than usual, including the construction of areas on weak and wetlands, as well as in regions with cold and hot climates. But even such a material for construction in the Arctic and Far North regions cannot be used without increasing the strength parameters, which requires further development of the theoretical basis for creating a heat-insulating glass composite based on it with high thermal insulation and strength characteristics [3].

Based on the above, the purpose of the work was to develop theoretical foundations and practical recommendations for the creation of highly effective thermal insulation and structural glass composites based on foam glass for the construction of buildings and structures, including in the Arctic and the Far North.

Figure 1 shows a structural and logical scheme for the development of technology for thermal insulation and structural glass composite.

According to the presented scheme and in accordance with the purpose of the work, the composition and structure of volcanic pumice and tuff were studied and analyzed, which allowed us to establish the amorphous-crystalline structure of both natural materials with high strength characteristics and good thermal (thermal insulation) characteristics. Therefore, when designing thermal insulation and structural glass composites (TCS), it was necessary to meet two conditions: to preserve high thermal properties and give it strength characteristics as a structural material. Such properties in the material can be provided when creating a fine-pored structure with isolated (closed) pores, which will provide high thermal insulation characteristics, and to increase the strength of the glass composite, it is necessary to form an amorphous-crystal frame, in which therefrom reinforcing role will be performed by crystal inclusions of a given size.

The difficulty of obtaining such a material is that the foaming capacity of the foam-forming mixture in the pyro-plastic state is negatively affected by the crystallization process. In essence, neither statistical nor classical (Griffiths) strength theory can be used to estimate the strength of a porous glass-crystal composite. For foamed materials (in particular, foam glass), the fluctuation theory of glass strength is also not applicable, since it is insufficiently studied and is often contradictory [4,5].

Therefore, to obtain glass composites with increased strength, it is necessary to create an amorphous-crystalline structure of the material, which would have increased strength due to crystal inclusions, and at the expense of an amorphous matrix would preserve high heat and sound insulation characteristics, preventing the formation of a solid crystal framework that increases heat and sound transmission in the material [6].

There are two ways to reinforce an amorphous matrix:

- physical-introduction to the amorphous matrix of a crystalline filler;
- chemical (or thermochemical) – introduction of components into the composition of the foaming mixture, which at foaming temperatures will release crystalline phases in the amorphous matrix.

According to the first method, it is technologically quite difficult to obtain an amorphous-crystal frame with a size of 0.7-30 µm, since this requires fine grinding of the initial components.

The second option also has its own difficulties related to the careful development of the chemical composition and temperature-time mode of foaming glass composite.

The properties of porous materials depend on the following factors [7]:

- the nature and distribution of porosity by volume of the material;
- the prevailing type of porosity;
- the shape and size of the pores;
- condition of the inner surface of the pores; - ratios of amorphous and crystalline phases.
According to [8], unhindered development of the unit cell of the foam of the correct geometric shape is possible at constant values of surface tension and viscosity. The presence of regions with different values of these properties or crystal phases in a substance in a pyroplastic state causes distortion of the cell geometry and the entire structure of the foam glass.

Therefore, the acceptable values of inclusions that do not reduce the structural and mechanical strength and do not cause violations of the structure of foam glass are the sizes of crystals that do not exceed half the thickness of the interstitial partition in the thinnest place (about 35-50 nm). Relatively smooth movement of intraplate fluid can be provided in a plate with a thickness equal to its bimolecular layer, only if this condition is met. The presence of large crystals or other inclusions in the foam-forming mixture, especially at the sintering stage, causes inhibition in the development of cell elements and leads to uneven development of the foam glass structure. Therefore, the probability of obtaining a light foam glass (p≤200 kg/m³) decreases due to the fact that in the melt forming the cells, the number of defects (thickenings) in the separation walls increases.

Mathematical planning of the experiment was used to increase the strength of the porous material. In the studied material, the response functions were the foaming coefficient, strength, density and thermal conductivity, which are influenced by independent variables (factors): soot content (%), specific surface area of the foaming mixture (m²/kg), foaming temperature (T°C), holding time (min). The research results are shown in Figure 2.
Figure 2. Influence on the value of compressive strength of the specific surface area and the amount of soot.

According to the developed model, it can be seen that the control of technological parameters will increase the theoretical compressive strength of the glass composite to 10 MPa.

The structure of cellular-porous materials cannot be described by a model of a homogeneous isotropic medium with isolated and non-contacting pores, so these relations will be even more complex for models of cellular-frame bodies.

The non-linearity of the dependence of mechanical properties on the porosity of the material is determined by the large unevenness of the distribution of stresses and deformations over the micro-volumes of the porous material during its deformation [9].

In contrast to solid media, the strength of which is predetermined by the presence of "dangerous" places-structural imperfections, the strength of highly porous bodies can be considered with a sufficient degree of approximation as the result of additive addition of coupling forces between the structure elements [10].

One of the main reasons for embrittlement of amorphous material is considered to be a decrease in the free volume below a certain critical level. An increase in the rate of deformation leads to a sharp increase in the inhomogeneity of the distribution of areas of reduced density (OPP), which are concentrated mainly in the shear bands, which eventually leads to the material decompression [11].

Thus, due to changes in the geometric dimensions of the pores, the formation of microfractures, closing and crumpling of internal contacts in porous materials, the same deformations correspond to more significant internal damage (defects) than in compact materials.

In a material with a cellular structure, the thickness of the interstitial partitions should be approximately the same. Significantly reduces the strength of the material the difference in thickness of the interpore partitions, the destruction of which leads to a redistribution of loads on more durable partitions. The thickness of interstitial partitions is characterized by:

- the thickness of the partition in its thinnest part, which is determined by the dispersion of the initial components and the method of porization;
- uniformity of the partition section along the entire perimeter of the pore;
- the heterogeneity of the thickness of the walls around porizovannogo volume, which is influenced by the uniformity of the temperature field in the gas swelling and uniform distribution in polzuzemoy mixture of blowing agent.

The strength of a porous material depends primarily on the character of the inner surface of the pore layer.
Depending on the conditions for the formation of a cellular structure, the pore layer (for mineral systems, the layer thickness is 15-30 microns) can be [12]:

- more loose than the material of the interporal partition (ragged surface);
- equal to the partition material (smooth surface);
- more dense and durable than the main partition material (glossy surface). The priming layer acts as a reinforcing zone in the case of a glossy surface. Loose Priportovy layer, diminish cross-section interporous partitions.

To improve physical and technical performance of insulation it is necessary to optimize the following characteristics of a cell structure: uniform distribution of porosity in the bulk material; the thickness of interporous partitions; density of interporous partitions; the shape of the pores; the nature of the internal surface of the pores; isolation of cellular structure.

B. K. Demidovich found that all mechanical properties of foam glass are determined by its structure and density, which, in turn, are due to the processes of preparation of both individual components and the foam-forming mixture itself, temperature-time modes of foaming and annealing of foam glass [13].

With an increase in water absorption, the strength decreases, which indicates that the number of defects in the structure of foam glass increases, which occur due to non-compliance with temperature and time regimes at the stages of foaming and annealing, as well as the process of crystallization of foam glass.

An increase in porosity in the material leads to a deterioration of the plastic and elastic properties of cellular materials. This is due to the fact that the effective cross-section and density of internal contacts are reduced, additional stress concentrators are created, and the strength of solids is generally reduced [14].

Optimization of the structure of foam glass and the introduction of crystal reinforcing components can increase the strength to 2.5-3 MPa (at a density of 250-300 kg/m3), but this is not enough to create a glass composite with higher strength indicators.

To confirm this hypothesis, a thermochemical method of reinforcing the glass composite structure was used. Compositions of complex gas-forming agents were developed, which would give crystalline phases when the amorphous matrix transitions to a pyroplastic state. To prevent bulk crystallization, the temperature-time mode of glass composite production was adjusted. For rice 5 it can be seen that in the amorphous matrix, crystal inclusions of a prismatic shape are clearly visible, which strengthen the structure due to the fact that they have an elongated shape and create a crystal framework. At the same time, amorphous layers are present between the crystals, which prevent heat transfer along the crystal frame, which allows maintaining high thermal insulation characteristics of the original matrix.
Heat transfer in porous systems is carried out in several ways:
- due to the thermal conductivity that occurs between the structural elements (contact thermal conductivity),
- through the medium that fills the pores (molecular thermal conductivity of the gas);
- due to convection in the pores (convective thermal conductivity);
- as a result of radiant heat exchange between inside the pores (radiation thermal conductivity).

![Figure 5. Electron microscopic images of glass composite samples.](image)

The contribution of each of these methods to the overall heat transfer in the material is determined depending on the temperature and porosity characteristics of the material. The main method of heat transfer at low temperatures is contact thermal conductivity. It acts as a function of the surface characteristics and thermal conductivity of the structural elements, as well as the porosity and area of internal contacts.

The contribution of radiation to heat exchange processes in porous bodies increases at elevated temperatures. The radiation coefficient of thermal conductivity $\lambda_{rad}$ is calculated using the formula [15]:

$$\lambda_{rad} = 2C_{SB}^2 b_{SB}T^2R$$

where $b_{SB}$ is the Stefan-Boltzmann constant, $C_{SB}$ is the degree of blackness of the surface, and $R$ is the average pore size.

Convective thermal conductivity $\lambda_{conv}$ should be considered in the presence of large pores in a porous material and significant temperature gradients (natural convection) or pressure (forced convection). The coefficient $\varphi_T$ of increase in thermal conductivity due to the presence of convection flows in natural convection and is determined from the ratio

$$\varphi_T = \frac{\lambda_{conv}}{\lambda_T} = 1 + \frac{2 \beta_{ob} \Delta T \rho C_p^{const}}{18 \lambda_T \lambda_{rad} \eta}$$

where $\beta_{ob}$ and $\eta$ are the coefficients of volumetric expansion and viscosity of the pore filler (gas or liquid); $C_p^{const}$ - the specific heat capacity of the material at constant pressure; $\Delta T$ - the temperature difference at the boundaries on both sides of the material layer thickness $h_i$, $S_i$ - the surface of the unit volume of the material; $g$ - acceleration of gravity.

Effective thermal conductivity of a porous body taking into account $\lambda_{conv}$ and $\lambda_{rad}$
where $G_F$ is the pore shape and orientation factor [18].

In closed gas-filled pores, the thermal conductivity of the gas plays an important role in heat transfer processes. If the average pore size is reduced to a value commensurate with the free path of the filler gas molecules, the effective thermal conductivity of the porous system may be less than the thermal conductivity of the gas, which is practically important, for example, in the manufacture of various types of heat insulators [19].

In conditions of insulating building materials (-30 to +40 °C) in the case of a uniform finely porous structure, the contribution of radiation and convection heat conduction can be neglected and the effective thermal conductivity of real porous systems can be calculated as the geometric mean of the thermal conductivities of the solid and gaseous phases, as well as humidity of the material.

To account for the crystal component of the amorphous matrix in the TCS structure, we have proposed a method for calculating the thermal conductivity coefficient using the correction coefficient $k$.

As the porosity of the material increases, its coefficient of thermal conductivity also decreases $\kappa$, which is related to the density $\rho$, specific heat capacity $c_i$ and thermal conductivity of the material by the ratio

$$\kappa = A_{\eta} \lambda_T / c_i \rho$$

where $A_{\eta}$ is the coefficient that depends on the choice of units [17].

The coefficient of thermal expansion of porous materials does not depend on porosity, and its value coincides with the table value for compact materials.

The main performance properties of the obtained TCS are presented in table 1.

**Table 1. Main properties of TCS.**

| The number of modifying additives in the composition of the gasifier, wt.% (over 100%) | Foaming interval, °C | The number of the crystal is symbolic phase, % | $\rho_{sp}$, kg/m$^3$ | $R_{sg}$, MPa | The thermal conductivity, W/(m K) | Kvsp |
|---|---|---|---|---|---|---|
| TCS.№1 4.5K/0.25C/0.25M | 800-820 | 7.6±0.2 | 200±10 | 4.9±0.1 | 0.05-0.06 | 4.9 |
| TCS.№1 4.5K/0.25C/0.25M | 850-870 | 13.9±0.2 | 260±10 | 6.4±0.1 | 0.08-0.09 | 3.8 |
| TCS.№2 4.5K/0.35C/0.30M | 800-820 | 9.8±0.2 | 210±10 | 5.3±0.1 | 0.06-0.07 | 4.5 |
| TCS.№2 4.5K/0.35C/0.30M | 850-870 | 14.4±0.2 | 280±10 | 6.8±0.1 | 0.08-0.09 | 3.7 |
| TCS.№3 4.5K/0.35C/0.35M | 800-820 | 10.3±0.2 | 240±10 | 5.4±0.1 | 0.07-0.08 | 4.4 |
| TCS.№3 4.5K/0.35C/0.35M | 850-870 | 16.3±0.2 | 310±10 | 6.6±0.1 | 0.09-0.10 | 3.5 |
By introducing various types of modifying additives into the foam-forming mixture, the character of the porous structure can be changed. For this purpose, the compositions of foam-forming mixtures were prepared, which would give crystal phases when the amorphous matrix transitions to a pyroplastic state. To prevent bulk crystallization, the temperature-time mode of glass composite production was adjusted. A complex modifying additive (C/S/M) was used as a combined gas-forming agent to create a material with polymodal porosity.

Depending on the shape and size of the particles of glass granulate and gas-forming agent, the structure of the glass composite is formed from the density of pore placement. The shape is quite complex and can change significantly depending on the factors that affect it.

As shown by electron microscope studies of the structure of porous glass composites on a complex gasifier, samples containing colemanite/carbon black/chalk, % in the following ratios have a high strength 4.5/0.35/0.3.

The dependence of glass composite strength on the ratio of maximum pore sizes (Dmax/dmin) and porosity uniformity (C/Cmax) was established. As you can see from the graph, the closer these ratios are to the unit (round pore), the higher the strength of the samples.

Figure 6. Micro-photos of samples foamed on a combined gas generator.

Figure 7. Graph of the dependence of the compressive strength on the ratio of maximum pore diameters (Dmax/dmin) and porosity uniformity (C/Cmax).
3. Conclusion
Thus, the regularities of the formation of porous glass composites, consisting in the reinforcement of the interporous partition by physical and thermochemical methods, are established. It has been confirmed that for the production of thermal insulation and structural glass composites with a compressive strength of 6.0–6.8 MPa, the ratio of the crystalline and amorphous phases should be 1:(6÷7), the ratio of cross diameters (Dmax/dmin) and pore sizes (C/Cmax) should be close to one (round-shaped pores, approximately the same size). As a result of the research, the values of technological parameters that are necessary to obtain glass composites with the specified properties were determined. Thus, the optimal foaming temperatures are 850–870 °C, and the established dependencies make it possible to determine the main properties of materials taking into account the technological mode of their production, as well as to evaluate the influence of each of the studied factors on the foaming coefficient, density, water absorption and strength of the glass composite.

The developed materials can be used for the construction of unique engineering structures-infrastructure objects, including spheres and hemispheres with reduced heat transfer, and, consequently, with minimal heat loss to the environment, pipelines, heating lines, etc.

Due to light prefabricated segments, such structures can be easily transported and assembled at the installation site, as well as dismantled and moved to new sites, which is especially important in the Northern regions of our country.

4. References
[1] Lesovik V S 2016 Geonika (Of Geodaetica) Examples of implementation in construction materials science: monograph 2nd edition, supplemented (Belgorod: BSTU Publishing house) 287 p
[2] Yatsenko E A, Smoliy V A, Kosarev A S, Goltsman B M and Deeva A S 2013 Synthesis of foam glass on the basis of combined industrial waste Scientific review no 8 pp 70–75
[3] Minko N I, Bessmertny V S, Puchka O V, Semenenko S V, Krakht V B, Melkonyan R G 2008 Penosteklo Scientific bases and technology: monograph (Voronezh: Scientific book) 168 p
[4] Zubekhin A P, Golovanova S P, Yatsenko E A and Yatsenko N D, Scientific bases of sintering in silicate technologies 2014 Technique and technology of silicates vol 21 no 2 pp 16–19
[5] Melkonyan R G, Beletsky B I, Melkonyan G R and Sarkisov P D 2011 Penosteklo Theory and practice of production of glass-like foam materials: textbook (Moscow: D. I. Mendeleev Russian state technical University) 186 p
[6] Wu J P, Boccaccini A R, Lee P D, Kershaw M J and Rawlings R D 2006 Glass ceramic foams from coal ash and waste glass: production and characterization Advances in Applied Ceramics vol 105 no 1 pp 32–39
[7] Gorlov Yu P 1989 Technology of thermal insulation and acoustic materials and products (Moscow: Higher school) 384 p
[8] Kazmina O V and Kuznetsova N A 2012 Getting a high-performance heat-insulating building material based on ash and slag waste from thermal power plants Refractories and technical ceramics no 1–2 pp 78–82
[9] Kazmina O V 2010 Influence of the component composition and oxidative-reducing characteristics of the charge on the processes of foaming of pyroplastic silicate masses Glass and ceramics no 4 pp 13–17
[10] Belov S V 1981 Porous metals in mechanical engineering 2nd ed reprint (Moscow: Mashinostroenie) 247 p
[11] Kazmina O V, Vereshchagin V I and Abiyaka A N 2009 Influence of preliminary preparation of glass charge and its degree of dispersion on the processes of silicate and glass formation Technique and technology of silicates vol 16 no 3 pp 1–7
[12] Shutov A I and et al 2007 Modeling of the structure of thermal insulation foam glass Glass and ceramics no 11 pp 22–23
[13] Demidovich B K 1972 *Production and application of foam glass* (Minsk: Science and technology) 304 p
[14] Yatsenko E A, Rytchenkova V A, Kosarev A S and Grushko I S 2010 Production of composite glass materials based on solid fuel combustion waste *Advances in chemistry and chemical technology* vol 24 no 6 (111) pp 81–85
[15] Cheremskoy P G, Slezov V V, Betekhtin V I 1990 *Pores in a solid body* (Moscow: Energoatomizdat) 376 p
[16] Kazmina O V, Vereshchagin V I, Semukhin B S, Mukhortova A V and Kuznetsova N A 2011 Influence of the crystal phase of the interpore partition on the strength of glass-crystal foam material *News of higher educational institutions Physics* vol 54 no 11–3 pp 238–241