Liquid-glass concrete of variable density

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Abstract. Research results of porous compositions based on sodium liquid glass and fillers of various origins are presented. Materials, regulating rheological properties and thermal transformations of liquid glass compositions were used as the fillers. Feasibility of multicomponent fillers introduction into thermal expansion compositions was substantiated. Combined fillers matching a gel-forming component and thermosetting materials that emit a gas phase are preferred for improving molding properties of compositions and forming a highly porous polymodal material. A porous aggregate with a density of 250 – 300 kg/m$^3$ was synthesized, providing high thermal resistance of the building envelope. Advantages of a liquid-glass matrix for producing lightweight concrete with a porous silicate aggregate are shown. Genetic commonality of an aggregate and a matrix contributes to the formation of durable concrete of a porous structure. Variants of the structure of variastropic liquid glass concrete, consisting of layers of various densities were proposed. Lightweight concrete of variastropic structure with a density of 800 kg/m$^3$ and compressive strength of 10 MPa has been developed. The integrated use of liquid glass to obtain aggregate and concrete will ensure a compact technological scheme. The research is aimed at creating a technology of heat-insulating materials that combine high porosity with shape stability.

1. Introduction
Liquid glass is an aqueous solution of alkaline silicates. Reactivity and adhesion of liquid glass are widely used to create composite materials. Rheological properties of liquid glass are regulated by various additives and change upon thermal effects [1 – 4]. Unique properties of liquid glass are used in the technology of porous structure materials [5 – 10]. Porization of liquid glass is a multi-stage process. Pores formation in liquid glass is carried out by swelling. Liquid glass expansion is accompanied by the formation of a highly porous structure with an uneven distribution of cells of various sizes and low mechanical strength [10]. Porization depends on the type and amount of water contained in the liquid glass. Introduction of powdered additives – fillers in liquid glass can change rheological properties of the composition and nature of swelling.

Prospects for energy-efficient construction are associated with the use of lightweight concrete [8, 9]. However, information on lightweight concrete based on liquid glass is scarce [10 – 12].

The purpose of the research is lightweight concrete synthesis of variable density; the main component of which is sodium liquid glass.

2. Materials and methods of research
Thermo technical and physic and mechanical properties of lightweight concrete depend on characteristics of the porous aggregate and the matrix, which holds aggregate’s particles together.
The object of the research was multifunctional compositions based on liquid glass, from which both components of lightweight concrete were synthesized.

Sodium liquid glass with a density of 1400 kg/m$^3$ was used in the experiments. Materials of various origins were introduced into the liquid glass as the filler additives.

The additives of the first group (oil shale, wood flour, coal-bearing rocks, and ashes from coal combustion) contained a burn-out component. The additives of the second group (clay, flask, bauxite, volcanic glass) contained hydrated minerals; its firing is accompanied by dehydration and water vapor formation. The additives of the third group III contained minerals (pyrite, calcite, dolomite), which emit a gas phase during thermal transformations. The additives of the fourth group IV contained a gelling component (cullet).

Raw materials were crushed to a specific surface area of 400 – 450 m$^2$/kg and mixed with liquid glass. To obtain concrete aggregate, granules with a diameter of 10 – 15 mm were formed and fired at the bloating temperature. Concrete mixtures were prepared by introducing a porous aggregate into a liquid-glass composition of a nominal mix. To accelerate hardening, concrete was subjected to heat treatment at temperatures of 100 – 300°C. Thermal transformations in the raw material mass were evaluated by nature of a porous structure and density of materials. Microstructure of materials was investigated using JSM-649OLV Energy scanning electron microscope. The swelling coefficient was determined as the ratio of sizes of the samples before and after firing.

3. Results and discussion

3.1 Liquid glass is porous filler’s basis

Numerous developments of recent years are devoted to the problems of porous concrete aggregates. A new generation of aggregates has been created: highly porous silicate nitrate granules [10 – 15]; foam glass ceramic multifunctional materials [16, 17]. Porization is a defining stage of lightweight concrete aggregate technology. For implementation of thermal swelling of a granular material the gas-forming processes in the raw material mass are used [17 – 20]. For porous granular materials of pyroplastic synthesis, resource-saving technologies using technogenic raw materials are preferable [13 – 15].

Wide distribution of porous granular aggregates in construction is hindered by the following problems: the need for high-temperature technological processes; low efficiency of materials porosity’s techniques. Highly porous materials based on expanded liquid glass are characterized by low water resistance and fragility [10].

Raw materials with molding properties and swelling ability are required to obtain a porous granular material.

Compositions consisting of liquid glass with additives of various compositions were studied. Concentration of additives in liquid glass is from 10 to 90%.

The effect of filler is manifested at preparation stage of the composition. With an increase in the content of a powder component, viscosity of the liquid glass composition increases (table 1). With the same content of fillers, the largest increase in viscosity of compositions is provided by additives of the first and second groups, which reduce the effect of adsorption water in liquid glass. Compositions with 60 – 70% of the filler acquire plasticity and are easily molded into granules.

| Type of additives | Structural strength of liquid glass composition, KPa, when the content of additives,% |
|------------------|------------------------------------------------------------------------------------------|
|                  | 10  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  |
| Group I          | 12  | 17  | 32  | 78  | 162 | 192 | 210 | 251 | 270 |
| Group II         | 10  | 15  | 30  | 82  | 157 | 207 | 218 | 232 | 252 |
| Group III        | 5   | 10  | 15  | 32  | 65  | 85  | 127 | 145 | 160 |
| Group IV         | 7   | 12  | 21  | 52  | 74  | 94  | 145 | 203 | 215 |
Samples were fired at temperatures of 450, 650 and 850°C (Figure 1). Compositions with high content of liquid glass are characterized by enlargement and rupture of cells. Destructive processes are caused by excessive vapor pressure arising from thermal transformations of liquid glass. With increase in the filler, swelling of compositions decreases at a temperature of 450°C (Figure 1). Presence of fourth group’s filler provides the greatest increase in the volume of a composition. Additives of the third group reduce porous ability of compositions and cause shrinkage of samples with high filler content.

Presence of 40 – 50% filler in compositions fired at a temperature of 650°C ensures stability of the porous structure. Additives perform a carcass-forming function in the composition. Different intensities of compositions’ swelling are due to the nature of thermal activity of the fillers. The highest coefficient of swelling is provided by fillers that emit a gas phase (third group) and have gelling effect (fourth group).

Compositions with low filler content (0 – 40%) melt at a temperature of 850°C. Structural changes in compositions with filler content of more than 45% are due to thermal activity of the additives. With increasing temperature, filler’s reactivity increases and possibilities of neoplasm’s synthesis expand due to the interaction of components. Additives of the fourth group form a pyroplastic mass, which is richly saturated with the gas phase during dehydration of liquid glass.

Thermal porization of liquid glass compositions is achieved in two ways: expansion of liquid glass; thermal transformations of fillers. The nature of porosity depends on filler’s composition. Additives of the first group form irregular pores, which are located mainly in the periphery of the granules. Additives of the second group provide formation of a small number of cells evenly distributed in the volume of the granule. The introduction of additives of the third group is accompanied by an increase in pore size. Additives of the fourth group increase granules’ swelling.

Figure 1. The effect of fillers on swelling of a liquid glass composition at various temperatures.
The greatest porization ability is characterized by liquid glass compositions with limited filler content. However, the molding properties of compositions are unsatisfactory.

To improve properties of molding material and penetrating ability, the combined fillers were introduced into the liquid glass compositions. Expediency of combining a filler of the fourth group, which provides a high degree of swelling, with additives that increase viscosity of the molding mixtures and contribute to additional porosity is shown. Analysis of the properties of various compositions revealed the preference of ternary fillers (table 2).

### Table 2. Effect of combined additives on swelling of the glass mass.

| Composition of a filler, % | Coefficient of swelling at the following firing temperature |
|---------------------------|----------------------------------------------------------|
|                           | 800°C | 850°C | 900°C |
| group I                   | 50    | 1.7   | 2.0   | 2.5   |
| group II                  | 50    | 1.7   | 1.9   | 2.3   |
| group III                 | 50    | 1.2   | 1.4   | 1.5   |
| group IV                  | 50    | 1.8   | 2.2   | 2.4   |
|                           | 25    | 2.0   | 2.5   | 2.6   |

The multicomponent composition of the filler provided an increase in porosity of compositions, and contributed to a decrease in the swelling temperature by 25 – 30°C. An increase in the coefficient of swelling was achieved due to phased participation of the components of the raw material mixture in formation of pores: foaming of liquid glass, burning out of organic substances, saturation of the softened mass with gaseous decomposition products of mineral additives and intermediate formations (Figure 2).

![Figure 2](image2.png)

**Figure 2.** Structure of granules from liquid-glass compositions with the various fillers: 1 – groups (I + IV); 2 – groups (I + III + IV); 3 – groups (II + III + IV).

The use of a multicomponent filler promotes the formation of additional pores in the silicate mass. Along with the main cells, the structure of calcined materials is saturated with small pores in the partitions between the cells (Figure 3).

![Figure 3](image3.png)

**Figure 3.** Microstructure of granules from liquid-glass compositions with the various fillers: 1 – groups (I + IV); 2 – groups (I + III + IV); 3 – groups (II + III + IV).
When comparing material costs for production of various porous aggregates, it was found that the costs of synthesizing a porous aggregate from liquid glass compositions are 30% higher than the costs for producing expanded clay aggregate, a traditional lightweight concrete aggregate. The effectiveness of liquid glass granules is determined by improved thermal performance. It is calculated that in order to provide a thermal resistance of 3.279 \((m^2\cdot{°C})/W\), the thermal insulation layer of liquid glass granules (thermal conductivity coefficient 0.06 W/m\cdot{°C}) should be 19.7 cm, and the expanded clay layer (thermal conductivity coefficient 0.09 W/m\cdot{°C}) – 36.1 cm.

3.2 Liquid glass is a matrix of porous concrete

Porous aggregate based on liquid glass compositions is the basis of lightweight concrete structure. Grain aggregates are connected by a matrix: its composition and structure affect the properties of lightweight concrete. The preference of a liquid glass binder as a matrix for the synthesized porous filler is substantiated: high binder ability of liquid glass; ability to control rheological properties of the concrete mixture; reliability of adhesion to grains of the aggregate having a related origin.

Molding mixtures from synthesized granules and a liquid-glass binding agent were investigated, which included liquid glass and additives of various groups (Section 3.1). Liquid glass compositions containing 40 – 45% of additives of the first and second groups are evenly distributed between the aggregate and provide necessary viscosity of the molding material.

Binding compositions with fillers of the second group form thin shells around the porous particles. This minimizes matrix’s content in the structure of lightweight concrete. With the ratio of “1: 2.0 – 1: 2.5” between the binder and the aggregate, a structure of large-pores concrete with contact monolithic granulation is formed (Figure 4).

**Figure 4.** Contact monolithic granules with a dense matrix (1) and a porous matrix (2).

The possibility of hydromechanical activation of liquid-glass compositions was revealed, which makes it possible to control rheological properties and hardening of the molding material (Figure 5).

**Figure 5.** Microstructure of the liquid matrix.
Binder compositions with additives of the fourth group, when a foaming agent is introduced, form a cellular structure, which serves as a matrix in lightweight concrete with a ratio of “1: 1.0 – 1: 1.3” between the binder and the aggregate. The preference for synthetic foaming agents for liquid glass is due to the anionic or nonionic type of substances. Such foaming agents are most effective in the range of pH = 7.0 – 10.5.

Binder compositions with 30 – 35% of additives of the first, second and third groups swell at a temperature of 200 – 300°C. Thermal swelling of the matrix allows you to get lightweight concrete with a stable porous structure with a ratio of “1: 1.5 – 1: 2.0” between the binder and aggregate (Figure 4).

3.3 Concrete of a variatropic structure

Variatropic lightweight concrete has directional heterogeneity and is characterized by variable values of density and strength over the cross section of the product. The products achieve a smooth transition from structural properties to thermal insulation properties [8].

The combination of lightweight concrete layers of different composition allows obtaining products with variable porosity. Variety of liquid glass compositions, provided by change in the composition and amount of fillers, allows you to accept various options of a variatropic structure (table 3).

| Concrete type                                      | Variotropic concrete layers |
|---------------------------------------------------|-----------------------------|
|                                                    | outer | central |
| No-fine lightweight concrete                       | +     |          |
| Lightweight concrete on porous aggregate with a dense matrix structure | +     |          |
| Lightweight concrete on porous aggregate with porous matrix structure |          | +        |
| Fine-grained lightweight concrete with a dense matrix structure | +     |          |
| Fine-grained lightweight concrete with a porous matrix structure |          | +        |

For example, lightweight concrete of variable structure includes a central layer of large-pores concrete with a density of 350 – 400 kg/m³. The outer layers of concrete are formed by fine-grained concrete with a density of 1000 – 1500 kg/m³ (table 4).

| Fine-grained lightweight concrete with a porous matrix structure | Coarse-grained lightweight concrete | Variotropic concrete |
|---------------------------------------------------------------|-----------------------------------|----------------------|
| Density, kg/m³                                               | 1300                              | 365                  |
| Strength, MPa                                                | 18                                | 5                    |
| 20 mm                                                        | 200                               | 10                   |
Variatrop concrete structure: central layer 50 – 80%; outer layers of 10 – 25%.

Structural characteristics of various compositions make it possible to regulate the structure of variatropic concrete and determine thermo technical and physic and mechanical properties of lightweight concrete. Porous granules distributed in the expanded matrix and form a cellular-granular structure. Porous granules bonded at the contact points by a liquid-glass composition form a large-pore granular structure.

4. Conclusions
High sensitivity of liquid glass to the material composition of fillers and thermal effects determines the multifunctionality of liquid glass compositions.

The purposeful choice of fillers allows you to adjust the viscosity and plastic properties of liquid glass and determines the nature of thermal swelling of compositions. Multicomponent composition of the fillers provides combination of various mechanisms of material porosity and stimulates low-temperature swelling of liquid-glass compositions.

The use of a liquid-glass matrix in lightweight concrete guarantees strong adhesion of expanded granules and possibility of intergranular space porosity.

Variatropic concrete takes advantage of liquid glass compositions of various densities to create effective heat-insulating materials.

References
[1] Mészárosová L and Drochytka R 2014 Adv. Mater. Research 897 117 – 120
[2] Radayev S, Seleznynova O, Ilyukhin K, Ivanov K and Forosevich N 2016 Mater. Scien. Forum 871 90 – 95
[3] Vinai R and Soutsos M 2019 Cem. Concr. Res. 116 45 – 56
[4] Oikawa K, Toyota K, Sakatani S, Hayashi Ya and Takizawa H 2019 Ceram. Int. 45 4201 – 07
[5] Hesky D, Aneziris C G, Gro U and Horn A 2015 Ceram. Int. 41 12604 – 13
[6] Coppola L, Coffetti D and Crott E 2018 Constr. Build. Mater. 173 111 – 117
[7] Miryuk O 2019 E3S Web Conf. 97 02025
[8] Lam T V, Vu D T, Dien V K, Bulgakov B I and Korol E A 2018 Magaz. Civil Eng. 84 173 – 191
[9] Raj A, Sathyan D and Mini K M 2019 Constr. Build. Mater. 221 787 – 799
[10] Mizuryaev S A, Chiknovorian A G, Solopova G S and Demidov R V 2016 Procedia Eng. 153 599 – 603
[11] Rashad A M 2015 Constr. Build. Mater. 93 1236 – 48
[12] Skoczylas K and Rucińska T 2018 Cement Wapno Beton 3 206 – 2015
[13] Tkach E and Rakhimov A 2018 IOP Conf. Ser.: Mater. Sc. Eng. 365 032014
[14] Zaetang Y, Wongsa A, Sata V and Chindaprasirt P 2013 Constr. Build. Mater. 48 585 – 591
[15] Liu Y, Shi C, Zhang Z and Li N 2019 Resour., Conser. Recyc. 144 297 – 309
[16] Xuan D, Tang P and Poon C S 2019 Cem. Concr. Comp. 95 128 – 136
[17] Badaniou A I, Taha H, Saadi A A, Stoleriu S and Voicu G 2015 Constr. Build. Mater. 84 284 – 293
[18] Guardia C, Barluenga G, Palomar I and Diarce G 2019 Constr. Build. Mater. 221 586 – 594
[19] Navarro R, Alcocel E G, Sánchez I, Garcés P and Zornoza E 2018 Constr. Build. Mater. 186 79 – 89
[20] Bumanis G, Novais R M, Carvalheiras J, Bajare D and Labrincha J A 2019 Appl. Clay Sci. 179 105147