Lightweight concrete based on crushed foam glass aggregate

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Abstract. Increased requirements for energy saving in the operation of buildings and structures, as well as the need to adjust the raw material base, presupposes the development and improvement of lightweight concrete technologies, including the use of effective lightweight aggregates, which include granulated foam glass. The goal of the study was to develop a method for selecting the composition of lightweight concrete with foam glass gravel as a large aggregate and foam glass powder as a fine aggregate. To achieve this goal, an experiment was carried out to optimize the composition of lightweight concrete and determine the optimal proportions of the used fractions of foam glass gravel. The raw mix for producing lightweight concrete included the following components: Portland cement, foam glass gravel (mixture of fractions), glass powder (crushed foam glass gravel of 0.315 mm in size), soda glass, super plasticizing admixture, air-entraining agent and water. As a result of the implementation of the experiment and the use of the apparatus for mathematical planning, processing and optimization of the data obtained, the optimal costs of main components were established, as well as the proportions of the content of coarse aggregate fractions.

1. Introduction
For decades, lightweight concrete has been positioned as a material that allows the manufacture of products that have the necessary bearing capacity and a relatively low density and thermal conductivity. This makes it possible to erect load-bearing or self-supporting building envelopes without the use of additional thermal insulation, which has a positive effect both on the durability of such structures and the parameters of energy saving and thermal comfort, and on reducing labor costs during construction and heat losses during operation [1-3].

Lightweight concrete is used in monolithic construction or as masonry blocks in two main groups: cellular concrete (foam and aerated concrete), lightweight aggregate concrete, as well as expanded polystyrene concretes [4–6]. Traditionally, expanded clay gravel and, in much smaller volumes, agglomerite and perlite gravel are used as lightweight aggregates. As a fine aggregate, crushed expanded clay or agglomerite is used, and expanded perlite sand or mineral granules, as well as expanded polystyrene granules [7–9].

The increased requirements for energy saving during the operation of buildings and structures, as well as the need to expand the raw material base, makes it expedient to use foam glass as a light aggregate for concrete [10–12]. Foam glass is a rigid cellular material that is obtained by high-

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temperature foaming of softened glass. The composition of the glass mixture is determined by the requirements for the final product. Mainly, modified aluminum silicate compositions are used; it is also possible to use cullet of packing or sheet glass [13–15].

According to the purpose, materials and products made of foam glass are divided into heat-insulating, sound-insulating and sound-absorbing (to protect against noise and create conditions for acoustic comfort in buildings), as well as into tailored materials (protection against electromagnetic waves, road construction, waterproofing systems, for small architectural forms, etc.). According to their shape, they are subdivided into blocks (Figure 1b), slabs, shaped articles, crushed stone (gravel) (Fig. 1a), as well as granular and microgranular foam glass. Foam glass is characterized not only by high strength and excellent thermal insulation properties, but also by complete environmental and hygienic safety.

![Figure 1. Foam glass gravel dispersed into fractions (a), and a block of foam glass (b).](image)

Foam glass gravel is a loose foam glass in the form of particles and pieces of irregular shape (Figure 1a). Features of the technology for the production of gravel on specialized production lines are in the correct selection of the mixture composition and determination of the optimal firing temperature. The mixture for producing foam glass gravel consists of finely ground glass (glass powder), a foaming agent and water. Unlike foam glass slabs, where soot or coke is used as a foaming agent, food glycerin is used in the technology of foam glass gravel. The fundamental difference in the production of slabs in comparison with gravel is that after production the slab requires additional annealing in a furnace with a gradual decrease in temperature for 10-12 hours, as well as trimming to give the slab the correct shape. The foam glass gravel leaves the smelting furnace already in the form of a finished product.

Foam glass gravel is used as backfill for winterizing the foundations of buildings, brick walls with well masonry, blind area and flat roofs. This article considers a new area of its application — as an aggregate for lightweight concrete.

2. **Experimental conditions**

The goal of the study, the results of which are presented in the paper, was to develop a method for selecting the composition of lightweight concrete with foam glass gravel as a large aggregate and foam glass powder as a fine aggregate. To achieve this goal, an experiment was carried out to optimize the composition of lightweight concrete and determine the optimal proportions of the used fractions of foam glass gravel.

Other The raw mix for producing lightweight concrete included the following components: Portland cement, foam glass gravel (mixture of fractions), glass powder (crushed foam glass gravel of 0.315 mm in size), soda glass, superplasticizing admixture, air-entraining agent and water.

During the experiment, the methods of mathematical planning and processing of results were used [16, 17]. The following parameters were taken as variable factors in the experiment: consumption of Portland cement ($X_1$), consumption of foam glass gravel ($X_2$) and consumption of glass powder ($X_3$).
The compressive strength of the samples ($Y_1$) was taken as a response function and optimization parameter. In parallel, the thermal conductivity of the resulting products and their average density were monitored. See table 1 for experimental conditions.

**Table 1.** Experimental conditions.

| Factor name                                | Symbol $X_i$ | Average factor value, $\bar{X}_i$ | Variation interval, $\Delta X_i$ | Factor values at levels |
|--------------------------------------------|--------------|-----------------------------------|---------------------------------|-------------------------|
| Portland cement consumption, [%]           | $X_1$        | 28                                | 4                               | 24/32                   |
| Foam glass gravel consumption,             | $X_2$        | 26                                | 3                               | 23/29                   |
| Glass powder consumption, [%]              | $X_3$        | 20                                | 4                               | 16/24                   |

**Figure 2.** Test of samples: a, b – general view of samples; c – determination of the thermal conductivity coefficient.

Concrete production was carried out in the following sequence: First, the dry components were dosed according to the composition of the mixture. Then foam glass gravel of three fractions was poured into a paddle mixer of periodic action and stirred for 3 minutes; after that Portland cement was added, stirred for 1-2 minutes; then glass powder was added; stirred for 1-2 minutes; soda glass was added and stirred for 1-2 minutes; water and superplasticizing admixture were added and stirred for 1-2 minutes, and last of all air-entraining agent was added; then the whole mixture was stirred for 5 minutes until a uniform consistency of the raw mixture was achieved.

The molding of standard samples with dimensions of 100×100×100 mm and 250×250×50 mm was carried out with vibration compaction of the mixture for 1-2 min. The manufactured samples were placed in a humidity chamber for 28 days. For compression strength test, samples of 100×100×100 mm were used (Figure 2a); For thermal conductivity test, samples of 250×250×50 mm were used (Figure 2b).

The study of the obtained polynomials was carried out by the method of analytical optimization [18, 19]. This method is based on two principles:
obtained mathematical models based on the results of the adequacy check, describe the process with an acceptable degree of probability; equations (polynomials) are functions of several variables to which the rules of mathematical analysis are applicable, including methods for studying functions for extremum in partial derivatives.

3. Results
As a result of carrying out a three-factor experiment, the matrix of which (in coded values of factors) was built according to the D-optimal design for a full quadratic polynomial, processing experimental data and testing statistical hypotheses, the following regression equation was obtained:

\[ Y_1 = 8.9 + 0.6X_1 + 0.4X_2 + 0.3X_3 + 0.2X_1X_3 - 0.3X_2^2 \]  

(1)

The equation includes significant coefficients only; coefficients smaller than the confidence interval \( \Delta b = 0.14 \) MPa were omitted (equal to zero), and the F-criterion turned out to be equal to 0.96, which is quite consistent with the result forecasting accuracy adopted in solving tasks of building materials technology.

\[ \frac{\partial Y_1}{\partial X_2} = 0.4 - 0.6X_2 = 0 \rightarrow X_2 = \frac{4}{6} = 0.67 \]

Substitute \( X_2 = 0.67 \) into equations (1):

The result is an optimized equation:

\[ Y_1 = 9.1 + 0.6X_1 - 0.3X_3 + 0.2X_1X_3 \]  

(2)

4. Discussion
By the magnitude and sign of the coefficients for variable factors, one can judge the strength and influence of each factor on the response function, that is, on the result of the experiment.

Figure 3. Graphical interpretation of the relationship \( Y_1 = 9.1 + 0.6X_1 - 0.3X_3 + 0.2X_1X_3 \) at \( X_2 = 0.67 \) (or in natural terms with a foam glass gravel content of 27±1%). Compressive strength, MPa: 1 – 9.6; 2 – 9.4; 3 – 9.2; 4 – 9.0; 5 – 8.8.

According to the graphical interpretation of equation (2), a nomogram was obtained, which makes it possible to select the preliminary values of the Portland cement and glass powder consumption to manufacture products of a given strength (Fig. 3). To clarify and verify the calculated data, a full-scale experiment is required.
An increase in the consumption of all variable factors in the intervals stipulated by the experimental conditions leads to an increase in the compression strength of lightweight concrete samples. The greatest influence on the strength is exerted by the Portland cement consumption (coefficient at $X_1$, equal to 0.6).

Analysis of the influence of foam glass gravel consumption shows that at average values of consumption, the strength of the samples increases, but at high consumption, a tendency to decrease in strength appears (coefficients at $X_2$ and $X_{22}$ equal to 0.4 and $-0.3$, respectively). The carried out analytical optimization for this factor made it possible to establish the calculated intervals of the optimal consumption of coarse aggregate in the range of 26-27%.

When implementing and analyzing the results of the experiment, the expediency of fractionation of foam glass gravel was established. To obtain the maximum strength of lightweight concrete, it is rational to use a mixture of fractions of 5-10 mm, 10-20 mm and 20-40 mm of foam glass gravel with a density of 150-180 kg/m³ as a coarse aggregate in a ratio of 30:30:40%.

Attention should also be paid to the increase in strength as a result of the combined effect of the Portland cement and finely ground glass consumption (the coefficient for pair interaction $X_1X_3$ equal to 0.2). This can be explained by the activation of silicates and aluminates contained in finely ground glass when interacting with minerals of Portland cement clinker. Therefore, glass powder obtained by crushing foam glass gravel with a density of 700 kg/m³ is recommended to be ground to a particle size of 0.315 mm or less.

The gel formed as a result of the alkali-silicate reaction is distributed in the pores of the foam glass gravel and therefore does not lead to the destruction of concrete. Moreover, the amount and rate of gel formation depend on a number of factors: temperature, humidity and permeability of concrete, its operating conditions, etc. For this reason, the conditions for the formation of an expanding gel in foam glass concrete as a result of the interaction of silica aggregate with free calcium hydroxide and cement alcalis require separate studies.

In the course of the experiment, it was found that the thermal conductivity of lightweight concrete of the average density grade D700 depends, first of all, on the correct selection of the fractional composition of the coarse aggregate.

As a result of the implementation of the methodology for selecting the main components and carrying out corrective mixes, the composition of lightweight concrete was obtained with the following percentage: Portland cement — 24-30%; foam glass gravel — 26-27%; glass powder — 16-23%; liquid glass — 0.5-0.6%; superplasticizer — 0.05%; water — 21-26%.

The average density of the samples of the obtained foam glass concrete was 700 kg/m³; dry heat conductivity — 0.13-0.15 W (m·K); compressive strength — 8.1-9.6 MPa. The analogue of comparison, cellular concrete with a similar average density, has a compressive strength of 3-4 MPa and a dry thermal conductivity of 0.18 W (m·K).

5. Summary
Lightweight concrete based on foam glass gravel using finely ground foamed glass in its properties fully meets the requirements for heat-insulating and structural lightweight concrete. To obtain the maximum strength and minimum thermal conductivity of concrete with an average density of D700, it is rational to use a mixture of foam glass gravel fractions 5-10 mm, 10-20 mm and 20-40 mm as a coarse aggregate in a ratio of 30:30:40%.

The synergistic effect of the combined action of the Portland cement and finely ground glass consumption on an increase in the strength of foam glass concrete can be explained by the activation of silicates and aluminates contained in finely ground glass when interacting with minerals of Portland cement clinker.

In the course of the experiment, the method was tested for designing the composition of lightweight concrete containing the following components: Portland cement, foam glass gravel, glass powder, liquid glass, superplasticizing admixture, air-entraining agent, and water. Strength and thermal
characteristics of the obtained lightweight concrete are 1.2–2.7 times higher than those of equivalent - cellular concrete of the same average density.

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