Lightweight concrete based on foam glass gravel: composition, structure and properties

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Abstract. The article discusses the research results, the purpose of which is to provide the possibility of increasing the physical and mechanical as well as heat-shielding properties of lightweight cement concrete based on foam-glass gravel. The authors also investigated the possibility of reducing the alkali-silica reaction occurring in such concretes. To evaluate the course of the alkali-silica reaction, a method is used based on the study of the microstructure of lightweight concrete samples. The article also assesses the physical and mechanical as well as thermal engineering properties of lightweight concrete based on foam-glass gravel. The determination of properties is carried out according to standard methods. Analysis of the microstructure lightweight concrete samples allowed to fix flowing alkali-silica reaction. To reduce the alkali-silicate interaction, the authors propose introducing into the concrete composition a complex additive consisting of a siliceous modifier and a plasticizing component. The developed compositions of lightweight concrete, belonging to the class of structural and thermal insulation, have a compressive strength of 6.84-9.05 MPa, a density mark grade of D500-D1500 and a thermal conductivity of 0.218-0.282 W/(m·°C).

Keywords: foam glass gravel, lightweight concrete, high-active metakaolin, porous aggregate, compressive strength, thermal conductivity, alkali-silica reaction.

1. Introduction

One of the main criteria in assessing the energy efficiency of building materials is their ability to have required physical and mechanical as well as heat-engineering properties. Such materials must have high thermal resistance, sufficient mechanical strength, resistance to aggressive environments, and be non-toxic and non-combustible. The market and research data show that lightweight concrete with porous aggregates has the most effective properties for the construction of buildings and structures [1–5]. A promising direction in improving the reliability and durability of lightweight concrete is the use of foam-glass gravel in their composition, which allows for improving their heat-insulating and strength properties [3, 6].

The research results cited in [7] indicate that foam glass produced in the form of granules and gravels has a bulk density of 150-350 kg/m³, thermal conductivity of 0.045-0.1 W/(m·K) and a strength of at least 0.5 MPa. The use of foam glass as an aggregate makes it possible to obtain heat-insulating and structural-heat-insulating lightweight concretes with an average density of up to 500 kg/m³ and 500-1500 kg/m³, respectively.

However, when using foamed glass gravels in cement binder composites, one should take into account the fact that the aggregates contain a large amount of amorphous silica. As a result of the interaction of amorphous silica with cement alkalis during long-term operation an alkali silica hydrogel is formed in the structure of FGG-concrete. The consequence of this interaction is the expansion of concrete as well as a decrease in its strength and durability. The described mechanism relates to the occurrence of alkali-silica reaction (ASR), which is a known problem that has been dealt with in many studies [8–16].

One of the effective ways to reduce the likelihood of ASR is adding high-volatile reactive additives to the concrete composition, which includes metakaolin. Metakaolin reacts with calcium hydroxide formed during hardening of cement. As a result, the number of new growths in the concrete body increases helping to reduce the formation of an alkali silica hydrogel. It is also known that metakaolin improves the structure of concrete, increases its physical and mechanical properties as well as thermal engineering properties [17, 18].
The aims of this work are to study the properties and possibilities of using foam-glass gravel in lightweight concrete, determination of alkali silica interaction in lightweight concrete based on foam-glass gravel in the study of the microstructure of samples as well as study of the possibility of improving the physical and mechanical as well as heat-engineering properties of FGG-concrete by introducing a complex siliceous additive into its composition.

2. Materials and Methods
The study used the following materials: foam-glass gravel fractions 5-10 and 10-20 mm, having a bulk density of 200-250 kg/m$^3$ and compressive strength in the cylinder of 0.5-1.0 MPa; silica sand with a bulk density of 1485 kg/m$^3$ and particle size modulus $M_k = 1.96$; portland cement with a compressive strength of 28 days at least 32.5 MPa; silica modifier – high-active metakaolin (HAM) with a specific surface area of 12630 cm$^2$/g; water-reducing component - S-3 plasticizer (S-3).

To select the composition of the concrete mixture, the apparatus of mathematical planning of the experiment was used. Since the foam-glass gravel has a porous structure, the preparation of the concrete mixture was carried out in the following sequence: initially, the foam-glass gravel was mixed with 2/3 of the volume of water, kept for 5 minutes, and then mixed with a previously prepared dry mixture of sand and cement. At the last stage, the remainder of the calculated amount of water was introduced into the resulting mixture.

Determination of compressive strength and average density of FGG-concrete samples was carried out according to standard methods at the age of 28 days.

The microstructure of FFG-concrete samples was studied using a HITACHI S-3400 N high-resolution scanning electron microscope.

3. Results and Discussion.
From the analysis of published data [3], it follows that when glassy porous aggregates are used in lightweight concrete, cement consumption for concrete grades in density mark D500–D1500 is 280–300 kg/m$^3$. In this case, the optimal water-cement (W/C) ratio is in the range of 0.4-0.6.

Another important characteristic when selecting the composition of FGG-concrete is the ratio of small (5–10 mm) and large (10–20 mm) aggregate fractions. It was shown in [3] that for various ratios of coarse and fine fractions of the foam-glass gravel and depending on the value of the W/C ratio, the content of cement paste in the concrete mix can be from 14 to 25%. Moreover, a decrease in the content of the coarse aggregate fraction entails an increase in the volumetric content of the cement paste. Thus, to ensure a more favorable consumption of cement and aggregate in the study, a mixture of two fractions (5-10 and 10-20 mm) of foam glass gravel in a ratio of 60/40 respectively, was used.

The content of quartz sand and foamed glass gravels (S/FGG) was taken in the following ratios: 80/20, 60/40, 40/60.

After testing, regression equations were obtained for the average density response function ($y_\rho$) and compressive strength ($y_R$) respectively:

$$y_\rho = -238.88x_1 - 13.67x_2 - 11.75x_1^2 - 115.25x_2^2 - 193.25x_1x_2 (1)$$

$$y_R = 7.06 - 2.57x_1 - 0.71x_2 - 0.17x_1^2 - 0.33x_2^2 + 0.75x_1x_2 (2)$$

The response surfaces describing the changes of FGG-concrete properties depending on the W/C and S/FGG are shown in Figure 1.
Figure 1. The response functions of the average density (a) and compressive strength (b) of FGG-concrete from the water-cement ratio and the content of foamed glass gravel in the ratio S / FGG.

When analyzing the data in Figure 1, it was found that the greatest compressive strength is achieved with a W/C of 0.4-0.5 and a content of FGG from 20 to 40%, while the average density of FGG concrete does not exceed 1500 kg/m³. The compressive strength varies inversely with the W/C value. It can be explained by the fact that the increased W/C results in the increased porosity of the cement matrix, leading to a decrease in strength of the composite.

The results of the physical and mechanical as well as heat-engineering properties of FGG-concrete are shown in Table 1.
Table 1. Physical and mechanical as well as heat-engineering properties of FGG-concrete.

| W/C | S/FGG | Compressive Strength, MPa | Thermal Conductivity, W/(m·°K) | Average Density, kg/m³ |
|-----|-------|---------------------------|-------------------------------|-----------------------|
| 0.4 | 80/20 | 10.93                     | 0.272                         | 1230                  |
| 0.4 | 60/40 | 6.53                      | 0.254                         | 992                   |
| 0.4 | 40/60 | 4.52                      | 0.263                         | 1120                  |
| 0.5 | 80/20 | 9.66                      | 0.375                         | 1480                  |
| 0.5 | 60/40 | 7.08                      | 0.267                         | 1190                  |
| 0.5 | 40/60 | 4.04                      | 0.258                         | 1040                  |
| 0.6 | 80/20 | 6.84                      | 0.324                         | 1321                  |
| 0.6 | 60/40 | 7.14                      | 0.324                         | 1411                  |
| 0.6 | 40/60 | 3.74                      | 0.207                         | 528                   |

The Table 1 and Figure 1 show that – at the same values of the water-cement ratio – the compressive strength of FGG-concrete decreases with an increase in the content of FGG in its composition.

The thermal conductivity of FGG-concrete according to Table 1 varies from 0.207 to 0.375 W/m·K. The lowest thermal conductivity is achieved at W/C = 0.6 and a FGG content of 60%. The amount of porous aggregate in the structure of the material significantly affects the value of thermal conductivity: the higher the content of FGG in the composition of concrete, the lower the value of thermal conductivity is, which is fully confirmed by the test results.

Thus, the composition of FGG-concrete with a foam-glass gravel content of 20-40% and a water-cement ratio of 0.4 to 0.5 is optimal and most effective. This composition provides the best combination of physical and mechanical as well as heat-engineering properties. Microstructures of FGG-concrete of this composition are shown in Figure 2.

![Figure 2](image-url)

**Figure 2.** Microstructure of FGG-concrete: (a) – same, with FGG fractions of 10–20 mm, magnification ×500; (b) – the boundary of the cement-sand mortar with FGG fractions of 5-10 mm, magnification ×500; (c) – same, with FGG fractions of 5-10 mm, magnification ×3000.

Figure 2 shows that the structure of FGG-concrete is loose, there are amorphous inclusions of calcium hydrosilicates in it (Figure 2a, pos. 1, 2), which indicates the completeness of cement hydration reaction. Flat or prismatic crystalline formations of calcium hydroxide (Figure 2b, pos. 4, 5) are observed only in cement-sand mortar. The absence of such formations at the "aggregate-cement stone" phase boundary is explained by the interaction of calcium hydroxide with amorphous aggregate silica. The result of this reaction is needle-shaped neoplasms (Figure 2a, b, c, pos. 3, 6-9), which indicates the occurrence of alkaline-silica interaction in FGG-concrete [8, 19].

In order to exclude the occurrence of ASR, the composition of the FGG-concrete was modified with a complex silica admixture consisting of highly active metakaolin (HAM) and water-reducing plasticizer S-3 (S-3). The content of the HAM was 5, 10 and 15%, replacing the corresponding amount of cement. The plasticizer dosage for all samples with a complex additive was 0.5% by weight of cement. The microstructure of the modified FGG-concrete with an indication of the interface between the aggregate and cement stone is shown in Figure 3.
Figure 3. The microstructure of modified FGG-concrete at x1000 magnification, containing metakaolin in an amount of 5% (a), 10% (b), 15% (c).

Figure 3 shows that after introducing a complex additive into the composition of FGG-concrete, a significant decrease in acicular neoplasms at the “aggregate-cement stone” phase boundary is observed due to the binding of calcium hydrosilicate plates to metakaolin, which results in a decrease of ASR. At this stage, there is also an improvement in the uniformity of the structure of FGG-concrete in comparison with the unmodified composition.

The effect of the complex additive on the compressive strength, average density and thermal conductivity of FGG-concrete is shown in Figure 4.

Figure 4. Change in the properties of FGG-concrete depending on the content of the complex additive: (a) – compressive strength, MPa; (b) – average density, kg/m³; (c) – thermal conductivity, W/(m·°K).

The data analysis in Figure 4 showed that a complex admixture contributes to an increase in the compressive strength of FGG-concrete compared to the control composition. The best effect is achieved when the complex additive contains 5% metakaolin.

Figure 4 also shows that with a decrease in the average density of FGG-concrete, its thermal conductivity decreases from 0.282 to 0.218 W/(m·°K), depending on the content of the complex additive.

4. Conclusions.
According to the study, the following conclusions:

1. It has been experimentally confirmed that on the basis of FGG it is possible to obtain lightweight concrete with a wide range of properties in terms of density, strength and thermal conductivity. The resulting compositions made it possible to obtain structural and heat-insulating lightweight concrete with a compressive strength of 3.74-10.95 MPa, an average density of 528-1480 kg/m3 and a thermal conductivity of 0.207-0.375 W/(m·K).

2. The analysis of the microstructure of FGG-concrete with an unmodified composition showed that needle-shaped neoplasms are observed at the interface between foam glass gravel and cement stone, which are the result of the interaction of calcium hydroxide with amorphous silica aggregate, resulting in an alkaline silica reaction.

3. The study of the microstructure of modified FGG-concrete revealed a significant decrease in acicular neoplasms at the aggregate-cement stone interface due to the binding of calcium hydroxide plates to metakaolin, which leads to a decrease in the course of the alkaline-silica reaction. At this stage, there is also...
an improvement in the uniformity of the structure of FGG-concrete in comparison with the unmodified composition.

4. The joint use of metakaolin and S-3 plasticizer helps to improve the physical and mechanical as well as heat-engineering quality indicators of FGG-concrete, which can contribute to increasing its effectiveness when used in wall enclosures of buildings and structures for various purposes.

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