Performance of Lightweight Concrete based on Granulated Foamglass

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Abstract. The paper presents an investigation of lightweight concretes properties, based on granulated foamglass (GFG-LWC) aggregates. The application of granulated foamglass (GFG) in concrete might significantly reduce the volume of waste glass and enhance the recycling industry in order to improve environmental performance. The conducted experiments showed high strength and thermal properties for GFG-LWC. However, the use of GFG in concrete is associated with the risk of harmful alkali-silica reactions (ASR). Thus, one of the main aims was to study ASR manifestation in GFG-LWC. It was found that the lightweight concrete based on porous aggregates, and ordinary concrete, have different mechanisms of ASR. In GFG-LWC, microstructural changes, partial destruction of granules, and accumulation of silica hydro-gel in pores were observed. According to the existing methods of analysis of ASR manifestation in concrete, sample expansion was measured, however, this method was found to be not appropriate to indicate ASR in concrete with porous aggregates. Microstructural analysis and testing of the concrete strength are needed to evaluate the damage degree due to ASR. Low-alkali cement and various pozzolanic additives as preventive measures against ASR were chosen. The final composition of the GFG-LWC provides very good characteristics with respect to compressive strength, thermal conductivity and durability. On the whole, the potential for GFG-LWC has been identified.

1. Introduction
Due to the tightening of the requirements for energy efficiency in Russia, the construction industry needs materials which provide not only the necessary load-bearing capacity of structures, but also have low thermal conductivity. The lightweight concrete with porous aggregates might be used for such purposes [1].

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Currently, the technology of waste glass processing into a highly porous granulated inorganic thermal insulation material – granulated foamglass (GFG) – has been actively developing in Russia. GFG can be used as an aggregate for lightweight concretes. It has a uniform distribution of cells, enclosed pores and a pronouncedly rough surface. Lightweight concrete based on GFG is characterized by high physical-mechanical and thermal characteristics [2–4]. Also, the application of GFG in concrete might significantly reduce the volume of waste glass and enhance the recycling industry in order to improve its environmental performance.

Due to the high content of amorphous silica in GFG, there is a necessity for a more thorough investigation of possible harmful alkali-silica reactions (ASR) in lightweight concretes properties, based on granulated foamglass (GFG-LWC). The problem of ASR in concretes has been investigated for many years. Usually, this problem occurs most frequently in the concrete containing heavy and fine reactive aggregates [5, 6]. ASR in lightweight concrete with GFG were also investigated by some scientists [7–9]. Some research results in these studies contradict each other. Currently, there is an absence of a clear understanding regarding the safety of GFG performance in cement composites, causing the need for studying ASR in GFG-LWC more comprehensively. Thus, the main aim was to study ASR manifestation in GFG-LWC.

2. Materials and methods
The following materials were used in the investigation at hand: GFG "Neoporm" from company "STES-Vladimir" (Russia), cement CEM 42.5 and CEM 42.5 NA (low alkali) from company Schwenk (Germany), fly ash from company Powerment (Germany) and microsilica from company Elkem (Norway). The chemical compositions of the materials are given in table 1.

| Material          | CaO   | SiO₂  | Al₂O₃ | SO₃   | Fe₂O₃ | MgO  | Na₂O₉eq | Others |
|-------------------|-------|-------|-------|-------|-------|------|---------|--------|
| Cement CEM I 42.5 | 63.38 | 18.66 | 6.31  | 3.31  | 3.03  | 3.01 | 0.87–1.01 | 1.29–1.43 |
| Cement CEM I 42.5 NA | 63.49 | 19.41 | 6.25  | 2.81  | 3.27  | 3.07 | 0.47–0.62 | 1.08–1.22 |
| GFG               | 9.75  | 68.97 | 1.72  | 0.09  | 0.35  | 3.42 | 13.49   | 0.61   |
| Microsilica       | 0.45  | 97.33 | 0.18  | 0.15  | 0.06  | 0.12 | 0.37    | 1.34   |
| Flyash            | 4.91  | 51.63 | 26.69 | 0.83  | 7.43  | 1.04 | 4.08    | 3.39   |

The compressive strength of GFG-LWC was investigated according to the Russian Government Standard (RGS) 12730. The sample size used was 100x100x100 mm. Thermal conductivity of GFG-LWC was tested according RGS 7076. In this method a stationary heat flow through the concrete sample (directed perpendicular to the front face of the sample) was created and the density of the heat flow as well as the temperature of the opposite face of the sample were measured. The sample size used was 100x100x20 mm. The potential reactivity of GFG to ASR was determined according to RGS 8269, which methods are similar to those of ASTM 1260, i.e. the chemical analysis of GFG and the expansion tests on concrete prisms. Conditions of the experiments are described in the section “Results and Discussion”. The size of the prepared specimens for the expansion tests was 160x40x40 mm. Scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD), X-ray fluorescence spectroscopy (XRF), and inductively coupled plasma atomic emission spectroscopy (ICP-AES) were used for characterizing the morphology, crystallinity and chemical composition of concrete constituents.
3. Results and discussion

Foamglass is a silicate material manufactured by thermoplastic methods. The results of the conducted XRF and XRD analysis show the content of amorphous silica in GFG to be about 70%. According to the RGS 8269, the granules were soaked in 1 M NaOH solution at a temperature of 80 °C for 24 hours. Concentration of silicon ions in the solution after soaking amounted to more than the allowed limit of 50 mmol/l [10]. This means that the GFG likely had a capability of interacting with cement alkalis. Therefore, further experiments on the concrete expansion were required.

Optimum compositions of GFG-LWC were developed. To do this, features and properties of GFG were taken into account, such as physic-mechanical characteristics of GFG depending on its fractional composition, features of cellular structure and the roughness of granules surfaces. GFG-LWC compositions with density of 400 to 800 kg/m³, compressive strength of 2.2 to 6.5 MPa and thermal conductivity of 0.09–0.15 W/(m·K) were obtained. Table 2 shows the final GFG-LWC compositions and their main characteristics.

The density of the samples for concrete expansion tests was 700±50 kg/m³. The experimental conditions of the expansion tests on concrete prisms were as follows: A) in the solution of 1M NaOH at 80 °C for 14 days; B) in a climatic chamber at 40 °C and 100% relative humidity for 12 months. The aggregate is considered as reactive if the extension of concrete samples in tests A and B exceeds the permissible limits 0.1% and 0.04%, respectively.

The experimental results show that the relative expansion of concrete prisms amounted to 0.055% and 0.031% for experiments A and B respectively, thus, the limit values were not exceeded (figure1). According to the conditions of the test, this result indicates the suitability of GFG for use in cement composites.

| Composition | Density, kg/m³ | Compressive strength, MPa | Thermal conductivity, W/m·K |
|-------------|----------------|---------------------------|---------------------------|
| GFG, kg/m³  | Cement, kg/m³  | W/C                       | gth                        | W / mK         |
| 180         | 120            | 0.83                      | 400                        | 2.4            | 0.09        |
| 170         | 200            | 0.65                      | 500                        | 3.6            | 0.11        |
| 160         | 280            | 0.57                      | 600                        | 4.4            | 0.13        |
| 140         | 360            | 0.55                      | 700                        | 4.9            | 0.14        |
| 130         | 440            | 0.52                      | 800                        | 5.5            | 0.15        |

Table 2. Properties of developed GFG-LWC.

Figure 1. The results of expansion test on concrete prisms.
The main part of the amorphous silicon oxide was transformed into a calcium silicate hydrate during the interaction with alkalis of cement. Shrinkage cracks could be seen in the drying samples after the experiment. In turn, the aggregate structure had a similar fracture pattern after passing test B, but the degree of destruction and the amount of silica hydrogel was greatly reduced (figure 2 c, d). Thus, results show that the expansion of samples is not an appropriate factor for evaluating ASR in concrete with reactive porous aggregates. Microstructural analysis and testing of the concrete strength is needed to evaluate the degree of damage due to ASR.

Figure 2. The microstructure of GFG-LWC after: a) storing in the 1M NaOH solution at 80 °C for 14 days; b) storing in a climate chamber at 40 °C and 100% relative humidity for 12 months.

The mechanism of reactive porous aggregate interaction with alkalis of concrete has been proposed on the basis of the obtained results. This mechanism differs from the ASR mechanism in the ordinary concrete, which is described in detail in the literature, see, for example [6]. In ordinary concrete ASR occurs in the interaction zone of aggregate and cement stone, see figure 3 a. Silicic acid salts, covering the surface of the aggregate with a semipermeable coating containing high content of calcium, which
absorbs water, expands in volume and subsequently creates internal stresses in concrete. It leads to cracking in concrete. In contrast to this, in the concrete with porous aggregates, ASR is a microstructural transformation of silica aggregate in the surface layer to the calcium silicate hydrate. Silicic acid salts may accumulate inside the pores of the aggregate without the formation of reaction products at the interaction zone of aggregate and cement stone (figure 3 b). Thus, ASR in the GFG-LWC does not lead to the occurrence of internal osmotic pressure. It contributes only to its partial destruction inside porous aggregate particles.

Thermal conductivity of GFG-LWC did not change due to ARS after the experiment (measured accuracy is 10%). Damage of aggregate grains due to ASR leads to reduction in strength characteristics of the concrete, while the formation of silica hydrogel in the pores of GFG causes an increase in the concrete density. Depending on the concrete composition, the compressive strength decreased by 20 to 30% and the density increased by 2 to 8% in comparison with the reference samples.

Additionally, the effects of some preventive measures against ASR were investigated. Low alkali cement as well as addition of fly ash and microsilica were considered in this respect. The effectiveness of each measure was evaluated in terms of the difference in relative extension of prisms, reduction in strength and increase in density of samples after passing test B, while the modified material was compared to the control composition of GFG-LWC. The results shown in table 3 demonstrate that the addition of microsilica was the most effective measure.

Figure 3. Scheme of ASR in concrete when using: a) dense aggregates; b) porous aggregates.
Table 3. Effectiveness of measures against ASR circumstances (in percent in comparison with control composition of GFG-LWC).

| Measure against ASR | Decrease in expansions of concrete prisms | Reduction in compressive strength | Increase in density |
|---------------------|------------------------------------------|----------------------------------|---------------------|
| Lowalkalicement     | 38.1                                     | 10.4                             | 1.8                 |
| Fly-Ash             | 32.5                                     | 8.6                              | 0.5                 |
| Microsilica         | 65.1                                     | 32.9                             | 4.9                 |

The obtained data were in agreement with microstructural investigations of the samples after passing the tests. According to the microstructural study, concrete modification by microsilica improved the uniformity of the interaction zone between aggregate and cement stone, reduced the number of shrinkage cracks of the pore walls and decreased the volume of silica hydrogel formed in granule pores.

The final composition of the GFG-LWC, i.e. that modified with microsilica, exhibits a high compressive strength as well as low thermal conductivity and good durability with respect to ASR. The obtained GFG-LWC is suitable for use in energy efficient buildings.

4. Conclusions
The main finding of the investigation at hand can be summarized as follows:

1. GFG has the capability of interacting with cement alkalis.
2. The GFG-LWC samples showed relatively low expansion of concrete prisms as a result of ASR. However, the expansion is not the determining factor for microstructural damage due to ASR when reacting aggregates are porous. In such cases, microstructural analysis and testing of the concrete strength are needed to evaluate the degree of concrete deterioration due to ASR.
3. The interaction mechanism of reactive porous aggregates with alkalis of concrete has been proposed on the basis of the obtained results. ASR does not lead to build-up of internal pressure in the GFG-LWC.
4. The effectiveness of low-alkali cement and use of various pozzolanic additives was tested as preventive measures against ASR. Microsilica revealed the best preventive capacity.
5. The compositions of GFG-LWC with the density of 400 to 800 kg/m$^3$, compressive strength of 2.2 to 6.5 MPa, heat conductivity of 0.09 to 0.15 W/(m·K) were developed for use in construction industry.

5. References
[1] Bazhenov Yu 2002 Technology of Concrete (Moscow: ASV Publ) p 500
[2] Yu Q, Spiesz P and Brouwers H 2013 Development of cement-based lightweight composites – Part 1: Mix design methodology and hardened properties Cem. and Conc. Compos. 44 17–29
[3] Al-Sibahy A and Edwards R 2012 Mechanical and thermal properties of novel lightweight concrete mixtures containing recycled glass and metakaolin Constr. and Build. Materials 31 157–167
[4] Zhang M and Gjirv O 1990 Characteristics of lightweight aggregates for high-strength concrete ACI Mater. J. 88 (2) 150
[5] Moskvin V and Royak F 1962 Corrosion of concrete under the action of cement alkali on aggregate silica Gosstroyizdat p 164
[6] Brykov A 2009 ASR and concrete corrosions *Cement and its Applications* 5 31–37
[7] Limbachiya M, Meddah M and Fotiadou S 2012 Performance of granulated foam glass concrete *Constr. and Build. Mat.* 28 (1) 759–768
[8] Mladenovič A, Šuput J, Ducman V and Škapin A 2004 Alkali-silica reactivity of some frequently used lightweight aggregates *Cem. and Conc. Research* 34 1809–16
[9] Bumanis G, Bajare D, Locs J and Korjakins A 2013 Alkali-silica reactivity of foam glass granules in structure of lightweight concrete *Constr. and Build. Mat.* 47 274–281
[10] GOST 8269-0-1997 Mountainous rock road-metal and gravel, industrial waste products for construction works – methods of physical and mechanical tests