Influence of light aggregate on structure formation of lightweight concrete

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Abstract. Recycling of glass industry waste is relevant in the world today. It is caused by the increase of environmental problems and devastation of natural resources. One of the option of cullet recycling is production of foam ed lightweight glass aggregate. It is energy efficient material with size up to 75 mm, irregular shape and relatively low strength. High specific surface area of aggregate leads to increase the cement consumption to achieve acceptable concrete compaction. This article presents the results of size gradings selection of coarse foamed glass aggregate and its water demand in concrete mix. The determination of structure formation period and water demand of foamed glass aggregate are presented. The influence of particle size distribution of lightweight aggregate on structure formation period of lightweight concrete is established. The density and compressive strength of structural lightweight concrete with foamed lightweight glass aggregate are 1468 kg/m³ and 19 MPa, respectively. The density and strength of insulating lightweight concrete are 1167 kg/m³ and 10 MPa, respectively. The cement consumption of structural and insulating concrete is 260 kg and 254 kg, respectively.

1. Introduction
Concrete is one of the most widely consumed materials in the world. Natural aggregates account for 70-80% of its volume. Extraction of natural aggregates for concrete production is harmful for environment. Recycled aggregates can replace natural aggregates in concrete and meet the technical requirements of construction projects. That is why it can be an economical and sustainable solution for the construction industry. A promising foamed aggregate for lightweight concrete is lightweight glass gravel. In comparison with expanded clay gravel it has higher thermal properties and can be obtained from cullet [1,2].

Glass waste has become a serious environmental problem due to the growing demand for landfills and natural resources. The increased attention to reduction the carbon footprint of the construction industry is also influential. Re-profiling glass waste into building material reduces the consumption of natural resources, minimizes greenhouse gas emissions and reduces the deficit of landfill [3,4].

In recent decades, several studies have been carried out to evaluate and study the potential of use glass waste in production of new concrete. In fact, glass waste can be included in concrete as recycled aggregate to replace natural aggregate (coarse and / or finely divided). It also can be used as powder with partial replacement of Portland cement. The main disadvantage of foamed lightweight glass aggregate is its amorphous nature, which contributes to the development of the alkali-silica reaction (ASR). There is the destructive reaction between alkali of cement and
amorphous reactive silica of glass. Due to a significant loss of strength and excessive expansion the use of glass waste in concrete production is limited [5,6,7,].

When mix design of lightweight concrete is selected, it is necessary to know the water demand and size grading of lightweight glass aggregate. The water demand and size grading of foamed glass aggregate in concrete mixture is poorly understood. Also, the influence of foamed glass aggregate on structure formation of concrete is unknown.

In this research, the water demand of foamed glass aggregate and evaluation of its influence on formation of concrete structure are studied. There are two ways to study the processes of structure formation [8]. The first method is to measure the plastic shear strength of the system by pulling out a rod with a shelf from the test mixture.

The second method is an ultrasonic method for studying the structure formation process of concrete mixtures. The method is based on the preparation of concrete mixture, which is placed in a specially hermetically sealed plastic mold with dimensions of 10x10x7 cm. Every 20 minutes for 10-12 hours, the speed of ultrasound transmission through the concrete mixture was determined using ultrasonic devices. In this way, you can study the kinetics of the formation of the structure of any cement system: cement paste, mortar, concrete mix. Its advantage is that the test is carried out on the same sample without breaking its folding structure [9]. This method is suitable for studying the water demand of foamed lightweight aggregate and structure formation of light concrete as well.

### 2. Materials and Methods

In this research, the following materials were used:

- foamed glass lightweight aggregate with $D_{\text{max}} = 20$ mm. To reduce the content of cement paste and increase the packing density of aggregate, it was decided to use aggregate with $D_{\text{max}} = 2.5-5$ mm to adjust required density of concrete;
- quartz sand with the fineness modulus of 2.1;
- Portland cement CEM II/A-S 42.5N was used as a binder. The main characteristics of materials are shown in Table 1.

To determine the physical and mechanical characteristics, samples of 100 x 100 x 100 mm cubes were used, and molding was performed with cantledge.

| Material            | Bulk density, kg/m$^3$ | Specific gravity, g/cm$^3$ | Compacted bulk density, kg/m$^3$ | Void ratio, % |
|---------------------|------------------------|-----------------------------|----------------------------------|---------------|
| Lightweight aggregate | 280                    | 2165                        | 320                              | 40.3          |
| Quartz sand         | 1510                   | 2650                        | 1 630                            | 39.7          |

The selection of concrete was carried out in accordance to Russian standard 27006-86 and recommendations proposed in scientific sources [10]. According to them, the preparation of concrete mixture with foamed glass lightweight aggregate should be carried out in two stages. At the first stage, it is necessary to obtain dry mixture consisted of cement and sand. The foamed glass lightweight coarse aggregate should be blended with 2/3 mixing water of required dosage and maintained the mixture for 5 minutes. At the second stage, dry mixture components should be mixed with coarse aggregate. Then the remaining water should be added to the concrete mixture.

The flowability of concrete mixture was determined by slump test in accordance to Russian Standard 10181-2014. The regime of concrete mixture compaction was selected which based on previously preliminary test results. It is known that the use of vibration only when compacting concrete mix with porous aggregates is ineffective. There is a segregation of the mixture as the filler floats up and mortar settles to the bottom of the mold [11]. To eliminate segregation the vibrating packing with earth pressure balance machines is applied.
Samples in the forms were stored for 3 days in standard curing conditions. At the age of 3 days, the samples were dismantled and then stored at a temperature of (20±2) °C and relative humidity (95 + 2)%.

The concrete mix compositions with lightweight aggregate are shown in the Table 2.

Table 2. Concrete mix compositions with lightweight aggregate.

| Composition | Cement, kg/m³ | Sand, kg/m³ | Water, kg/m³ | Lightweight aggregate, kg |
|-------------|---------------|-------------|--------------|--------------------------|
| I           | 254           | 509         | 127          | 123                      |
| II          | 260           | 908         | 156          | 87                       |

The water demand of lightweight coarse aggregate was determined with the use of ultrasonic method. The method consists of preparing cement paste with different w/c content with was in range of 0.876 · $C_{sc}$, $C_{sc}$ and 1.65 · $C_{sc}$, where $C_{sc}$ - coefficient is equal to w/c ratio of standard consistence of cement paste [12]. The prepared cement paste with different w/c was placed into plastic form with cell size of 10x10x10 cm. Then the ultrasonic velocity in time with using device PULSAR-2.2 was determined. The time of structure formation is characterized by sharp speed increase of ultrasonic velocity [13] (Figure 1). It has been found that the time of structure formation is characterized by a sharp increase in the temperature of the mixture and it correlates with data above (Figure 2). Figure 3 presented the dependence of the time of structure formation of cement-based materials versus water-cement ratio.

Figure 1. Ultrasonic velocity through cement paste vs time of hardening: 1 - 0.876 · $C_{sc}$; 2 - $C_{sc}$; 3 - 1.65 · $C_{sc}$.
**Figure 2.** Heat release of hardening of cement paste vs time of hardening: 1 - $0.876 \cdot C_{sc}$; 2 - $C_{sc}$; 3 - $1.65 \cdot C_{sc}$.

**Figure 3.** Time of structure formation of cement paste vs water-cement ratio.

The key results of ultrasonic velocity and temperature of concrete mixture while hardening are presented in Figure 4 and 5. Before test, the large fractions of foamed glass were crushed and fractioned to get lightweight aggregate.
Next, the lightweight aggregate was dried up in oven until it reached a constant weight. Afterwards, the concrete mix with absolute aggregate volume of 500 l was prepared and placed in a plastic mold with a cell size 10 cm. The weight of aggregate \((W_A, kg)\) was calculated as:

\[
W_A = 0.5 \cdot \rho_A, \tag{1}
\]

\(\rho_A\) – density of lightweight aggregate.

Every 30 minutes, the ultrasonic velocity was determined and the temperature of the concrete mixture was measured.

The concrete mixture with 1 cm slump was prepared and the water demand of lightweight aggregate was determined. The consumption of materials for one cubic meter is presented in Table 3.

| Table 3. Content of concrete mixture. |
|--------------------------------------|
| Materials                           | Weight of materials for one cubic meter of the concrete mixture, kg |
| CEM II/A-S 42.5N                    | 650                                                      |
| Lightweight aggregate               | 335                                                      |
Water demand of cement paste in concrete was equal to 0.25 which was found according to the described method (Fig. 2):

\[ W_c = (W / C) \cdot C_c, \]  

(2)

\( W / C \) – water/cement ratio in concrete; \( C_c \) - cement consumption, kg.

The water demand of the aggregate \( W_a \) in concrete was calculated according to the obtained water value in cement paste [14]:

\[ W_a = \frac{W - W_c}{W_a} \cdot 100, \]  

(3)

\( W \) – mixing water in concrete, kg; \( W_a \) weight of dried aggregate, kg.

It was determined that the water demand of foamed lightweight glass aggregate is 21.6%.

3. Results

The lightweight concrete with density of 1167 kg/m³ and 1468 kg/m³ with and mark D1200 and D1500 was obtained. The strength of lightweight concrete is presented in Table 3. The structure of obtained concrete with foamed lightweight glass aggregate is presented in Figure 6.

Table 4. Mix proportion and strength of lightweight concrete.

| Composition | Cement, kg/m³ | Quatz sand, kg/m³ | Water, kg/m³ | Lightweight aggregate, kg | Strength, MPa |
|-------------|---------------|-------------------|--------------|--------------------------|---------------|
|             |               |                   |              | 2.5-5                    | 5-20          |
| I           | 254           | 509               | 127          | 123                      | 10,26         |
| II          | 260           | 908               | 156          | 87                       | 57            | 19,06        |

Figure 6. Structure of concrete with foamed lightweight glass aggregate.

4. Conclusions

It is experimentally established that properly selected granulometry of aggregate allows to achieve the necessary formability without cement overdose. It allows to reduce the cost of concrete with lightweight glass aggregate, as well as reduce the consumption of natural resources. The determined
water demand value of aggregate allows selecting correct mix proportion in future. The density and compressive strength of structural lightweight concrete with foamed lightweight glass aggregate are 1468 kg/m$^3$ and 19 MPa, respectively. The density and strength of insulating lightweight concrete are 1167 kg/m$^3$ and 10 MPa, respectively. The cement consumption of structural and insulating concrete is 260 kg and 254 kg, respectively. It was found that the lightweight glass aggregate with fraction 5-10 mm actively affects the structure formation by immobilizing the mixing water.

References
[1] Semeynykh N, Sopegin G and Fedoseev A 2018 Bull. of MGSU 13 203
[2] Mohajerani A, Vajna J, Cheung T, Kurmus H, Arulrajah A and Horpibulsuk S 2017 J. Constr. and Build. Mat. 156 443
[3] Zhang B, He P and Poon C S 2020 J. of Cl. Pr. 255 120
[4] Mohajerani A, Vajna J, Cheung T, Kurmus H, Arulrajah A and Horpibulsuk S 2017 J Constr. and Build. M. 156 443
[5] Zheng K 2016 J Cem. and Concr. Comp. 67 30
[6] Thomas M, Dunster A, Nixon Ph and Blackwell B 2011 J. Cem. and Concr. Comp. 33(3) 359
[7] Du H and Hwee T 2013 J. Cem. and Concr. Comp. 35(1) 118
[8] Bazhenov Y, Gorchakov G, Alimov L and Voronin V 1978 Concrete with specified properties (Moscow: Stroyizdat) p 53
[9] Alimov L, Voronin V and Larsen O 2020 J. Tech. and Tech. of sil. 27 20
[10] Limbachiya M, Meddah M and Fotiadou S 2012 J. Constr. and Build. Mat. 28(1) 759
[11] Sopegin G 2018 Master's Journal 1 104
[12] Popov M 2015 J. Sci. Rev. 16 162
[13] Smoly V, Kosarev A and Yatsenko E 2016 J. Sc. alm. 11(25) 233
[14] Alimov L, Voronin V, Larsen O and Korovskyakov V 2018 J. Adv. in Int. Syst. and Comp. 692 601