A study of the alkali-silica reaction in recycled glass concrete

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Abstract. Recently, it has been paid more and more attention to the concept of sustainable development. One of these technologies is the production of “green concrete”. It can be created by replacing natural concrete aggregate with secondary one. Therefore, white glass cullet was used as a replacement for 30% of coarse and fine aggregates in this study to design “green concrete”. It was designed four concrete mixes for the investigation. Measurement of the fresh concrete mixes’ performance showed that the use of glass aggregates reduces its workability. But it can be increased by using chemical admixtures. The highest strength - 28.94% more than the control sample, was obtained by a sample that contained coarse of glass aggregate and had low water-cement ratio. Sample №3 had lower strength only for 1.62% than sample №1 among mixtures with normal W/c ratio. Исследование фазовых превращений показало

1. Introduction
The concept of sustainable development combines three main areas: economic, environmental and social, which are aimed at the unity of mankind with the environment [1]. One of the important aspects of sustainable development is the development of solid waste processing technologies. The construction industry has the greatest potential for this because of the high resource intensity of production. Therefore, the replacement of natural components with secondary resources in concrete technology is an urgent task. Such technologies are defined as “green” because they use secondary resources and the production process does not lead to environmental destruction [2].

One of the potential secondary resources for concrete production is cullet. It can be used not only as coarse or fine aggregate [3-5], but also as active mineral admixture [6, 7]. But there is a serious problem for the widespread use of glass in concrete is caused by the reaction of alkali in cement with silica from aggregates.

Today, there is a general definition for chemical reactions "silica acid - alkali" that is formulated the American Institute of Concrete as ASR (alkali–silica reaction) – development reactions of expanding between aggregate containing active silica and alkalis obtained from cement hydration products or from external sources (groundwater, alkaline solutions contained or used in the construction). Si – O – Si bonds in silica are destroying during the interaction of alkalis with the concrete aggregate under the action of OH⁻ ions. As a result, an alkali silica gel with a loose structure is formed, which tends to absorb water from other parts of the concrete. This causes local internal expansion and tensile stresses within the concrete [8, 9]. Some forms of silica can react so slowly that the gel has enough time to expand into the pore network without causing an accumulation of internal
stresses. Therefore, it is difficult to predict the potential reactivity of the aggregate. Moreover, the reactivity of various forms of silica in concrete aggregate depends on its physical properties, that is, on the degree of ordering of the silicate structure. Amorphous glass is quite reactive because of active ion-exchange surface. Therefore, glass usage in concrete mixes can be a potential threat to its durability [10, 11].

Microcracks can form in glass aggregates when they are crushed or when preparing a concrete mixture. This leads to an increase in the active specific surface of the aggregate. It was previously noted that an increase in the size of glass particles increases the risk of interaction between silica and alkalis due to an increase in the active surface [12, 13]. But the authors of [14, 15] found that ASR occurs only on the inner surface of cracks of glass particles (Figure 1).

![Figure 1. Gel formation during ASR passage in cracks on a glass surface a) [14] b) [15]](image)

There is also an opinion [16] that the color of glass can affect its crack resistance. So, for example, transparent glass is more susceptible to microcracks. It was determined that brown glass particles did not have cracks even after crushing and could be considered as a non-reactive aggregate.

2 Experimental programs

2.1. Materials and mix proportions

In this research, Portland cement CEM I manufactured by Heildeberg cement Ukraine that conformed to the requirements set out within EN 197-1 was used as a binder. There were two types of aggregate: natural and recycled. As a coarse aggregate was used granite crushed stone particle size 5–10 mm originated from the Kremenchug quarry and white cullet fraction 5–10 mm. As for fine aggregate, river sand obtained from Bezlyudovka quarry and the cullet fraction 0.16–2.5 mm was also used. The cullet was crushed and sieved. Production of concrete for this test was conducted at the concrete laboratory at Kharkiv National University of Civil Engineering and Architecture. The preparation of the concrete mixture was carried out in accordance with DSTU 2.7-214: 2009 (Ukrainian standard 2009). Three samples (1-3) with a water/cement ratio (W/C = 0.5) and one sample (4) with low W/C were made. Concrete mixture No. 1 was considered as a control sample. In sample 2, 30% of fine aggregate was replaced with a fine fraction of transparent cullet, in sample 4, 30% of coarse aggregate was replaced with the corresponding fraction of transparent cullet. Concrete mixture 3 contained 30% of coarse and fine glass particles. The compositions of concrete are shown in Table 1.

2.2. Specimen preparation and measurement

Production of concrete samples was carried out by mixing for 5 minutes the corresponding mixtures, molding cubes with dimensions of 10 × 10 × 10 cm, followed by hardening in a chamber at t=18±2 °C and air humidity of 80–90%. The workability tests of the concrete mixture were carried out on the slump of a standard cone in accordance with EN 12350-2. The physical-mechanical properties of the samples were determined according to DSTU B V.2.7-214: 2009. The compressive strength was
determined at the age of 1, 3, and 28 days. To determine hydrated neoplasms, samples 2 and 4 were investigated using differential thermal analysis DTA in the temperature range of 20 ... 1000 °C. DTA studies were carried out on the solution part of the samples after 1 month of hardening, taken from the surface and center of the sample.

Table 1. Composition of concrete mixtures (kg/m³)

| Component                      | Number of compositions |
|--------------------------------|------------------------|
|                                | 1         | 2     | 3     | 4     |
| Aggregate                      | 770       | 770   | 539   | 539   |
| Sand                           | 490       | 343   | 343   | 490   |
| Cement                         | 280       | 280   | 280   | 280   |
| Crushed glass (coarse)         | -         | -     | 231   | 231   |
| Glass sand                     | -         | 147   | 147   | -     |
| Water                          | 140       | 140   | 140   | 90    |
| W/C ratio                      | 0.5       | 0.5   | 0.5   | 0.32  |

3. Results and discussion
During the study, the basic properties of concrete mixtures with glass aggregates were determined. Evaluation of the workability of the concrete mixture was carried out immediately after its preparation. A draft of 70 mm was obtained for sample No. 1. In concrete mixtures with coarse and fine glass aggregate, a decrease in cone precipitation in sample No. 2 to 40 mm, No. 3 to 20 mm was observed. This could be caused by an increase in the interparticle friction force due to the angular shape of the cullet particles. The compressive strength of concrete with glass aggregates was slightly lower than that of the control sample, but this difference is not significant (Figure 2).

Figure 2. Compressive strength of concretes of composition 1-3

The most effective from the point of view of compressive strength was composition No. 3. The difference with the control sample was only 1.62%. A comparative assessment of the increase in the compressive strength of concrete of composition No. 4 and the control composition is shown in Figure 3. The compressive strength of concrete with glass aggregate is 28.9% higher than that of the control composition. This may be due to a lower water-cement ratio and, as a consequence, a decrease in the development of the ASR reaction.
The results of thermal analysis of samples No. 2 and No. 4 are shown in Fig. 4 and in tables 2-3. The endoeffect area in the range of 60 ... 215ºС, characteristic for the hydrosilicates of the tobermorite group and ettringite, in sample No. 4 was SdTₐ = -206.75 square grams with weight loss m = 48.89 mg. In sample No. 2, the endoeffect area in the same region was SdTₐ = -84.56 square grams with weight loss m = 29.42 mg.

Figure 3. Compressive strength of concretes of composition 1, 4

![Figure 3](image)

![Figure 4](image)

**Figure 4.** The results of thermal analysis of samples a) No. 4; b) No. 2
Table 2. Weight loss.

| Sample № | Weight, mg | Mass losses which are corresponded to endo-effects, mg |
|----------|------------|------------------------------------------------------|
|          |            | 60…215 °C | 460…510 °C | 570…600 °C | 760…850 °C |
| 4        | 750.5      | 48.89     | 3.97       | 7.04       | 12.60      |
| 2        | 774.5      | 29.42     | 3.02       | 4.41       | 11.37      |

Thus, the amount of tobermorite gel in sample No. 4 exceeds its amount in sample No. 2 by 2.44 times, which may indicate a more complete passage of hydrolysis processes in cement. At the same time, the width of the endoeffect in sample No. 2 is much smaller than in sample No. 4, and its temperature range is shorter. This may indicate that the amount of ettringite in sample No. 4 is less than in sample No. 2.

The endoeffect area in the range 460 ... 510°C (crystalline form of portlandite) in sample No. 4 is $S_{dTA} = -9.54$ square grams with mass loss $m = 3.97$ mg. In sample No. 2, $S_{dTA} = -5.8$ square grams with weight loss $m = 3.02$ mg. Obviously, the amount of portlandite in sample No. 2 was 3.12 mg, which is 27% less than in sample No. 4. This may indicate a more complete binding of calcium hydroxide in sample No. 2, or a more complete passage of hydrolysis reactions in sample No. 4.

The endoeffect in the range of 570 ... 600 °C in both samples is probably due to the inversion conversion of $\beta$-quartz unstable at these temperatures to a more stable $\alpha$-quartz, stable to temperatures of 870 ... 900 °C. In sample No. 4, the area of this effect is $S_{dTA} = -4.80$ square grams with a mass loss of $m = 7.04$ mg.

In sample No. 2, the area of this effect is much smaller and amounts to $S_{dTA} = -1.79$ square grams with weight loss $m = 4.41$ mg. This may indicate that in sample No. 2, quartz to a much lesser extent entered into a pozzolanic reaction with cement lime with the formation of calcium hydroxides.

In the range of 760 ... 850 °C, in both samples endo effects are evident, which are typical for medium and low basic hydrosilicates. The total area of these effects in sample No. 4 is $S_{dTA} = -11.84$ square grams. with mass loss $m = 12.13 + 0.47 = 12.60$ mg. The total area of these effects in sample No. 2 is $S_{dTA} = -9.81$ square grams. with weight loss $m = 11.37$ mg. This indicates that the amount of low-basic calcium hydrosilicates in sample No. 4 is greater than in sample No. 2.

It can be seen from the table 2 that in sample №4, the number of hydrosilicates of varying degrees of basicity significantly exceeds their number in sample №2. The amount of portlandite in sample №4 also exceeds its content in sample №2. This may indicate that the degree of cement hydration in sample №4 is higher than in sample №2, and the high content of hydrosilicates confirms that Ca(OH)$_2$ in sample №4 more intensely enters the pozzolanic reaction than in sample №2, which leads to the formation of hydrosilicates.

4. Conclusions
The results obtained in this experimental study demonstrate that glass aggregates can be used as a substitute for natural ones, but no more than 30% of their content. It is also recommended to use chemical additives to reduce water/cement ratio, which may influence on the development of destructive reactions. A longer experiment is supposed to be carried out to determine the development of the alkali-silica reaction and how it may effect on the strength of concrete in the long term.

Partial replacement of coarse and fine natural aggregates with cullet aggregates reduces the overall compressive strength. Partial replacement of only coarse aggregate while reducing the water-cement ratio leads to an increase in compressive strength of concrete and a more complete course of hydration processes.

It should be noted that the conclusions herein may be limited to the scope of the work.

References
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