Production of lightweight geopolymer concrete

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Abstract. Lightweight concrete has been known all around the world for decades. As a masonry material, there is an advantage: it has sufficient mechanical strength despite of its light weight. This research focuses on the production of recycled concrete based lightweight geopolymer concrete samples using glass foam aggregates. During the research geopolymer and concrete samples were made and finally their properties were investigated and compared. In the research work an alkaline silicate reaction (ASR) was also studied on the glass foam lightweight aggregates, which is very important for concrete failure. Material structural and morphological tests were obtained by scanning electron microscopy (SEM) to characterize the geopolymer concrete samples. Compressive strength of lightweight concrete and lightweight geopolymer was determined at the age of 7 days. Glass foam is suitable for use as a lightweight aggregates for workability. Based on the 7 days compressive strength results no crust typical of the ASR reaction was detected on the surface of the mixtures.

1. Introduction
Lightweight concrete is a modern building material with innovative properties such as low density, low thermal conductivity and it has sufficient strength despite of its light weight. Mainly it is used for the production of large wall elements and thermal insulation boards.

This type of concrete can replace conventional concrete, where low dead loads and good thermal insulation (such as wall elements, floor thermal insulation) is required [1].

In order to reduce the energy consumption of buildings, it is necessary to improve the thermal insulation capacity [2].

Natural aggregates are used to produce concrete. As for concrete is mainly consists of aggregates (70-80 %), there is a need to reduce this, because the amount of natural resources is rapidly depleting. Recycled aggregates could be used to replace these primary materials. This would be also economically advantageous and could be a sustainable solution for the construction industry. As with other materials [3, 4], it is important to know the porosity of the aggregates.

Da Silva Fernandes et al. [5] replaced natural aggregates with glass foam (10-30 %) in their research. During their tests, foam glass was made of soda-lime glass waste, and rice husk ash and calcium carbonate as a foaming agent. Compressive strength of lightweight concrete samples was determined at 3, 7, 28, 56, 90 days and consistency was also tested. Based on their results the larger the size and concentration of the recycled primary materials, the lower the compressive strength of concrete. The highest strength was achieved with 10 % glass foam. In this case glass foam size was 4.8 mm and the compressive strength was 38 MPa after 90 days.

The term geopolymer was coined by Davidovits in 1970. He is described geopolymer as a semi-crystalline three-dimensional silico-aluminate material. Geopolymer is amorphous synthetic materials with an inorganic polymer structure. It can be prepared in an alkali activator (NaOH and Na₂SiO₃ or
KOH and \( \text{K}_2\text{SiO}_3 \) by the reaction of aluminosilicate-oxides. Geopolymers are today’s modern and potential eco-friendly building materials. Some properties of these materials are good mechanical strength, resistance against acid and fire, encapsulation of toxic substances \([6, 7, 8, 9, 10]\). During the research work geopolymer and concrete samples are made with lightweight aggregates (glass foam). The tests results are compared and analysed.

2. Materials and methods

2.1 Sample preparation

During the research work lightweight geopolymer and concrete samples were made. In the research work the following materials were used to prepare recycled concrete based geopolymer and concrete samples: recycled concrete powder, CEM-1 52.5 R cement, quartz sand, glass foam, quartz powder, silica fume, as well as alkali activator (NaOH solution) with sodium waterglass (Na\(_2\text{SiO}_3\)), flux and water. The geopolymer samples were prepared by the following procedure (Fig. 1.).

![Figure 1. Sample preparation steps for geopolymer](image)

NaOH solution was prepared from sodium-hydroxide flakes and distilled water in order to achieve 10 M concentrations. The required particle size of recycled concrete powders was obtained by planetary ball mill. After the recycled concrete powder was dried to weight constancy it was sealed in an air-proof container for further investigations.

During the experiment four types of mixtures were made from geopolymer and concrete and 5 samples were prepared from each mixture (Table 1. and Table 2.).

In the tables GP denotes geopolymer, while C denotes concrete. „R” represents the reference sample, i.e. the mixture without glass foam. “5% Q” means that the mixture contains 5 w/w% glass foam and quartz powder, in the case of “5% S” means the amount of glass foam and silica powder.

### Table 1. Composition of geopolymer with 10 M NaOH

| Sample ID | Alkali activator \[m/m\%\] | Flux agent \[NaOH, Na\(_2\text{SiO}_3\)\] | Distilled water \[w/w\%\] | Concrete powder \[w/w\%\] | Sand \[w/w\%\] | Glass foam \[w/w\%\] | Quartz \[w/w\%\] | Silica fume \[w/w\%\] |
|-----------|---------------------------|--------------------------|----------------|-----------------|----------------|-----------------|----------------|----------------|
| GPR       | 20.66                     | 5.16                     | 1.65           | 4.81            | 45.18          | 22.54           | -              | -              |
| GP5%      | 17.43                     | 3.49                     | 2.73           | 5.80            | 46.92          | 20.11           | 3.53           | -              |
| GP5% Q    | 17.43                     | 3.49                     | 2.73           | 5.80            | 41.99          | 17.99           | 3.53           | 7.06           |
| GP5% S    | 17.43                     | 3.49                     | 2.73           | 5.80            | 41.99          | 17.99           | 3.53           | 7.06           |

### Table 2. Composition of concrete

| Sample ID | Cement \[w/w\%\] | Sand \[w/w\%\] | Water \[w/w\%\] | Flux agent \[w/w\%\] | Glass foam \[w/w\%\] | Quartz \[w/w\%\] | Silica fume \[w/w\%\] |
|-----------|-----------------|----------------|----------------|-------------------|---------------------|------------------|--------------------|
| CR        | 44.40           | 37.30          | 18.2           | 0.10              | -                   | -                | -                  |
| C5%       | 42.67           | 35.79          | 17.48          | 0.13              | 3.92                | -                | -                  |
| C5% Q     | 42.67           | 27.95          | 17.48          | 0.13              | 3.92                | 7.85             | -                  |
| C5% S     | 42.67           | 27.95          | 17.48          | 0.13              | 3.92                | -                | 7.85               |
After mixing the samples were cured. In case of geopolymer preparation the samples were put in a sealed container and were cured at room temperature for 24 hours and after at 60°C for 72 hours in a confined space. Concrete samples were cured at 7 days under water.

2.2 Testing methods
During the research work alkaline silicate (ASR) reaction was investigated for the glass foam. This phenomenon is very important, because it contributes to the formation of cracks and thus to failure of the product. In the research work morphological tests were made by Carl Zeiss EVO MA 10 scanning electron microscope (SEM). High resolution electron micrographs were taken at various magnifications and the interface between the glass foam and the paste was observed. Chemical elemental composition was determined by EDS (Energy Dispersive X-ray Spectroscopy) method. Density of geopolymer samples and concrete were also determined. Compressive strength of hardened samples was also determined by at 7 days.

3. Results and discussion

3.1 Examination of alkaline silica reaction (ASR) on glass foam
Alkali-silica reaction (ASR) is a deteriorative reaction, which takes place within the structure of the concrete. It is alkaline resistance test is important to investigate, because strong alkali has an effect on the aggregates. As a result of this various physical and chemical changes may occur on the surface of the aggregate, which can lead to the failure of the concrete in a long term period [11].

Silicon is a substance, which is a highly soluble under acidic or alkaline conditions. Under ambient conditions, fine-grained amorphous silica can much easier to dissolve in high-pH solvents, than crystalline quartz. The presence of alkalis affects the reactivity of the aggregates and the extent of reaction. Therefore, in the case of an aggregate, the higher alkalinity ratio means more expansion, in fact the concrete has a higher concentration of OH⁻ in the porous solution and thus more silica.

The ASR reaction is essentially a dissolution reaction, which takes place within the structure of the concrete. During the reaction, a hygroscopic gel is formed, which swells with water causing expansion. It is contributes to the formation of cracks and thus to failure [11, 12].

The result of ASR is a several of successive reactions, including the dissolution of metastable silica, formation of a nano-colloidal silica sol, gelation of the sol, and swelling of the gel:

\[(\text{SiO}_2\text{)}\text{solid} \rightarrow (\text{SiO}_2)\text{wet} \rightarrow (\text{SiO}_2)\text{sol} \rightarrow (\text{SiO}_2)\text{gel} \rightarrow \text{swelling of the resulting gel} \]  \[11\].

A highly degraded solid SiO₂ can be directly converted to SiO₂ gel, as long as there is enough silica between the chains. The process of dissolving silica and silicates in water mainly involves the hydrolysis of Si-O-Si bonds, which results in the release of silica (Si(OH)₄) and various silicates in the aqueous phase [13, 14, 15, 16]. Temperature, pH and ionic strength significantly affect the solubility of the amorphous and silica forms in solution. It is well known, that in an alkaline medium the hydroxyl ions gradually attack the (≡Si-OH) bonds, and resulting in the dissolution of the silica network [17, 18].

In this research work glass foam aggregates were soaked in 1 M NaOH solution. The SEM micrographs (Fig. 2.) show that after soaking for 1 hour a layer formed on the porous walls of the glass foam, which is a typical layer of the ASR reaction. This layer is made up of small (3-6 µm) spherical parts and the size of the bulbs increases with rising soak time. It can be seen in the micrographs, that the structure of glass foam, which was soaked for 24 hours has been damaged. The Na content of the layer is higher, than the Na content of raw glass foam, which means that glass foam and alkaline solution interacted.
3.2 Chemical composition and morphology on concrete and geopolymer samples

In this study chemical composition of concrete and geopolymer samples was determined by EDS and moreover the surface of the samples was examined by SEM. A comparison of test results of concrete and geopolymer samples were made, when both mixtures contain the same additives in different quantities. As geopolymer is made from soda alkaline solution, the Na content is much higher in this mixture. The most important compounds in cement are clinker minerals. These are alite, belite, felite and celite. Clinker minerals contain high amounts of CaO, so the concrete sample contains high amount of Ca. As celite (tetracalcium-aluminate-ferrite), which is one of the clinker minerals, contains Fe₂O₃ that is the reason why Fe was identified in the concrete sample.

### Table 3. Chemical elements composition of concrete and geopolymer samples

| Elements | Concrete samples [wt%] | Geopolymer samples [wt%] |
|----------|------------------------|--------------------------|
| O        | 34.74                  | 31.95                    |
| Na       | 1.07                   | 19.01                    |
| Si       | 12.47                  | 38.84                    |
| Ca       | 42.59                  | 5.46                     |
| Mg       | 2.61                   | 1.11                     |
| Al       | 4.37                   | 1.56                     |
| K        | 0.47                   | 1.00                     |
| Fe       | 1.67                   | 1.08                     |
| Total    | 100                    | 100                      |

SEM micrographs were taken of the surface of concrete and geopolymer samples made with lightweight aggregate. The interface of lightweight aggregate and the matrices (hydrated cement gel and
geopolymer matrix) was studied. It can be seen on the micrographs, that glass foam aggregate is well impregnated by the matrix material. In case of concrete, the interface between the aggregate and matrix is fairly drawn. In the case of geopolymer, glass foam was incorporated into the matrix structure.

![Concrete sample at 1000 X magnifications](image1.png)

![Geopolymer sample at 1000 X magnifications](image2.png)

**Figure 3.** SEM micrographs of the mixtures

3.3 Density and compressive strength on concrete and geopolymer samples

Density of the hardened samples was determined by their weight and volume. It can be concluded, that concrete samples have higher density, than geopolymer, but these values are within the range for lightweight concrete ($\rho < 2.0 \text{ g/cm}^3$). It can be seen, that the use of lightweight glass foam aggregates reduced the density of hardened samples.

![Density of samples](image3.png)

![Compressive strength of samples](image4.png)

**Figure 4.** Density of samples (a) and Compressive strength of samples both concrete and geopolymer application. As a result of the ASR examination, crystal growth was observed on the surface of the glass foam cells. These are clearly observable on SEM micrographs. However, in the case of hardened samples SEM micrographs at the aggregates interface showed no change after 7 days. The intensified ASR reaction has shown encouraging results on the hardened specimens. There are not crust characteristic of the ASR reaction was identified on the surface of the glass foam in the mixture. In the case of geopolymer the sodium hydroxide was involved in the formation of the chemical bond. It can be seen on the compressive strength test result glass foam can be used as a lightweight aggregate in concrete and geopolymer.

4. Conclusion

In this research work glass foam has been used as a lightweight aggregate in concrete and geopolymer. Based on the mixture preparation the workability of glass foam is sufficient to be used as a lightweight aggregate. The glass foam was soaked in a 1M solution of NaOH and according to the results growth was observed on the surface of the glass foam cells. These are clearly observable on SEM micrographs. However, in the case of hardened samples SEM micrographs at the aggregates interface showed no change after 7 days. The intensified ASR reaction has shown encouraging results on the hardened specimens. There are not crust characteristic of the ASR reaction was identified on the surface of the glass foam in the mixture. In the case of geopolymer the sodium hydroxide was involved in the formation of the chemical bond. It can be seen on the compressive strength test result glass foam can be used as a lightweight aggregate in concrete and geopolymer.
lightweight aggregate in concrete. However, increase the strength of the geopolymer matrix curing conditions needs to be changed.

Preliminary experiments were carried out during the research work, so the Authors plan to carry out further investigations.

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