Waste glass as a replacement for fine fraction in high-performance concrete

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Abstract. Research project is focused on the experimental verification of high-performance concrete (HPC) with full replacement of fine fraction. This paper deals with HPC mixtures containing recycled glass materials (waste glass powder from municipal waste, waste glass powder from photovoltaic panels, grinding waste glass from jewellery). The research is based on the results of previous student grant. A recipe that was made during 2017 is used and optimized according to the waste glass powder properties. The influence of different local sources is monitored. The HPC mixtures are tested for mechanical properties (flexural strength, compressive strength) and compared with the results from the previous research. Flowability is tested and all the mixtures are workable. The mixture with grinding glass (GG) showed the highest results in flexural and compressive strength compared to the reference sample, the use as a substitute for fine fraction in HPC is conceivably attitude. The municipal waste glass mixture and the mixture with the waste glass from photovoltaic panels is not usable as HPC.

1. Introduction

Last few years, things like decreasing amount of non-renewable materials (and sources) belong to the main issues to deal with. Meanwhile, the high energy consumption to obtain these materials has negative impact on the environment – it happens during the mining, processing and subsequent using the materials \cite{1}. It is probably time to think about what the real issue is – the decreasing number of non-renewable materials or the threat it poses to the environment?

Despite the factors mentioned above, utilization of non-renewable materials continues. With the use of non-renewable materials, a large amount of waste is produced – in fact, it concerns more or less all new materials. Almost 40\% of waste comes from civil engineering. According to the latest available data (2014) it was almost 18 million tons \cite{2}. The thing is, that this waste, once produced, needs to be stored somewhere, or better – recycled.

After the water, concrete is the second most used material in the world. About 7-8 \% of total CO\textsubscript{2} production is from cement fabrication. Therefore, in recent years, is an effort to reduce this material or to lower environmental impacts by using new types of optimized or recycled concrete \cite{3}.

Recycling in its original meaning is returning to the process in which the waste originated (original purpose or same system). In a broader sense, recycling can be considered as any reuse of material – it doesn’t have to be necessary the utilization in the same system as it was before. However, any return of the waste to the process is considered as success – at least for our environment.

In recent years is increasing tendency to use special kinds of concrete with greater strength, resistance or durability. Such concretes are usually classified in group of High Performance Concretes (HPC) or
Ultra High Performance Concrete (UHPC). HPC or UHPC have very small fraction of used aggregates compared with ordinary concrete and they also have very small water/cement ratio due to the use of superplasticizers. Unfortunately, these concretes have almost always a large amount of cement. One of the sustainable approaches is to replace some components with more environmentally friendly materials.

One of the appropriate materials is glass, which is one of the most recyclable materials (almost 100%) [4]. On one hand, glass is chemically resistant to external influences, have excellent heat-insulation properties. On the other hand, it is non-decomposable material, therefore it is necessary to landfill waste glass – but due to the transporting and landfilling waste glass, impurities may occur. Utilization of waste glass in construction industry is convenient, because the demands of glass purity are decreasing.

There are several studies that deal with replacing some of the concrete components by glass. Two main ways to use waste glass in concrete are possible – aggregate replacement or cement replacement. There are also researches that combine these attitudes.

Hongjian Du and col. investigated the influence of replacing cement by glass powder in high volume up to 60% to mechanical and durability properties of concrete [5]. Topcu and col. investigated the tensile bending strength of concrete with waste glass as coarse aggregate [6]. Waste glass powder was used as a pozzolanic material in Shayan and Xu research – they replace up to 30% of cement in concrete mix [7]. Another research groups were investigated possibility of replacing aggregate with waste glass in concrete [8–10]. Based on them, it could be told, it is more suitable to use waste glass as a fine aggregate in concrete. Schwarz and col. compared the properties of concrete containing waste glass powder with concrete containing fly ash [11]. There are several studies to investigate the amount of waste glass powder in concrete [10,12,13]. There are different results, replacement range varied from 10% to 40% - ideal amount should be around 10% - 20% [10]. Soliman and Tagnit-Hamou developed ultra-high-performance glass concrete with a compressive strength up to 220 MPa. However, this is the only one study dealing with ultra-high-performance concrete (UHPC) [14].

Waste glass utilization is appropriate in HPC (or UHPC) because less water is used there than in regular concrete. With growing amount of water, the risk of alkali-silica reaction (ASR) increases. There may be a lot of situation which may cause degradation of concrete, when considering replacing silica powder by waste glass powder, one of the most important causes is ASR.

It is important to notice that on basis of alkali-silica reaction are significant only aggregates with amorphous silica [15]. Beside amount of waste glass powder in concrete, there is question about size of particles. There were few researches made on this topic [7,16,17]. Research by Z. Bažant found that particles smaller than 0,25mm caused no expansion. On the other hand, particle size around 1,5mm caused excessive expansion [16]. Based on this researches, it is possible to say, that the waste glass powder is suitable for utilization in high performance concrete as partial replacement as fine aggregate in concrete. The potential risk is lower compared to coarse aggregate - it is known that particles smaller than 1mm are reactive too, but the pressure is so small that there are no cracks at the surface. More detailed research or experiments are not part of this work.

According to Carsana and col. research that investigated comparison between waste glass and other supplementary cementitious materials, mortars with waste glass showed long term durability – the samples did not show any degradation after seven years’ immersion in water and compressive strength was higher [18].

There are many types of waste glass, which could be possibly useful for this issue. This paper investigates utilization of grinding glass, waste glass from municipal waste and from photovoltaic panels as a replacement for fine grains. The research is partially based on the results from previous work and should verify the results and the effect of changing local resources – especially cement [19].

2. Materials
First experiments were made based on the original basic recipe optimized during our research program in 2017. The reference mixture of HPC (REF), the mixture with grinding glass (GG) and the mixture with waste glass powder from municipal waste (MWG) were made and tested to verify the strength, freeze-thaw resistance and other properties. [19] HPC was made following the basic recipe (Table 1).
This approach was chosen to verify the effect of changing local raw materials and sources and the age of waste glass powder on the mechanical properties of high performance concrete. In 2018, new mixtures followed the basic recipe were made (Table 1). Cement I 42.5R, technical silica sand, silica fume, superplasticizers and water were used. Silica powder was added in the reference sample (REF2). After that, the basic recipe was changed – silica powder was replaced with grinding glass (GG2), then with the milled waste glass from municipal waste (MWG2). The weight of fine fraction stayed the same (325kg/m³).

Same thing was done with powder from photovoltaic panels (PP2A). However, these samples cracked and it was not possible to test them.

Table 1. Basic recipe used in 2017, repeated in 2018 – Reference sample(REF1,2), grinding glass(GG1,2) and milled waste glass(MWG1,2).

| Component (kg/m³)                          | REF1,2 | GG1,2 | MWG1,2 | PP2A |
|-------------------------------------------|--------|-------|--------|------|
| Cement I 42.5R                            | 680    | 680   | 680    | 680  |
| Technical silica sand                     | 960    | 960   | 960    | 960  |
| Silica powder (ground quartz)              | 325    | 0     | 0      | 0    |
| Grinding glass                            | 0      | 325   | 0      | 0    |
| Milled waste glass                        | 0      | 0     | 325    | 0    |
| Photovoltaic panels powder                | 0      | 0     | 0      | 325  |
| Silica fume (microsilica)                 | 175    | 175   | 175    | 175  |
| Superplasticizers                         | 29     | 29    | 29     | 29   |
| Water                                     | 171    | 171   | 171    | 171  |

It follows that two HPC samples remained (GG2, MWG2) to examine and compare with reference sample (REF2). The differences were evident in the structure of concrete.

The next step was to optimize the recipe containing photovoltaic panels powder. The possibility of an unwanted reaction that led to the cracks in the concrete structure was eliminated by excluding silica fume (microsilica) from the mixture (Table 2.). Water-cement ratio was increased to 0,27. These steps proved mixture usable, cracks were successfully eliminated.

Table 2. Optimized recipe 2018 – Photovoltaic panels (PP2B).

| Component                                | PP2B  |
|------------------------------------------|-------|
| Cement I 42.5R                           | 650   |
| Technical silica sand                    | 1200  |
| Photovoltaic panels powder (ground quartz)| 240   |
| Silica fume (microsilica)                | 0     |
| Superplasticizers                        | 30    |
| Water                                    | 180   |
3. Experiments
For now, samples made according to the basic recipe (Table 1.) and optimized recipe (Table 2.) have been tested – REF2, GG2, MWG2, PP2b. Prepared samples were examined to determine:

- Flow table test
- Tensile bending strength
- Compressive strength

3.1. Flow Table Test
The mortar flow is a relative measure of workability similar to slump. This method is suitable for cement mortars and fine-aggregate concrete. Mortar flow test is described in the Czech standard CSN EN 1015-3 (2000). Mortar flow is most sensitive to water and air content. This test determines how much a mortar sample flows when it is unconfined and consolidated. Mortar is placed inside conical form. When the form is removed, the mortar is vibrated as the flow table rises and drops 15 times. The mortar changes from a conical shape. Mortar flow is reported as the final diameter of the mortar on the flow table.

3.2. Tensile Bending Strength
Tensile bending strength is described in Czech standard CSN EN 12390-5. The test is realized on block specimens with dimension 40 x 40 x 160mm. Flexural strength is defined by three-point press according to CSN EN 1015-11. The test is over after the sample breaks. The highest force registered during the test is used for calculation tensile bending strength. It is always necessary to test at least three samples.

3.3. Compressive Strength
Compressive strength is verified on fragments of samples after flexural strength test. The tested surface $A_c$ is 40 x 40 mm. There are certain conditions to keep – about samples (EN 12350-1, EN 12390-1, EN 12390-2 or EN 12504-1), machine (EN 12390-4) and procedure. The test is done when the sample breaks. The maximum measured force is recorded. The whole method is described in CSN EN 12390-3. All results are evaluated by methods mathematical statistics.

Tensile bending strength and compressive strength tests were made after 28 days.

4. Results and Discussion
The samples were tested to determine the properties of concrete. The following chapter describes the results and discussions of all tests.

4.1. Flow Table Test
The effects of waste glass powder on the workability of fresh concrete were tested. Until now, the dependence between the spill rate and the strength has not been found [20]. The workability of fresh concrete with the waste glass powder replacement was different, but not inferior (Figure 1., Figure 2.). As a result of the flow table test on the workability of the fresh concrete, the slump value was determined to be 23.5 – 28.2 cm (Table 3.)
Figure 1. Flow table test REF₂ (left), GG₂ (right).

Figure 2. Flow table test MWG₂ (left), PP₂B (right).

Table 3. Results of flow table test.

| Type of sample | Spill (cm) |
|----------------|------------|
| REF₂           | 25         |
| GG₂            | 23.5       |
| WGP₂           | 26.75      |
| PP₂B           | 28.2       |

4.2. Tensile Bending Strength

In previous research was proven, that the longer hardening time has positive impact to the tensile bending strength [19]. Mixture with grinding glass (GG₁) and mixture with milled waste glass (MWG₁) were compared with the reference sample contains silica powder (REF₁) in 2017. It was the first basic research on this topic and the results were usable. However, it was necessary to repeat the experiments to provide the workability of the mixture and to investigate the influence of the use of different local sources in the mixture. Influence of the higher age of waste glass powder was monitored as well.

Mixtures and samples (based on the original recipe from 2017) were made in 2018 – reference sample (REF₂), mixture with grinding glass (GG₂), mixture with milled waste glass (MWG₂) and new mixture with powder from photovoltaic panels (PP₂B).
**Figure 3.** compares the results from 2017 (REF$_1$, GG$_1$, MWG$_1$) with the one from 2018 (REF$_2$, GG$_2$, MWG$_2$). Values from the mixture PP$_{2B}$ are new, so they have no comparison. In 2018, the values of tensile bending strength mixture with grinding glass (GG$_2$) were 15% lower compared with the reference sample (REF$_2$). The similar results were provided in 2017 (20%). Milled waste glass sample (MWG$_2$) values are even lower than in 2017. Additional optimization of current MWG$_2$ recipe will be required before next experiments, otherwise this mixture could not be used as HPC. It seems that higher age of milled waste glass and freshness of cement or its slight differences can affect partially the resulting mechanical properties of HPC.

![Chart showing tensile bending strength results comparison](chart.png)

**Figure 3.** Tensile bending strength results comparison – years 2017, 2018 and values of new recipe from 2018.

### 4.3. Compressive strength

The compressive strength test was performed on sample fragments. The differences in the structure are visible – samples with waste glass powder have more pores in the structure (**Figure 4.** and **Figure 5.**). Different particle size may also have impact to the results. Another factor could be chemical composition. Due to these facts, the compressive strength is lower. However, mixture with grinding glass provide usable results. Mixture with waste glass from photovoltaic panels has the lowest results (**Figure 6.**). The use of different age of local sources have influence on the results – especially freshness of cement. The decrease of the compressive strength in mixture with waste glass powder from municipal waste can be caused by the chemical reaction created by cement with waste glass powder.

![Image of samples after flexural strength test](samples.png)

**Figure 4.** Fragments of samples after flexural strength test REF$_2$ (left), GG$_2$ (right).
5. Conclusion
Waste glass powder, obtained from different sources, was used as a full replacement of silica powder in high performance concrete. The samples were examined in several tests. This research builds on previous study from 2017. This paper was made to compare the results from 2018 with the results from 2017, monitored the influence of the use of different local materials and freshness (especially cement) and the influence of age of the waste glass.

Glass powder from grinding jewellery, milling municipal waste and photovoltaic panels was used. These sources are only a part of the waste that can be reused as a replacement in concrete.

During the first round of experiments, basic recipe optimized during 2017 was used. The utilization of waste glass powder from photovoltaic panels has proven to be inappropriate in this case. The cracks appeared and the samples had to be excluded from further testing. The recipe was optimized during this research and the samples with waste powder from photovoltaic panels were tested as well.

The tests to find out tensile bending strength and compressive strength were made on samples with grinding glass, milled waste glass and glass from photovoltaic panels. The results of new mixtures containing the waste glass were compared with the reference sample. A comparison with the results of previous research (2017) was made as well.

Especially the mixture with waste glass powder from grinding glass achieved usable numbers. The flow table test ends up with spill range 23.5 cm. However, the workability was the worst of the tested samples. The tensile bending strength was 84.2% compared with the reference sample (considered as 100%). The compressive strength was 80.8% compared with the reference sample (considered as 100%).
The mixture containing the glass powder from milling municipal waste had convenient workability. However, the results of tensile bending strength test and compressive strength test were slightly worse, compared with reference sample and mixture with grinding glass. The recipe should be optimized before further testing, because the mixture does not have any high performance parameters yet.

Photovoltaic panels powder used in a HPC mixture that was made according to the recipe from 2017 was unsuitable, the cracks appeared. The recipe was optimized; flow table test provides workability of the mixture. The tensile bending strength test and the compressive strength test was made as well – the results were low compared to the reference sample and compared to other mixtures with waste glass. We suppose that even after further optimizing the recipe, this mixture will not be usable in term of high-performance concrete. It is probably due to a different chemical composition of the glass from photovoltaic panels.

The risk of alkali-silica reaction must be dealt with for these concrete mixtures. Tests will be conducted in the following research. A long-term experiment should verify the low ASR risk. The samples will be visually checked and tested every year. Up to this point, the potential risk of ASR was based on other researches work.

Based on research, the use of waste glass powder in high performance concrete is a suitable way to reduce the need for primary raw materials used to produce concrete. Waste glass properties are conveniently advantageous for use in concrete (pozzolanic properties, similar chemical composition etc.). Due to the increasing tendency to use special concrete with higher strength or durability, it is necessary to find sustainable approach to replace non-ecological components like cement. In view of the deteriorating condition of our planet, this approach is necessary and will continue to increase in the next years. The resulting strength values demonstrate the potential to use grinding glass powder as a replacement for the fine fraction in HPC.

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