The use of steel slag in concrete

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Abstract. This paper presents the results of a research dealing with the use of unstable steel slag as a 100% substitute for natural aggregate in the production of concrete. Portland cement CEM I 42.5N and alkali activated hybrid cement H-CEMENT were used as the binder. The test results confirm the possibility to use steel slag as the filler in the production of concrete.

1. Introduction
Concrete is one of the most commonly used materials in the building industry. It is a universal building material (composite) that can be used in a variety of environments (dry, water, underground, in hot or cold climatic zones). Another advantage of this material is the possibility to change its properties depending on the requirements of the construction project and the price. Concrete consists of three main components: binder, filler and water. The most commonly used filler is natural aggregate of different fractions. The most frequently used aggregate fractions for structural concrete are 0/4 mm, 4/8 mm and 8/16 mm fractions. This article presents the results of an experimental research dealing with the preparation of concrete based on steel slag, which was used as a 100% substitute for natural aggregate using two types of binders. The first type of binder was Portland cement CEM I 42.5N and alkali activated hybrid cement H-CEMENT from Považská cementáreň, a.s.

At present, we are familiar with the results of an experimental research on the use of steel slag in the production of concrete. It describes a partial replacement of natural aggregate by steel slag in the production of concrete with the strength of 30, 50 and 70 MPa [1].

A comparison of the physical and mechanical properties of concrete with a different content of steel slag as a substitute for natural aggregate with the maximum grain size of 12.5 mm and concrete based on natural filler – limestone are presented in [2]. The results of a research, where 60% of steel slag was used as part of the binder in combination with 20% of Portland cement and 20% of active magnesium in order to produce a concrete composite which was subsequently hardened in CO2 environment and a pressure of 0.1 MPa are described in [3]. We are also familiar with research the results, where steel slag was used as a partial substitute for natural aggregate in the production of asphalt concrete [4]. The use of steel slag from Sisak Iron works Company in combination with natural aggregate road base layer and their strength parameters are described in [5]. The ecotoxic properties of concrete based on granulated slag from the production of gray iron are described in [6].

Steel slag is an additional component in steel production and has an irreplaceable role from many points of view. Nowadays, steel is mainly produced in oxygen converters and in electric arc furnaces. The presence of steel slag, depending on the used technology and the number of other parameters,
such as the composition of the charge, the amount of added slag-forming additives, etc., varies within relatively wide limits, ranging from app. 20 to app. 250 kg per ton of crude steel. Depending on the nature of the process and its course, the chemical composition of the resulting slag types and their properties differ considerably as well. However, steel slag is not a mixture of oxides, but a complex system in which we can identify more than 100 components that cannot be mechanically separated.

When using steel slag as an artificial aggregate in the building industry, the following obstacles must be taken into account:

- high specific density of steel slag is beneficial in some areas of application, but has an adverse effect on the cost of slag transportation, especially at distances over 50 km;
- the content of free oxides of CaO and MgO is associated with lower volumetric stability of steel slag. These free oxides may hydrate with the access of moisture and gradually increase their volume, resulting in the disintegration of slag.

2. Material and methods

2.1. Steel slag

The experimental research of a 100% substitution of natural aggregate with steel slag took advantage of cast converter slag with the fr. of 0/8 mm, which was subjected to the tests of grain size, volume density and water absorption, as well as an elemental analysis. The results of the grain analysis, which was carried out according to CSN EN 933-1, are presented in figure 1.

![Cumulative Grain Size Curve](image)

**Figure 1.** Cumulative grain size curve of 0/8 mm steel slag fraction.

Figure 1 shows the cumulative grain size curve of 0/8 mm steel slag fraction, which was obtained by sieving of steel slag through a set of screens with the square mesh size of: 0.063; 0.125; 0.25; 0.5; 1; 1.6; 2; 4; 5.6; 8; 10 and 12.5 mm. It should be noted that prior to the grain size test, the steel slag was not washed with water on 0.063 mm screen. The share of fine particles sifted through 0.063 mm screen is 5.7%. The mean grain parameter d50 as an important parameter characterizing grain size is 1.3 mm what means the value of the particle diameter at 50% of cumulative distribution.

The volume density and water absorption of steel slag with the fr. of 0/8 mm were determined according to CSN EN 1097-6 by pyknometric method. The results of the determination are presented in table 1.

| Parameter Description                                      | Value         |
|------------------------------------------------------------|---------------|
| ρ<sub>a</sub> bulk density of grains                        | 3.742 Mg·m⁻³  |
| ρ<sub>rd</sub> bulk density of grains after drying in a drier| 3.439 Mg·m⁻³  |
| ρ<sub>ssd</sub> bulk density of grains saturated with water and surface dried | 3.520 Mg·m⁻³  |
| WA<sub>24</sub> water absorption                            | 2.34 %        |

**Table 1.** Values of volume density and absorption power of steel slag with the fr of 0/8 mm.
2.2. Cement, additive and water
Two types of cements were used to design the experimental concrete formula based on steel slag. They were Portland cement CEM I 42,5N and alkali activated hybrid cement H-CEMENT. The properties of H-CEMENT are described in [7]. These two types of cements were supplied by Považská cementáreň, a.s. Company. The additives were: superplasticizer Sika® ViscoCrete®-225 Powder and retardant additive RETARDAL 540, which delays the beginning of the hardening of concrete according to the cement dose. Tap water from the water supply system was used as the mixing water.

2.3. Mix design
Three mixes with the designation of RL1, RL2 and RL3 have been designed within the scope of the experimental research.

- **RL1 mix** - contained 0/8 mm steel slag fraction as filler, 380 kg of H-CEMENT, 241 kg of water, Sika superplasticizer in the amount of 0.5% of the cement weight, and retardant additive in the amount of 0.4% of the cement weight.
- **RL2 mix** - contained 0/8 mm steel slag fraction as filler, 380 kg of Portland cement CEM I 42,5N, 241 kg of water, Sika superplasticizer in the amount of 0.5% of the cement weight, and retardant additive in the amount of 0.4% of the cement weight.
- **RL3 mix** - contained 0/8 mm steel slag fraction as filler, 380 kg of Portland cement CEM I 42,5N, 241 kg of water, Sika superplasticizer in the amount of 0.5% of the cement weight. No retardant additive was used.

2.4. Testing the concrete properties
The following fresh concrete properties were tested: the consistency of fresh concrete - the slump test according to CSN EN 12350-2 immediately after mixing and after 30 minutes, the density of fresh concrete according to CSN EN 12350-6. The strength characteristics of hardened concrete were tested according to CSN EN 12390-3. Cube strength of concrete was tested after 3, 7, 14, 21 and 28 days, prism strength was tested after 28 days. The modulus of elasticity was tested according to CSN ISO 6784 from the deformability properties.

![Figure 2. Autoclav ing curves for testing the volume changes of concretes.](image)

The durability of concrete based on steel slag was tested under conditions of higher temperature and pressure. The determination of the volume changes of concrete was carried out in a 540 litre laboratory autoclave at the maximum saturated steam pressure of 1.2 MPa and the maximum temperature of 189 °C. 150 mm cubes were used as the test specimens. The temperatures and pressures in the testing laboratory autoclave were set according to the autoclave curves presented in figure 2 in order to determine the volume changes of concrete based on steel slag.
3. Results and discussion

The results of the tested properties of fresh concrete mixture and the physical-mechanical and deformation properties of hardened concrete based on steel slag aggregate are presented in Table 2.

| Formula | RL1 | RL2 | RL3 |
|---------|-----|-----|-----|
| Slump test immediately after mixing [mm] | 258 | 255 | 249 |
| Slump test after 30 min. [mm] | 185 | 255 | 165 |
| Density of fresh concrete [kg/m$^3$] | 2728 | 2863 | 2717 |
| Concrete cube strength[MPa] | | | |
| after 3 days | 9.1 | 21.2 | 18.0 |
| after 7 days | 16.7 | 28.0 | 22.6 |
| after 14 days | 22.3 | 31.8 | 27.0 |
| after 21 days | 27.6 | 36.3 | 30.1 |
| after 28 days | 29.1 | 37.4 | 34.6 |
| after 90 days | 38.4 | 44.2 | 38.0 |
| Concrete prism strength[MPa] | | | |
| after 28 days | 29.0 | - | 31.2 |
| after 90 days | 37.5 | - | 34.3 |
| Concrete modulus of elasticity[MPa] | | | |
| after 28 days | 32837 | - | 32509 |

The results of the slump test clearly show that the consistency of all concrete mixtures immediately after mixing (RL1, RL2, and RL3) corresponds to the slump degree of S5 and the slump degree of S4 after 30 minutes in the case of mixtures RL1 and RL3. There is an evident decrease in the slump value immediately after mixing and after 30 minutes in case of RL1 mixture, and it is 73 mm (28%). The value of RL3 is 84 mm (34%).

The density values of fresh concrete RL1 and RL3 are almost identical, with a visible increase in RL2 mixture. This increase was caused by the segregation of the steel slag grains during the production of the concrete mixture and the reflection of the mixing water during the production of the test specimens.

Table 2 clearly shows a gradual increase in the cube strength of the concretes based on steel slag and H-CEMENT (RL1 formula) in comparison with the concrete based on steel slag and Portland cement CEM I 42.5 N (RL2, RL3). The strength of RL1 concrete after 3 days clearly shows a 2 to 2.3 times lower value of concrete strength compared to concrete RL2 and RL3. After 7 days, the strength of RL1 concrete is 1.4 and 1.7 times lower than that of RL2 and RL3 concretes. Even after 28 days, the RL1 concrete cube strength is lower compared to formula RL2 and RL3 based on Portland cement. After 90 days, the values of the cube strengths of samples RL1 and RL3 became equal.

Looking at the values of the modulus of elasticity of concrete based on steel slag (see Table 2), it is obvious that the average values of the modulus of elasticity of the concrete based on steel slag and H-CEMENT (RL1 formula) and the concrete based on steel slag and Portland cement CEM I 42.5N (RL3 formula) are almost identical, although H-CEMENT belongs to the cement strength class of 32.5.

Figure 3. View of the test specimen after autoclaving A) RL1 mix, B) RL3 mix.
The results of the durability tests of concrete based on steel slag have unambiguously shown the suitability of H-CEMENT as the binder for the production of concrete based on steel slag under conditions of higher temperature and pressure. The above presented fact is confirmed by figure 3, which compares the test specimens after the autoclave process. The picture clearly shows that the concrete based on steel slag and Portland cement disintegrated into concrete rubble. The concrete based on steel slag and H-CEMENT did not show any evidence of disruption of the test specimens after the autoclave process, on the contrary, the strength was increased from the initial value of 29.13 MPa to 43.03 MPa (i.e. by 32%).

4. Conclusion
The presented results of the experimental research have confirmed the suitability of the use of H-CEMENT binder in the production of concrete based on steel slag, which is represented in 100% volume replacement of natural aggregate. It has been proven that: the use of H-CEMENT in the production of concrete mixture based on steel slag results in an even increase in strength when compared to the concrete mixture based on steel slag with CEM I 42.5N. The cube and prism strengths of the concrete mixture with steel slag and H-CEMENT are the same. The modulus of elasticity of the concrete mixture using H-CEMENT and CEM I 42.5N is identical. After the autoclaving of concrete with steel slag and CEM I 42.5N, the test specimens were completely destroyed, confirming that CEM I 42.5N is unsuitable for the use as the binder for unstable steel slag in conditions of higher temperature and pressure.

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