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High performance concrete containing lower slag amount: A complex view of mechanical and durability properties

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ABSTRACT

A wide set of parameters of concrete containing 10% of ground granulated blast furnace slag as Portland cement replacement involving basic material characteristics, mechanical and fracture-mechanical properties, durability characteristics, hydric and thermal properties and chloride binding characteristics is determined and compared with the parameters of reference Portland cement concrete with otherwise the same composition. The experimental results show that the replacement of Portland cement by even such a low amount of ground granulated blast furnace slag as environmental more friendly and still valuable alternative binder either affects positively or at least does not worsen in a significant way the substantial properties of hardened concrete mix. The mechanical and fracture-mechanical properties are found to be very similar as compared to the reference mix, the liquid water transport parameters of the mix containing slag are significantly better, the basic durability characteristics such as the frost resistance and corrosion resistance similar and very good, the resistance against de-icing salts slightly worse. These findings may be significant for the future use of slag in the countries where its available amount is decreasing and its more efficient use as a binder than it was common to date can appear necessary.
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1. Introduction

The application of slag as binding agent for composite building materials has a rather long tradition. Ground granulated blast furnace slag (GGBFS) has been used since 1940s either as a component of blended cement or partial replacement of Portland cement [1–8]. Alkali activators stimulating the latent pozzolanic properties of GGBFS made also possible its utilization as a sole binder [9–16] instead of cement.

The motivations for using GGBFS in concrete production are mostly economical and ecological. Nowadays, the cement producers in Europe are supposed to meet the tightened up ecological legislative, the restrictions upon emission limits in particular. The increasing prices of fuel for burning the clinker are another burden. GGBFS is one of the ways how to deal with the increasing ecological and economical requirements. It is a waste material, thus cheaper than cement, and its use instead of a part of cement decreases the overall CO_2 consumption. In addition, GGBFS increases the workability of concrete, improves strength, reduces the hydration heat, permeability, porosity and alkali–silica expansion [17–20] which is another bonus. The optimum amount of GGBFS is usually in the range of 40–60% of the total mass of binder; its higher content can already impair the 28-days compressive strength of hardened concrete [5,6,20]. So, a relatively high amount of cement can be safely replaced by slag which leads to a tendency to use as much slag in concrete as possible.

However, the sources of GGBFS are not unlimited. In some countries, there is already shortage of high-quality slag which is necessary for concrete production. In Czech Republic, since 2008 no GGBFS is available on the free market. Cement producers make use of all slag produced in the country and still complain of its lack. Therefore, a necessity of an even more efficient use of slag as a binder than it was common to date can appear in the near future. One of the possibilities is to utilize slag for the production of high performance concrete (HPC) as it was indicated already some years ago [21]. Slag may also no longer be considered just as a waste material which is supposed to get rid of but rather a worthy binding agent improving the properties of Portland cement based concretes. This can lead to its use in lower amounts which are just necessary to obtain the denser microstructure of cement matrix; the structure compacting which accompanies the use of slag as

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partial Portland cement replacement is a consequence of the secondary pozzolanic reaction resulting in the consumption of $Ca(OH)_2$ and C–S–H structures formation [22].

The majority of investigators was concentrated on studies of the effect of higher amount of slag on concrete properties until now, driven by the above mentioned motivation to use as much slag as possible. The analyses mostly began at 20% of the total mass of the binder. The properties of concrete with lower amount of slag as cement replacement were studied much less often so that they were not so thoroughly explored. This paper intends to contribute to the extension of knowledge of the concrete mixes containing lower amount of slag. A representative set of parameters of concrete containing 10% of slag as Portland cement replacement including basic material characteristics, mechanical and fracture-mechanical properties, durability characteristics, hydric and thermal properties and chloride binding characteristics is investigated and compared with the parameters of corresponding Portland cement concrete. The set of measured parameters is sufficiently wide to make possible to perform even very complex computational service life analyses where they can be used as input data.

2. Experimental methods

2.1. Basic material characteristics

The consistence of fresh concrete mixtures was analyzed by the slump test according to ČSN EN 12350-2 [23], using a conical mould (upper diameter 100 mm, lower diameter 200 mm, height 300 mm). The result of the slump test (in mm) was the difference between the height of the mould and the uppermost point of the specimen after the test.

As fundamental physical material characteristics, bulk density ρ_b (kg m^{-3}), open porosity (Vol. %) and matrix density ρ_{mat} (kg m^{-3}) were determined using the water vacuum saturation method [24]. Each sample was dried in a drier to remove majority of the physically bound water. After that the samples were placed into a desiccator with deaired water. During three hours air was evacuated with vacuum pump from the desiccator. The sample was then kept under water not less than 24 h.

From the mass of the dry sample m_d, mass of water saturated sample m_w, and mass of immersed water saturated sample m_a, the volume V of the sample was determined from the equation

$$V = \frac{m_w - m_a}{\rho_w} \quad (1)$$

where ρ_w is the density of water. The open porosity, bulk density and matrix density were calculated according to the equations

$$\psi_0 = \frac{m_w - m_d}{V\rho_w} \quad (2)$$

$$\rho = \frac{m_d}{V} \quad (3)$$

$$\rho_{mat} = \frac{m_d}{V(1-\psi_0)} \quad (4)$$

Characterization of the pore structure of studied materials was performed by mercury intrusion porosimetry. This well known method is based on intrusion of mercury to the porous sample by gradually increasing intrusion pressure while mercury penetrates to smaller pores. The experiments were carried out using the instruments PASCAL 140 and 440 (Thermo Scientific). The range of applied pressure corresponds to pore radius from 2 nm to 2000 μm. Since the size of the specimens is restricted to the volume of approximately 1 cm^3 and the studied materials contained some aggregates about the same size, the porosimetry measurements were performed on samples without coarse aggregates.

The matrix density was determined by the helium pycnometry as well, for the sake of comparison. The method is based on measurement of the real volume of a sample using helium which has very small atoms easily penetrating into a porous system. The measurements were performed by Pycnomatic ATC equipment (Porotec, Germany).

2.2. Mechanical and fracture-mechanical properties

The measurement of compressive strength and bending strength was done using the hydraulic testing device VEB WPM Leipzig 3000 kN having a stiff loading frame with the capacity of 3000 kN. The compressive strength was tested according to the standard ČSN EN 12390-3 [25]; a constant loading rate of 0.2 MPa/s was imposed on the specimens. The bending strength was determined using the procedure described in ČSN EN 12390-5 [26], with the loading rate of 0.04 MPa/s. The basic tests were performed after 28 days of standard curing. The details of the specific tests where mechanical properties were used as criteria for durability assessment are given in Section 2.3.

The effective fracture toughness was measured using the effective crack model [27] which combines the linear elastic fracture mechanics and crack length approaches. A three-point bending test of a specimen having a central edge notch with a depth of about 1/3 of the depth of the specimen was used in the experiment. The loaded span was equal to 300 mm. A continuous record of the load–deflection (F–d) diagram was used for the calculation of effective fracture toughness. An estimate of fracture energy was obtained from the F–d diagram according to the RILEM method (work-of fracture).

2.3. Durability tests

Frost resistance tests were carried out according to ČSN 73 1322/Z1:1968 [28]. The samples were tested after 28 days of concrete maturing and standard curing. The total test required 100 freezing and thawing cycles. One cycle consisted of 4 h freezing at −20 °C and 2 h thawing in 20 °C warm water. Frost resistance coefficient K was determined as the ratio of bending or compressive strength of specimens subjected to 100 freezing and thawing cycles to the strength of reference specimens which did not undergo the frost resistance test.

The resistance of studied concrete against de-icing salts was measured according to ČSN 731326/Z1:1984 [29]. The tested specimens were saturated by water and put into a bath with 3% NaCl solution. Then, freeze/thaw cycles were applied. In one cycle the tested specimen was cooled at first in an automatic conditioning device from 20 to −15 °C during 45 min, then it was left at −15 °C for 15 min, subsequently heated to 20 °C during 45 min and left 15 min at that temperature. After every 25 cycles the specimens were removed from the bath, their mass loss due to spalling of particles on the surface was determined, the NaCl solution replaced and specimens put into the bath again. The test was supposed to be finished either after the prescribed number of cycles or after the mass loss exceeded 1000 g/m^2.

The corrosion resistance in various environments was tested according to the procedure developed at the Brno University of Technology. The specimens were prepared in 100 × 100 × 400 mm molds and placed into a climatic chamber with 100% relative humidity environment. After 24 h they were demolded and stored in the same environment for another 27 days. Then, the specimens were cut to 100 × 100 × 50 mm blocks and put in groups of three into the corrosion environments specified in Table 1. One set of specimens was just after the 28-days curing subjected to the compressive-strength test to obtain reference strength value. Test of concrete carbonation was performed in a desiccator where the CO_2 concentration was kept at 65 ± 5 vol. % (the concentration was measured by an IR probe). The carbonation took place in an environment above saturated KNO_3 solution (85 ± 5% relative humidity). The specimens denoted as "air" in Table 1 were stored in common laboratory conditions at 21 ± 2 °C and 45 ± 5% relative humidity; those marked "distilled water" were in distilled-water bath which was replaced every 10 days. The duration of the corrosion test was 60 days. Then, the specimens were subjected to the compressive-strength test. The way of loading the specimens is shown schematically in Fig. 1 as the test was not quite a standard one. The coefficient of corrosion resistance K_{cr} was then determined as the ratio of the compressive strength after 60 days in a corrosion environment and compressive strength after 60 days in laboratory conditions. All the specimens were water-leached after the compressive-strength test and the pH value was determined by potentiometry. X-ray diffraction analysis (Bruker D8 Advance device) in the range of Θ-angle of 5–80° was done as well to test the possible appearance of new phases. The specimens exposed to the CO_2 action were after the compressive-strength test subjected to the phenolphthalein test where 1% solution of phenolphthalein in 70% ethanol was spread on the fracture area. The violet coloring gave evidence that the pH value of the pore solution in the cement gel was higher than 9.5.

2.4. Hydric properties

The wet cup method and dry cup method [24] were employed in the measurements of water vapor transport parameters. The specimens were water- and vapor-proof insulated by epoxy resin on all lateral sides, put into the cup and sealed by technical plasticine. The impermeability of the plasticine sealing was achieved by heating it first for better workability and subsequent cooling that resulted in its

Table 1
Corrosion environments used in the tests.

Environment	Concentration
Air	–
Distilled water	–
$MgCl_2$ (g L^{-1})	17.76
NH_4Cl (g L^{-1})	2.97
Na_2SO_4 (g L^{-1})	14.79
HCl (mol/L)	10^{-3}
CO_2 (vol. %)	65 ± 5

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