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A study on replacement of sand by granulated ISP slag in SCC as a factor formatting its durability against chloride ions

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ABSTRACT

Self compacting concretes (SCCs) modified by different volumes of granulated imperial smelting process (ISP) slag were tested during the research program. Granulated ISP slag was used as a replacement for natural sand. Mechanical properties of such SCCs are already known, but their durability and possible life span of structures made out of them need to be studied further. The conducted tests were focused on chloride ions infiltration into SCCs. The tests were planned in such a way that the achieved results would allow to use a theoretical diffusion model proposed by Szweda and Zybura. The model was verified by a comparison with the results acquired in a real diffusion. Finally, the forecast durability of concrete structures made out of tested SCCs was calculated. The foreseen life span of the structures was differentiated due to thickness of concrete coating of rebars. The proposed approach to SCC with ISP enables reliable prediction of its durability over time and precise technical life span of the structure made out of it. The study proved that replacing sand by ISP slag, even for small ratios, is counterproductive from the durability point of view. It can become feasible, only if an environmental impact study demonstrates it as a very good solution from that point of view.

1. Introduction

Since its invention in the late 1970s, self compacting concrete (SCC) has been becoming more and more popular in the construction industry. Typical modern SCC is characterized by a slump value higher than 200 mm and a slump flow value (the diameter of the concrete pat as described by EN 12350-8) higher than 600 mm. Currently, SCCs are being harnessed for a wide range of demanding civil engineering and structural applications such as underwater foundations, tanks for liquids and gases, bridges, and tunnels (De Schutter et al., 2008). In comparison with ordinary concrete, the creation of SCC mix requires larger quantities of cement, admixtures, and additives. It is also associated with some durability issues of mixes based on different mineral admixtures as reported by Yazıcı (2008). First, an excessive price of a cubic meter of SCC was "covered" by the ability to pour a mix rapidly and consolidate it with no additional costs. The better quality of the end product was of interest too. To limit the production costs and CO_2 footprint of SCCs, numerous attempts were made to use different waste materials for their composition. So far, fly ash and silica had been the two main waste materials utilized in the production of SCC successfully. Hence, researchers decided to focus on the utilization of other waste materials (Yeau and Kim, 2005). Granulated imperial smelting process (ISP) slag (Ferreira et al., 2016) was chosen as the most promising material for SCC production. This waste material is created during the ISP of zinc and lead. ISP is responsible for 13.2% of global zinc production, which in turn is associated with the creation of 975,000 tons of slag per year (Morrison et al., 2003). Some researchers have already tested the influence of granulated ISP slag on the chosen properties of SCC (Tripathi and Chaudhary, 2016). During these tests, sand was partially replaced by slag. SCCs with the addition of granulated ISP slag are characterized by slightly smaller values of compressive strength and other mechanical properties (Atzeni et al., 1996) than SCCs fully based on natural sand. Longer curing time is also needed to reach the same mechanical characteristics of SCC without slag. According to the researchers, these research programs have given a lot of useful information about SCCs with ISP slag, but less knowledge about their durability (Yiğiter et al., 2007). Forecasting and designing the durability of ISP-modified SCC would allow for successful application of this kind of material in concrete production and substantially reduce the amount of ISP slag being land-filled (Weeks et al., 2008).

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Researchers conform that harnessing the theoretical diffusion model proposed by Szweda and Zybura (2013) would enable a feasible prediction of the life span of structures made out of ISP-modified SCC. Technical lifetime of concrete structures, especially bridges, tunnels, viaducts, multistory garages, and marine structures is directly influenced by ion chloride corrosion (Ladomersky et al., 2016). SCCs are very often used to erect road and marine infrastructures, which are exposed to marine atmospheres and require regular de-icing. Ion chlorides that penetrate into concrete will eventually trigger corrosion of steel rebars and stirrups. The corrosion of steel reinforcement will start when the concentration of chloride ions reach the critical value of cement mass originally used for the mix preparation (Angst et al., 2009). Decomposition will occur from the passive layer of the cement in the steel by attack of chlorides. The steel will oxidize, expand and break the bond between rebar and concrete matrix. Subsequently, the coating area will crack and full deterioration process of a concrete structure will start (Andrade et al., 2001). Corrosion of steel reinforcement is now recognized as the major cause of degradation and disintegration of concrete components and structures in many parts of the world (Hansson et al., 2012). Keeping in mind all the above facts authors decided to conduct a research program dedicated to chloride ions infiltration into SCC modified by granulated ISP slag. The tests were planned in such a way that the achieved results would allow to use the theoretical diffusion model proposed by Szweda and Zybura (2013). The theoretical model was then verified by comparing with the results achieved in a real diffusion. The key objective of the research program was to estimate the durability of concrete structures made out of tested SCCs. Reliable prediction of the technical life span of concretes with granulated ISP slag would enable their reasonable application in civil and structural engineering (Della et al., 2000).

2. Chloride diffusion and migration

The rate of penetration of chloride ions into moist concrete is described by the diffusion process. Therefore, the evaluation of the protective properties of concrete coating of steel reinforcement is determined by the values of diffusion coefficient (Castellote et al., 2001). There are three main methods of measuring the diffusion coefficient of chlorides in moist concrete: two diffusion methods and one migration method. The first diffusion method is based on establishing the value of the stable flowing stream of chlorides and subsequent calculation of the diffusion coefficient using Fick's first law (Castellote and Andrade, 2006). The second diffusion method is based on establishing the diffusion coefficient by comparing the distribution of the concentration of chlorides in concrete (determined by experiments) with the numerical solution of a diffusion equation according to Fick's second law (Loser et al., 2010). A major disadvantage of both the methods is the long duration needed for conducting the tests. In the case of ordinary concrete, characterized by a not-so-dense internal structure, it takes roughly a year to achieve a stable flow of chlorides. The examination of SSCs with much tighter internal structure (in comparison with ordinary concrete) would require much longer time and therefore very difficult to conduct and hence not feasible. The third method (a migration method) is an accelerated method based on forcing the flow of chlorides with the help of an electric field. The accelerated method of testing the diffusion of chlorides through concrete was first used by Whiting (1981). The method was then adopted as a routine test in AASHTO T277 and ASTM C1202-97 standards. This method, however, has its own limitations. During the test, instead of the diffusion coefficient, one gets the value of a flowing electric charge. Additionally, during the test, not just the current associated with the flow of chlorides but also the total value of the current passing through the sample are measured. Most of the charges are transported by the hydroxyl ions (due to their almost twice larger mobility than chloride ions). High voltage drop (60 V) and the release of significant quantities of heat associated with it also influence the flow rate of chlorides (Feldman et al., 1994). Tests conducted according to the migration method of chlorides are usually carried out by placing a thin specimen of concrete between two compartments filled with chloride solutions of different concentrations and therein electrodes connected to a source of current (Andrade, 1993). Based on the analysis of changes in the concentration of chlorides penetrating the specimen through the cathode chamber, the mass flow in the stable state is determined and the apparent diffusion coefficient can be assessed. Andrade et al. (1994) proposed to use Nernst-Planck equation for calculating the apparent diffusion coefficient using the results of the migration tests, which has been successfully employed since then (Tang and Nilsson, 1992). The coefficients obtained during the tests of migration and diffusion can be compared. Achieved differences can be scaled using correction coefficients (Zhang and Gjørv, 1994). Calculated values of coefficients were differentiated due to the distribution of the concentration of chlorides in the concrete, after varied duration of the test (Zhang and Gjørv, 1995). Andrade et al. (1994) argued that differences between results achieved by diffusion and migration methods (smaller value of diffusion coefficient established using migration method) are caused by electroosmosis and the formation of electrically neutral particles of $CaCl_2$. Taking all the above facts into account, researchers of this study decided to harness the migration method for establishing diffusion coefficients of SCCs modified by ISP slag. The influence of addition of ISP slag addition on the properties of the protective concrete coating of reinforcing steel was of special interest. Obtained values of diffusion coefficients enabled to forecast the expected technical life span of concrete structures made of material in question. Diffusion tests were also conducted as a reference for results of migration tests. Both sets of results were compared, and reliability of the theoretical model based on migration results was discussed and assessed.

3. Materials and mix composition

Cement CEM I 42.5 R was chosen and used as a binder. Soundness of the utilized cement was checked by Le Chatelier test (expansion of 0.3 mm), initial setting time test (173 min) and compressive strength test after 2 and 28 days of curing (28.9 and 58 MPa, respectively). The used cement was characterized by chloride content (Cl^-) equal to 0.081%. The detailed chemical composition of the used cement is given in Table 1. The fineness of the cement was equal to 0.34 m^2/g. The SCC mix composition was designed using method described by Szwabowski and Gołaszewski

Table 1
Chemical composition and size distribution of granulated ISP slag and cement CEM I 42.5 R.

Constituent	Content (%) by mass		ISP		
	ISP	Cement	Sieve size (mm)	Fraction (%)	Passing (%)
Fe_2O_3	27.9	2.85	0.000–0.063	0	0
SiO_2	24.4	19.5	0.063–0.125	1.2	1.2
CaO	17.6	63.3	0.125–0.250	2.1	3.3
Al_2O_3	15.3	4.89	0.250–0.500	7.2	10.5
MgO	6.4	1.29	0.500–1.000	28.4	38.9
SO_3	–	2.76	1.000–2.000	37.6	76.5
Na_2O	–	0.14	2.000–4.000	20.2	96.7
K_2O	–	0.90	4.000–8.000	3.3	100.0
Zn	5.8	–		$\Sigma = 100.0$	
Pb	2.6	–			