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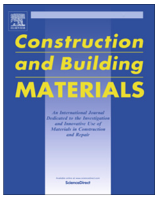

Shrinkage of self-compacting concrete made with blast furnace slag as fine aggregate

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HIGHLIGHTS

- Replacing sand by slag gives rise to mixtures with higher total pore volume.
- At early ages SCCs with slag show similar strength, but in the long term it increases.
- SCCs with slag show a higher autogenous shrinkage.
- Due to their higher porosity, SCCs with slag are less stiff and lose water faster.
- SCCs containing slag show higher total shrinkage.

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ABSTRACT

The aim of this experimental work was to study shrinkage evolution with age in self-compacting concretes (SCC) in which part of the fine aggregate was replaced by granulated blast furnace slag (GBFS) as sand. Seven types of SCC were made with a w/c ratio of 0.55 and different slag contents. The results show that replacing sand by GBFS gives rise to mixes with higher pore volume but with slightly finer porous structure (smaller median pore and threshold diameters). At early ages slag SCCs have similar compressive strength to that of the reference concrete, although in the long term their strength increases as a result of slag reactivity. We also observed that the higher the slag content, the higher were both autogenous and drying shrinkage and consequently also total shrinkage. In comparison with the reference concrete, the increase in total shrinkage was found to be of the order of 4% and 44% when 10% and 60%, respectively, of the sand was replaced by slag.

1. Introduction

Melted slag from a blast furnace can be subjected to various cooling techniques in order to obtain products with a wide range of end-uses. Granulated blast furnace slag (GBFS) is obtained by the rapid cooling of liquid slag. At least two-thirds of its mass consists of vitreous slag [1], which has hydraulic properties when activated and leads to the formation of C–S–H. It has a similar chemical composition to that of crystallized slag, although as it has been subjected to rapid cooling its ions are not given time to organize themselves into a crystalline network and solidify into a vitreous state. As is well known, the hydraulically active component resides in the vitreous phase and the crystalline phase can be considered as almost inert. It is generally thought that the greater its disordered structure the greater is its reactivity [2], although some authors consider that the presence of a small proportion of the crystalline phase may be conducive to increased slag reactivity. The hydraulic capacity of slag is highly attenuated and is slow to appear. There are three methods of accelerating its hydration reactions: (i) by the use of chemical activators, (ii) increasing its specific surface and (iii) by raising its temperature. Portland cement is a good slag activation catalyst as it provides the three main compounds that activate slag: lime, calcium sulphate and alkalis [3]. Granulated slag is formed by small alveolar particles with sharp edges [1].

A number of studies have been published on the use of blast furnace slag as aggregate in concrete and some standards, such as ASTM C33, ASTM C989, EN-206 or EN-12620 also provide specifications for using this slag as aggregate. In many cases a problem arises when the authors do not specify whether they have worked with granulated or crystallized slag, which makes it difficult to reach general conclusions. Furthermore, in the studies which do indicate that granulated slag has been used, the results do not always coincide. According to Mosavinezhad and Nabavi [4] adding

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GBFS to replace sand yielded increased compressive strength but gave lower flexural strength. Shi et al. [5] and Saito et al. [6] point out that at early ages the compressive strength of concrete using GBFS as fine aggregate is lower than concrete made with river sand, but at 91 days the strength is higher. Scandiuzzi and Battagin [7] also obtained better long-term strength due to the latent hydraulicity of the slag. On the contrary, Topçu and Bilir [8] point out that the compressive strength, flexural strength and modulus of elasticity are reduced due to the higher porosity of the mixture and that shrinkage cracking is also reduced. Yüksel et al. [9] and Yüksel and Genç [10] also maintain that replacing sand by GBFS may give rise to concretes of higher porosity and lower strength, according to the replacement ratio employed. However, when no more than 20% of the sand is replaced by slag, the concrete maintains a similar porous structure and GBFS has a positive effect on the concrete's durability properties [11,12].

Replacing part of the aggregates by slag with hydraulic capacity could in theory give rise to concretes susceptible to higher shrinkage, partly due to the volume reduction of the cementitious materials that occurs during their hydration (chemical shrinkage). The lower the w/c ratio, the higher is this shrinkage, especially when the w/b ratio falls below 0.4 [13,14]. However, as can be seen from certain studies [6,8], using GBFS does not necessarily lead to higher shrinkage. GBFS reactions form additional C–S–H phases, which means that the pore network becomes more compact. Indeed, Arellano et al. [15] found that a dense and strong slag–paste interfacial zone was noted as a result of the blast furnace slag participation in the reactions. Increased matrix strength or density reduces material deformability [16] and thus restricts shrinkage. However, very few studies on the use of GBFS as fine aggregate have included the concrete shrinkage involved.

Our objective in this experimental work was therefore to study shrinkage in self-compacting concretes (SCC) in which part of the limestone aggregate had been replaced by GBFS as fine aggregate and to compare the results obtained with those from concretes with no slag content. Due to the fact that shrinkage is directly related to the porous structure of the material, the microstructure of the different types of concrete was analysed in order to explain the behaviour observed. Using GBFS as aggregate firstly has the advantage of recycling waste and secondly the amount of natural aggregate used in the mix is reduced, with consequent savings in natural resources and the energy required for their extraction, together with a reduction of the amount of pollutants released into the atmosphere.

2. Experimental program

2.1. Concrete mixtures, materials and mixing procedure

Seven types of concrete were made: a reference (SCC-0) and six with different percentages of fine aggregate replaced by slag (in weight): 10% (SCC-10), 20% (SCC-20), 30% (SCC-30), 40% (SCC-40), 50% (SCC-50) and 60% (SCC-60). In order to obtain strengths approaching those normally used for building, all of them were manufactured with a 0.55 w/c ratio. The characteristics of each mix are shown in Table 1. All SCC mixes showed a slump flow of about 700 mm and good resistance to segregation in the segregation test.

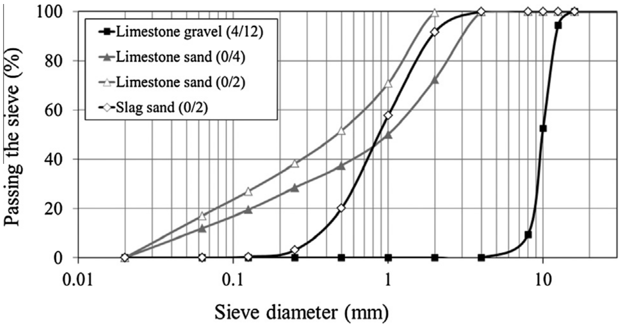

Fig. 1. Grading curves of slag and aggregates.

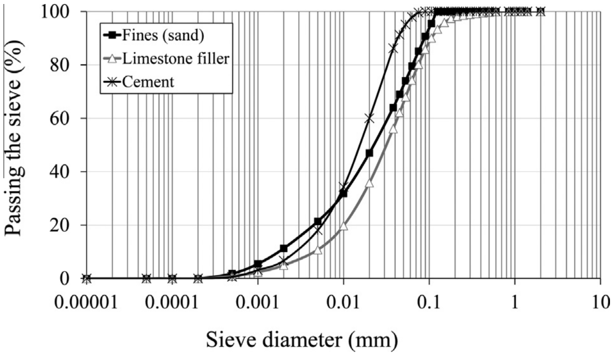

Fig. 2. Grading curves of cement, aggregate fines and limestone filler.

All the studied mixes were made with 375 kg/m^3 of CEM II/B-M (S-L) 42.5R cement, and 25 kg/m^3 of fly ash. The granular skeleton was composed of three fractions of crushed limestone aggregate: 4/12 mm coarse aggregate, 0/4 mm coarse sand and 0/2 mm fine sand, with a fines content (particle size <0.063 mm) of 1.0%, 12.0% and 17.1%, respectively (Fig. 1). The process of replacing sand by slag was carried out by firstly removing the fine sand only, and when this was exhausted (in concretes SCC-20–SCC-60), by also removing part of the coarse sand. Limestone filler was added to these mixes to make up for the lack of fines in the slag. The grading curves of the fines of aggregates and the filler were determined by means of laser diffraction (Fig. 2). As can be seen in this figure, the aggregate fines are finer than the limestone filler used. The basic GBFS used had high SiO$_2$ and CaO contents, with a CaO/SiO$_2$ ratio of 1.31. As regards its mechanical properties, the slag had a Micro-Deval index much lower than that of the limestone aggregates, and therefore had greater resistance to wear. The properties of the sand and slag are shown in Table 2 and the composition of the slag is shown in Table 3. The admixture used was a polycarboxylate-based superplasticizer (Viscocrete 3425). The concrete test specimens were made by filling moulds with a single uncompacted lift of SCC.

2.2. Test program and methodology

2.2.1. Shrinkage test

Prismatic specimens measuring 100 × 100 × 400 mm were used to determine autogenous shrinkage and total shrinkage. Temperature and weight loss were also measured in order to obtain further information on this phenomenon. Thermocouples were inserted into the centre of the specimens immediately after casting to determine the evolution of temperature rise due to the hydration reaction.

Table 1
Mixture proportions of concretes.

Mix	Sand replacement ratio (%)	Cement (kg/m^3)	Fly ash (kg/m^3)	Water (l/m^3)	WEA (kg/m^3)	Coarse aggregate (kg/m^3)	Coarse sand (kg/m^3)	Fine sand (kg/m^3)	Limestone filler (kg/m^3)	Slag sand (kg/m^3)	Paste volume (dm^3)
SCC-0	0	375	25	220	4.4	656.6	829.7	260.3	0.0	0.0	410.9
SCC-10	10	375	25	220	4.2	656.8	829.6	124.8	26.9	102.7	412.1
SCC-20	20	375	25	220	4.4	656.6	818.4	0.0	53.6	205.4	413.9
SCC-30	30	375	25	220	4.6	656.5	691.4	0.0	71.4	308.0	415.1
SCC-40	40	375	25	220	4.8	656.3	564.4	0.0	89.1	410.6	416.2
SCC-50	50	375	25	220	5.2	656.0	437.5	0.0	106.8	512.9	417.6
SCC-60	60	375	25	220	6.0	655.4	310.5	0.0	124.4	614.7	419.3

(WEA: water enhancement admixture).