Construction and Building Materials 129 (2016) 98–105

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Restrained shrinkage behavior of Self-Compacting Concrete containing ground-granulated blast-furnace slag

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HIGHLIGHTS

- Restrained shrinkage behavior of Self Compacting Concrete with GGBS is studied.
- Effect of GGBS proportion, curing regime and degree of restraint is reported.
- Appropriate use of GGBS for degree of restraint and curing conditions is reported.

ARTICLE INFO

Article history:
Received 28 March 2016
Received in revised form 10 October 2016
Accepted 31 October 2016
Available online 9 November 2016

Keywords:
Self Compacting Concrete
Shrinkage
Cracking
Degree of restraint
Ground-granulated blast-furnace slag

ABSTRACT

The restrained shrinkage cracking and relaxation behavior of Self Compacting Concrete (SCC) containing different proportions of ground granulated blast furnace slag (GGBS) is studied. The effects of GGBS proportion, degree of restraint and curing regime are specifically addressed. The results show that GGBS improves the cracking resistance and relaxation behavior of SCC relative to control. Curing condition and degree of restraint play a significant role on the cracking and relaxation behavior of SCC. The results revealed that GGBS can replace cement by up to 70% and 50% for low and high degree of restraint, respectively, provided moist curing is adopted.

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1. Introduction

Self-Compacting or Self-Consolidating Concrete (SCC) is a class of concrete that, when poured inside a formwork, compacts itself due to its own weight without segregation and bleeding while flowing through reinforcing bars. As a result, the use of SCC reduces skilled labor cost and construction time. In addition, when building new developments with several similar buildings, the self-compaction feature ensures homogeneous mechanical properties of concrete across all buildings and all structural elements.

Typically, SCC uses less volume of coarse aggregates, less w/c ratio, and employs superplasticizers. The use of superplasticizers produces highly deformable SCC [1]. The low volume of coarse aggregates comes at the expense of increased volume of cement powder, leading to heat generation problems and higher costs in addition to the increased total shrinkage [2,3]. To address these issues, the cement powder in SCC is partially replaced with supplementary cementitious materials (SCMs) [2,4–7]. Usually, these admixtures include Fly Ash (FA), Micro Silica (MS), and ground-granulated blast-furnace slag (GGBS). The mineral nature of these SCMs, reduces cost and improves both fresh and hardened properties of SCC [5,7,8], and promotes sustainability through the use of by-products. For instance, GGBS is a by-product of iron making and when mixed with ordinary cement provides a durable concrete that extends the life of reinforced concrete structures. GGBS slows down the setting process of concrete, leading to a gain in strength over an extended period of time. A concrete supplemented with GGBS has the capacity of lowering heat generation during hydration process and increasing resistance against attacks of sulfate and chloride, making it suitable for marine applications.

Although SCMs have the direct advantage of reducing the amount of cement, it was demonstrated that the cracking potential for the SCC mixes was affected significantly by the type and proportion of these admixtures, curing regime, and degree of restraint [9]. For instance, Yasumoto et al. [10] showed that the resistance level of SCC to shrinkage cracks was quite different depending on type of powdered materials used. In addition, laboratory tests demonstrated that the degree of autogenous shrinkage of SCC depends on powdered material types used and it becomes

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http://dx.doi.org/10.1016/j.conbuildmat.2016.10.115
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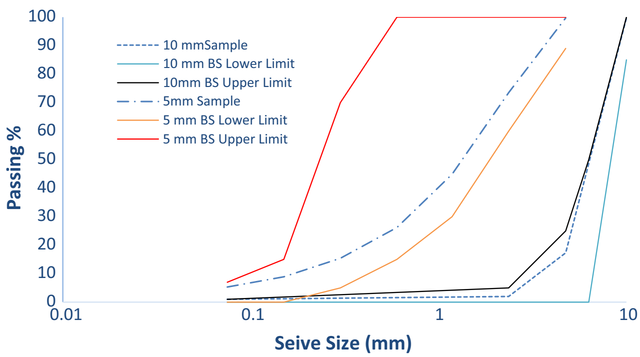

Fig. 1. Grading curves for the 10 and 5 mm aggregates.

especially larger with increasing of GGBS content [11–13]. Akkaya, et al. [14] on the other hand concluded that using supplementary cementitious materials increases the drying shrinkage and decreases the autogenous shrinkage, however, no significant difference in the total shrinkage was noticed and under restraint condition using such materials was shown to delay the age of cracking. In a recent study by Wei and Hansen [15] GGBS was used to replace the cement by 30% and 50% and the early age restrained shrinkage was assessed by using a uniaxial restrained test. The results showed a delay in the tensile stress development and cracking time due to the replacement of cement by GGBS, especially with the 50% replacement. The slag effect on delaying cracking time was also pronounced in high w/cm (0.45) mixtures [15].

To achieve a sufficient strength capable of reducing the cracking of concrete, curing has to be taken into consideration [16] especially when SCMs are used, since the pozzolanic reaction happens only in the presence of water [17]. Bilodeau et al. [18] suggested that using moist curing for seven days with mixes containing fly ash gives the maximum compressive strength, in contrast, the continued presence of water is required for GGBS reaction to continue and attain the maximum strength [19]. This is due to the slower, but prolonged reaction (hydraulic and pozzolanic) between cement hydration products and GGBS, which contributes significantly to strength.

Cracking potential of SCC is influenced by the shrinkage and relaxation characteristics, as well as, the early strength and tensile stress development of the mix under restrained conditions. These interdependent characteristics are governed by environmental and material parameters. The focus of this paper is to investigate the effect of GGBS replacement level, curing regimes, and the degree of restraint on the cracking potential of various SCC mixes.

2. Materials and methods

The main parameters that influence the cracking potential of SCC containing GGBS as SCM include the proportion of GGBS, the curing condition, and the degree of restraint. Therefore, the current testing regime was designed to study the effects of these parameters on the cracking potential and relaxation of such concretes.

2.1. Materials

Ordinary Portland cement (Type I) with specific gravity of 3.15 and fineness of 359 m^2/kg, ground granulated blast furnace slag (GGBS) with specific gravity of 2.9 and fineness of 380 m^2/kg, and Class F Fly Ash with a specific gravity of 2.3 and activity index of over 75% at 28 days determined according to BS EN450, were used in this research. The activity index of GGBS with 50% and 70% replacement of cement by mass was determined at the ages of 7 days and 28 days in accordance with BS 6699 and BS EN 15167-1:2006. For 50% GGBS, the activity index was found to be 84% and 94% at 7 and 28 days, respectively; while for 70% GGBS replacement, it was 65% and 86% at the same ages. The activity index values at 7 and 28 days meet the requirements of BS 6699 and BS EN 15167-1. The coarse aggregate was 10 mm crushed Gabro aggregates with water absorption and specific gravity of 0.9%, and 2.96, respectively. The fine aggregates consists of crushed dry sand, crushed washed sand and dune sand with absorptions and specific gravities of 1.5%, 1.4%, and 0.8%, and 2.78, 2.74, and 2.63, respectively. Grading curves for the 10 and 5 mm aggregates are presented in Fig. 1. Poly-Carboxylate Based High Range Water Reducing Admixture (HRWRA) CHRYSO® Fluid Optima 230 was used in addition to the Viscosity Enhancer Admixture (VEA) Feyplast® SUB-AQUA.

2.2. Mix proportions and test matrix

A total of five SCC mixes with a target compressive strength of 60 MPa were designed and tested. Table 1 presents the composition and the 28 day compressive strength of the SCC mixes. The control mix contained cement only and no other SCM. GGBS partially replaced the cement in three mixes by 35%, 50%, 70% while the fourth mix had a combination of 35% GGBS with 35% fly ash. The content of coarse and fine aggregates was in line with the recommendations of the European Guidelines for Self-Compacting Concrete [20].

All mixes have water to binder (w/b) ratio of 0.36, total binder content of 450 kg/m^3 and fine to total aggregate (FA/TA) ratio in the range of 0.57 to 0.6. The dosages of admixtures were adjusted such that the mixes exhibited similar fresh properties as illustrated in Table 2. Slump Flow in the range of 600 to 750 mm, a T_{500} time between 3 to 10 s and L-Box ratio $\geqslant 0.7$ were targeted in this study based on existing guidelines [21,22].

Three different curing regimes were adopted in this study. In each, regime the specimens were sealed for 24 h after casting and then either exposed to air drying (curing regime 1), or wet cured for three days (curing regime 2) or seven days (curing regime 3) before being exposed to air drying. The curing regimes were

Table 1
SCC Mixes Proportions.

Mix No.	w/b	Cement	Supplementary Cementitious Materials (SCMs)			Total (Cement + SCMs)	Coarse Agg.	Fine Agg.	HRWRA	VEA	fc′ 28 days
		kg/m^3	Type	% used to replace the Cement	kg/m^3	kg/m^3	kg/m^3	kg/m^3	L/m^3	kg/m^3	MPa
1	0.36	450	–	–	–	450	736	1101	6.5	0.6	69
2	0.36	292	GGBS	35	158	450	747	1096	5.5	–	61
3	0.36	225	GGBS	50	225	450	748	1094	6	0.5	65
4	0.36	135	GGBS	70	315	450	738	1083	5.5	0.6	62
5	0.36	136	GGBS	35	157	450	775	1017	6.5	0.5	58
			Fly Ash	35	157						

HRWRA: High Range Water Reducing Admixture: VEA: Viscosity Enhancer Admixture: SCMs: Supplementary Cementitious Materials.

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