Construction and Building Materials 170 (2018) 660–667

Contents lists available at ScienceDirect

Construction and Building Materials

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

Mechanical characteristics and durability of self compacting concretes produced with ladle furnace slag

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HIGHLIGHTS

- The main target of this research is to investigate the potential to use ladle furnace slag (LFS) as an alternative filler material for the production of SCC.
- Durability properties of low and medium strength SCCs produced with addition of LFS were evaluated and compared with those measured on reference SCCs produced with addition of limestone filler.
- Water absorption, carbonation resistance, chloride induced corrosion and resistance to freeze-thaw attack were assessed.
- Addition of LFS enhanced all durability properties tested.
- LFS produced SCC may significantly extend the service life of concrete structures, especially when carbonation is the main aggressive factor.

ARTICLE INFO

Article history:
Received 10 May 2017
Received in revised form 22 February 2018
Accepted 11 March 2018

Keywords:
Selfcompacting concrete
Ladle furnace slag
Durability
Sustainability

ABSTRACT

Steel making slag is the process for producing steel from iron or scrap. Modern steelmaking processes can be broken into two categories: primary and secondary steelmaking. Secondary steelmaking is most commonly performed in ladles and often referred to as ladle. The main by-product of this process is ladle furnace slag (LFS). In this paper self-compacting concrete (SCC) mixtures were produced, in which, filler was replaced by LFS. Three different strength classes were tested and LFS was used in different contents ranging from 45 to 92.5 kg/m^3. SCC mixtures were tested in the fresh state for fluidity, passing ability and resistance to segregation. In the hardened state these mixtures were tested for compression strength, resistance to carbonation, sorptivity, resistance to chloride penetration and to freeze-thaw. The results concluded that, LFS enhances the durability characteristics of concrete leading to environmentally friendly concrete mixtures with lower cost.

1. Introduction

Self-compacting concrete (SCC) is a special type of concrete developed during the last two decades. This is characterized by the potential to improve the quality of concrete elements as well as the quality of the whole construction procedures. It is widely used in different applications such as ready-mixed concrete and the precast industry because of its many advantages. It can spread into moulds by the force of gravity and fill restricted areas without the need of concrete vibrators, reducing, this way, potential accidents (noise injuries, vibration white finger), enhancing the working environment and the quality of the structure, lowering the manpower need and accelerating the construction process [1–3]. Filling ability, segregation resistance and passing ability are the main fresh properties of SCC. Self compactability is connected with the dosage of fine materials. The materials passing the 0.125 mm sieve are regarded as fine. Their amount should be in the range of 380–600 kg/m^3, according to the European Guidelines for Self Compacting Concrete [4].

Limestone powder is most commonly used as filler material in SCC mixtures. In Greece, limestone powder production is limited (two mines nationally) and its cost is rather high, so unappealing to engineers. Therefore, the replacement of this material is critical. So far research has shown that replacing either cement or lime filler or both in SCC is feasible and some industrial by-products have already been used in this direction with hopeful results [5–7].

The main by-product of secondary steelmaking process is ladle furnace slag (LFS). It constitutes mainly of calcium oxides as well as silica, magnesium and oxides [8]. Several researchers have shown that LFS performs latent hydraulic and pozzolanic properties and could be used as an alternative binder for cement and concrete

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https://doi.org/10.1016/j.conbuildmat.2018.03.091
0950-0618/

production [9–15]. The presence of free lime and magnesia in LFS could cause some problems due to delayed expansion phenomena [16] and several methods have been proposed for the control of the long term expansion of LFS such as rapid cooling of LFS [17], weathering in outdoor conditions for a period of at least six months [18,19], its use in ternary systems with siliceous material and cement [20], and mixing with inert material [21]. The reactivity of the furnace slag, as an additional binder, increases significantly with its fineness. This increase can be achieved by selecting the finer fragment of the material or by grinding it, although with the latter one a higher final strength is developed [22]. Papayianni and Anastasiou [23] reported that although sieving can give very fine material with increased specific surface, ground LFS developed higher strength levels. They attributed this trend to the increase of the reactive constituents in the ground material due to the process of grain crushing. Regarding strength development, they concluded that ground LFS at 20% cement replacement rate developed 93.3% of the strength of the reference mortar.

Because of the increased fineness of the material, several investigators researched the possibility to use it as a filler material in order to increase the total powder content in self compacting (SCC) concrete [24–27]. They reported that LFS can be used to increase powder content in SCC without compromising self-compactability, strength or durability.

Increased LFS content reduced the risk of segregation provided that a suitable dosage of superplasticizer has been used to ensure adequate fluidity [26], while SCC mixtures prepared with LFS performed lower superplasticizer demand compared with traditional SCC mixtures prepared with limestone filler [24]. LFS had a positive effect on strength development concerning 28-day and 120-day compressive strength [26] and increased the durability performance of the mixtures [25–27]. SCC with ladle furnace slag in its composition found to be more susceptible to spalling effects after fire exposure compared to limestone SCC mixtures because of the pore refinement in the concrete matrix [25].

The main target of this research is to investigate the potential to use ladle furnace slag (LFS) as an alternative filler material for the production of SCC.

2. Materials and methods used

2.1. Design materials

Thirteen different self-compacting concrete mixtures were produced. The mixtures belonged in the strength classes C25/30, C30/37 and C35/45 according to EN206-1 [28].

The cement used in all concretes was Blended Portland Cement, of the type CEM II A-M/42.5 N conformed to the European standard EN 197-1 (Table 1). SCCs were produced and tested in fresh condition according to the instructions of EFNARC [4]. The maximum size of coarse aggregates was 16 mm and composed of crushed granite. On the other hand, the fine aggregates used, consisted of limestone sand. Three mixtures were used as reference concretes, one for each strength grade; C25/30, C30/37 and C35/45 (SCC1, SCC6 and SCC13 respectively), in which the additional filler material used was limestone filler.

Table 1
Chemical characteristics of the materials used.

Percentage (%)	CEMII (A-M) 42.5N	Limestone filler	Ladle furnace slag
SiO_2	23.85	1.80	6.53
CaO	58.20	65.70	30.86
Al_2O_3	5.22	0.45	2.33
Fe_2O_3	4.13	0.08	8.69
K_2O	0.68	–	0.31
Na_2O	0.32	–	0.33
TiO_2	0.24	0.17	0.14
P_2O_5	0.06	0.02	0.02
MgO	3.20	0.68	4.52
SO_3	3.30	0.05	–
LOI	1.57	30.85	3.19
Specific weight (kg/m^3)	3.10	2.65	2.45

Ladle furnace slag was used as an alternative filler material replacing aggregates in four SCC mixtures at percentages of 15% and 25% per weight of cement (SCC2, SCC3, SCC7 and SCC8 respectively). In order to further improve the environmental footprint of the concretes, cement content was also reduced at percentages of 10% and 15% in six more mixtures (mixtures SCC4, SCC5, SCC9, SCC10, SCC11 and SCC12). In these cases LFS was added at percentages of 15% and 25% per weight of the reduced cement (Table 1). Ladle furnace slag is a fine material with 100% passing the 96 μm sieve and 95% passing the 45 μm sieve.

SCC gains its fluid properties from an unusually high proportion of fine aggregate, combined with polycarboxylate ether-based superplasticizers. The dosage of this admixture and the properties of fresh mixtures are presented for all concretes in Table 2. Segregation of SCC was evaluated through the visual analysis index method of the slump cone test.

2.2. 2Mixing, curing and testing procedure

The concretes were produced and compacted according to EN 206-13 [28]. The specimens were molded in the appropriate casts, according to the requirements of the property measured. After demoulding specimens were inserted in a curing chamber (20 ± 2 °C temperature and >98% air humidity) till the time of the test.

The mechanical properties measured in all SCC mixtures were the compressive strength and the splitting tensile strength. The compression testing machine used in all cases was Buehl&Fabel with 3000 KN capacity. The compressive strength was measured using cubes with an edge of 150 mm, according to [29], at the ages of 2, 7, 28 and 90 days. The durability properties examined were the water absorption, the carbonation resistance, the resistance to chloride attack and the resistance to freezing and thawing of concrete mixtures. Specimens of different size were used for assessing the durability characteristics and different curing scenarios followed according to the relevant standards of each property.

The water capillary absorption was measured according to the procedure described by RILEM TC116 [30] which constitutes specimen weight change due to water uptake (capillary absorption). Pre-weighted 150-mm cubes were used. The absorbed water quantity was estimated at different time intervals.

The accelerated carbonation test was conducted on 60 × 100 mm cylindrical specimens, initially wet cured for three days and thereafter left in the laboratory air environment (relative humidity = 50–60% and temperature = 20 ± 2 °C) for 25 more days. At the age of 28 days, the specimens were placed in an accelerated carbonation chamber with relative humidity = 55–60%, temperature = 21 ± 2 °C and CO_2 = 1%, where they were cured for 60 days. A second series of 60 × 100 mm cylindrical specimens was exposed after the age of 3 days in outdoor conditions and remained in unsheltered exposure conditions for 24 months. This environment corresponds to the exposure class XC4 according to EN206-13 [28].

Chloride diffusion was estimated using the NordTest Build 492 test [31]. This is a quantitative method which determines the chloride migration coefficient of concrete specimens, using a non-steady-state migration experiment. The depth of chloride penetration was determined from the colour change in the area where the presence of chlorides chemically reacted to form silver chloride.