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Behavior of self compacting concrete containing ladle furnace slag and steel fiber reinforcement

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ABSTRACT

Self compacting concrete mixtures with the use of ladle furnace slag as filler and steel fibers as reinforcement were produced and tested in the laboratory. Different contents of ladle furnace slag filler, ranging from 60 to 120 kg/m^3, and steel fibers, ranging from 0% to 0.7%, were used. The different mixtures were tested in the fresh state for fluidity, passing ability and resistance to segregation and in the hardened state for compressive strength, fracture toughness, freeze-thawing resistance and chloride penetration resistance. The test results showed that ladle furnace slag can be used as filler for self compacting concrete, as adequate consistency and workability was achieved, while compressive strength and durability were improved. Ladle furnace slag can also be combined with steel fibers, which considerably increase fracture toughness, in order to produce a high performance self compacting concrete using a low-cost industrial by-product such as ladle furnace slag.

1. Introduction

Self compacting concrete (SCC) is receiving increased attention from concrete designers over the past years due to its technical benefits; high consistence for concrete placement over heavily reinforced elements, ability to fill irregularly shaped formworks, improved final surface, shortened construction time and reduced labor costs. The constituents of SCC do not vary greatly from ordinary concrete, but most commonly include the use of filler and chemical admixtures, while fiber reinforcement is also used in some cases. These constituents along with the required flowability alter the mix design process compared to ordinary concrete. Several reports investigate optimal mixture design methods by using either statistical methods [1], or by measuring fresh concrete properties and especially flowability [2], while Ferrara et al. [3] attempt to model the paste rheology in fiber-reinforced SCC. The performance of SCC mixtures with varying mix design parameters has been investigated by Khayat [4], while other researchers have also focused on the mechanical strength and durability properties of SCC with mineral admixtures commonly used in ordinary concrete [5,6]. Based on the existing scientific knowledge and applied research, technical guidelines have been established both in Europe [7] and in the USA [8], which point out to the fact that, since high fluidity and robustness should be the basic characteristics of SCC, special attention is required when proportioning SCC mixtures compared to ordinary concrete production. Increased powder content by the use of suitable filler, modifications in aggregate gradation and use of chemical admixtures are often required in order to achieve the desired properties of fresh SCC. These changes often increase initial concrete production cost and, therefore, low-cost alternatives for high-performance SCC are sought, such as the use of industrial by-products as supplementary materials [9].

The requirement for increased powder content in SCC has been addressed either by increasing the binder content or by using other types of fine material such as limestone filler. The present study focuses on the use of ladle furnace slag (LFS), a by-product of the steel production process, as a means for increasing the total powder content in SCC. LFS is a fine material that shows some weak pozzolanic and latent hydraulic properties [10], but in its raw state does not qualify as a type II addition in concrete [11]. However, research shows that it is possible to use LFS in construction applications such as soil improvement [12] and masonry mortar production [13]. Shi [14] suggests chemical activation in order to improve the cementitious properties of LFS, while Anagnostopoulos et al. [15] explore its use as filler in concrete. Fiber reinforcement, on the other hand, is a well-known practice used to improve toughness and to reduce crack growth in concrete [16], while the use of different fiber sizes [17] and different fiber types [18] has varying effects on fresh and hardened concrete properties. Many types of fibers have been used successfully as self compacting concrete reinforcement, but the most common are either steel

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or synthetic fibers. Brown et al. [19] report that SCC of adequate flowability and increased residual strength and toughness can be produced at fiber reinforcement concentrations up to 0.3% by volume for synthetic fiber and up to 0.5% by volume for steel fiber, El-Dieb [20] investigates similar steel fiber contents for the production of ultra-high-strength SCC, while Khayat and Roussel [21] explored SCC mixtures with steel fiber concentrations up to 1.0% by volume with the use of viscosity modifying agents. The combination of steel fiber reinforcement up to 1.0% by volume with SCC provides a technical solution for structural applications requiring highly flowable concrete of increased ductility and durability. Applying a self compacting approach to fiber reinforced concrete could improve fiber dispersion, reduce the risk of inadequate workability and facilitate placement and compaction. However, the fibers are expected to reduce the flowing and passing ability of fresh SCC, which is already sensitive to mix design alterations. This issue has been addressed in the literature by applying limits to fiber content and size, while increased use of chemical admixtures is often advocated [22,23].

The objective of this study is to test the possibility of using LFS as a low-cost alternative material in SCC and especially to determine its effect on fresh concrete properties, mechanical strength, including toughness, as well as freeze–thaw resistance and chloride ingression resistance. Different amounts of LFS addition have been used in mixtures with varying fiber contents in order to produce robust SCC mixtures with relatively low cement content.

2. Experimental setup

2.1. Materials

Portland cement CEM I42.5 N was used in all mixtures as binder. A quantity of 350 kg/m^3 was selected for all the test mixtures, in order to achieve an economic SCC mixture. Since increased powder content is required to meet the flow and passing ability requirements in SCC, ladle furnace slag (LFS) obtained from a local steel industry in Thessaloniki, Greece, was used as filler. The LFS used was sieved in order to pass from the 100 μm sieve and its chemical characteristics, as well as those of the Portland cement used, are shown in Table 1. The lime-pozzolan strength was determined for LFS according to ASTM: C593-06 and was found equal to 1.01 MPa and 1.28 MPa for 7-day and 28-day compressive strength, respectively.

A polycarboxylic based superplasticizer and a water-soluble polymer based viscosity modifying agent (VMA) were used as chemical admixtures. The aggregates used were local crushed limestone, with apparent specific density equal to 2650 kg/m^3 and water absorption for saturated surface dry condition equal to 1.0%. The aggregates were provided in three fractions; 0–4 mm, 4–8 mm and 8–16 mm, which were mixed in order to produce the aggregate gradation curve shown in Fig. 1.

Table 1
Characteristics of the fine material used for FRSCC test mixtures.

Material constituents (%)	CEM I42.5 N	Ladle furnace slag
SiO_2	19.60	32.41
CaO	66.84	50.65
Al_2O_3	2.40	1.36
Fe_2O_3	8.11	2.66
SO_3	1.24	2.30
MgO	3.91	2.77
K_2O	1.08	0.06
Na_2O	0.57	0.78
Loss on ignition	1.91	6.72
Fineness (R_{45} retained, %)	1.50	22.00
Apparent specific density kg/m^3	3140	2555

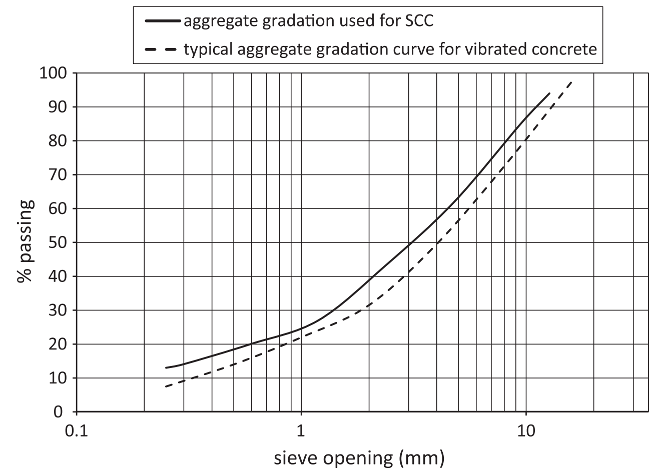

Fig. 1. Aggregate mix gradation.

2.2. Mix design

Different rates of ladle furnace slag were used; 60, 90 and 120 kg/m^3, producing three series of test mixtures; A, B, and C, respectively. Since the cement content was kept constant at 350 kg/m^3 and the fraction of the fine aggregate lower than 125 μm was 40 kg/m^3, the total powder content ranged from 450 kg/m^3 to 510 kg/m^3. The water to cement ratio was kept equal to 0.50 in all mixtures, but with increased LFS content, the water to powder ratio decreases. Also, in order to achieve the required fluidity, a reduced maximum aggregate size as well as increased fine aggregate content are suggested [24]. In all the test mixtures, crushed limestone of 16 mm maximum size was used and fine aggregate consisted 50% of the total aggregates, producing an aggregate gradation curve suitable for SCC. A second parameter for the test mixtures was the content of steel fibers; hook end steel fibers of 30 mm length and length to diameter aspect ratio equal to 60 were used at rates of 0%, 0.4% and 0.7% by volume. The maximum fiber content was limited to 0.7% by volume, based on previous experience and literature, in order to achieve adequate fluidity and self-compactability [21,25]. Chemical admixtures were used in order to achieve the desired fresh mixture properties. A polybarboxylic-based superplasticizer was used in all mixtures in order to improve workability, but in mixtures with lower water to powder volume, higher dosage of superplasticizer was required, while in mixtures with steel fibers, the use of a viscosity modifying agent was necessary to avoid segregation. A total of 9 test mixtures was produced in the laboratory, as shown in Table 2.

The mixing sequence involved dry-mixing the aggregates and then adding cement, ladle furnace slag, water with chemical admixtures and fibers for a total mixing time of 4 min. The fresh concrete properties were measured within 30 min after mixing and, subsequently, the molds were filled without compaction. The specimens produced were cured in a climatic chamber with 20 °C and 95% RH for 28 days and then stored in outdoor conditions.

2.3. Testing Methods

The self compactability of the fresh concrete mixtures was assessed by measuring slump flow, T_{500} time, L-box passing ratio and segregation resistance. The slump flow and T_{500} time were used to determine the flowability and viscosity of the fresh mixtures, respectively. A slump flow value between 500 and 700 mm was considered acceptable [26]. The L-box was used to determine