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EAF SLAG IN SELF-COMPACTING CONCRETES

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Abstract. *Self-compacting concrete (SCC) captures a growing interest because of its several advantages in technical, economic and environmental terms. Especially the attention for the environmental aspects moves the research towards recycling industrial by-products, as fly ash and steel slag. In particular, there are few experimental works about the use of EAF slag in SCC. This paper summarizes the first results of an ongoing experimental work to investigate the use of EAF slag in SCC as medium aggregate.*

Key words: *self-compacting concretes, EAF slag, medium/coarse aggregates, compressive strength.*

1. INTRODUCTION

Self-compacting concrete (SCC) was first developed in Japan [1] in order to create uniformity in the quality of concrete by controlling the problem of insufficient compaction by a workforce that was lacking skilled labour and by the increased complexity of designs and reinforcement details in modern structural members. Durability was the main concern and the purpose was to develop a concrete mix that would reduce or eliminate the need for vibration to achieve consolidation and in effect SCC flows under its own weight and maintain homogeneity while completely filling any formwork and passing around congested reinforcement, which means a reduced cost of placement, a shortening of the construction time and therefore an improved productivity, especially in precast concrete plants. In the hardened state, it equals or excels standard concrete with respect to strength and durability, by offering an excellent surface finish without blowholes or other surface defects, because of the optimised combination of the individual components of the concrete mix [2]. The prospects for SCC can be retrieved in [3].

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The SCC differs from conventional concrete in the following three characteristic features, namely, appropriate flowability, non-segregation, and no blocking tendency. An increase in the flowability of concrete is known to increase the risk of segregation. Therefore, it is essential to have proper mix design. Due to its rheological requirements, filler additions (both reactive and inert) are commonly used in SCC to improve and maintain the workability, as well as to regulate the cement content and to reduce the heat of hydration. Part of this powder content can be effectively replaced by mineral admixtures like fly ash, silica fume, etc. [4]

The present work has been conceived following the general purpose of testing new sustainable production processes, as these involved by the SCC, in the construction field, in order not just to save natural raw materials and reducing energy consumption, but also to recycle industrial by-products. In particular, the present paper summarize initial experimental investigation to quantify the influence of electric arc furnace (EAF) slag on the properties of fresh and hardened self-compacting concretes.

Electric arc furnaces (EAF) and blast furnaces represent the main steel making processes used in the Italian iron metallurgy. Two million tons of slags are yearly produced by Italian electric arc furnaces[5].

With regard to the environmental laws in force, a portion of this by-product of the iron industry is processed in order to take on proper technical features and it is mainly used as aggregates for road construction (e.g. asphaltic or unbound layers) and as armourstones for hydraulic engineering constructions (e.g. stabilisation of shores); other possible applications are under study and this work would be an example.

Procedures like a treatment of the liquid slag, an appropriate heat treatment and a suitable processing have been developed to ensure that the quality of steel slags is always adequate for the end use. It was shown [6,7] that a proper treatment aimed to stabilize slag by exposing them to outdoor weather and regular spraying for at least 90 days, may eliminate any subsequent expansive phenomenon, allowing a safe use of such slag as aggregate in concrete production.

After this processing the slag is double crushed and the resulting materials are divided and commercialised in different fractions (three for the material here considered).

Depending on the respective field of application, the suitability of steel slags has to be proven by determining the technical properties as well as the environmental compatibility. For this reason test methods have been developed to evaluate the technical properties especially the volume stability and the environmental behaviour. To determine the environmental behaviour, leaching tests have been developed in order to verify that the potential toxic compounds are under the limit values reported in the Italian standard [8].

To the best knowledge of the authors, the present literature does not offer examples about the use of EAF slag in SCC in substitution to medium or coarse aggregates.

In [9] ground granulated blast-furnace slag was added as fine in substitution to cement in SCC; similarly, in [10] EAF slag, combined with AOD slag, was used as filler in SCC, but since some investigation [11] revealed that EAF slag, as fine aggregates in the ordinary concrete, caused pop-out in concrete walls, the more appropriate use of EAF slag seems to be in substitution to medium or coarse aggregates. In this sense, there are some works which are referred to the use of EAF slag in ordinary concretes [12, 13].

In this work the use of EAF slag in substitution to medium aggregates in SCC was preliminarily investigated, first in combination with limestone filler and afterwards with other industrial by-product, as fly-ash, and recycled aggregates, which was obtained by crushing precast production waste.

The workability-related fresh properties of SCC were observed through slump flow diameter, V-Funnel flow time, J-Ring and L-Box tests. The only hardened property that was included in this study was the 28-days and 24-hours compressive strength, since early compressive strength is very important for precast structures.

2. Experimental Setup

2.1 The EAF slag and the other materials

Steel slag, originated in electric arc furnaces for continuous steel production, have stone-like appearance, black colour with small white agglomerations of calcium carbonate and high roughness. This study dealt with a EAF slag whose chemical and physical properties are described in Table 1.

Table 1 Main characteristics of EAF slag aggregate

Size (mm)	4.0-8.0
Bulk specific gravity (kg/m^3)	1940
Water absorption (%)	2
Los Angeles loss (%)	17
$Fe_{[O]}$ (%)	30.31
SiO_2 (%)	13.7
CaO (%)	26.3
Al_2O_3 (%)	6.0
MgO (%)	3.4
MnO (%)	6.0
Na_2O (%)	0.3
P_2O_5 (%)	0.6

All the materials used in this study were readily available on the market.

In this research ordinary Portland cement, EAF slag, sand, gravel, limestone filler and superplasticiser were used.

Besides, binary and ternary compositions were studied, by combining first EAF slag with fly ash and after with fly ash and recycled aggregates, obtained by crushing precast production waste.

The concrete mixtures were prepared with cement CEM I 52.5 whose characteristics are tabled in Table 2. Crushed limestone fine (0-4 mm) and medium/coarse aggregates (4-8 mm and 6-12 mm) was used in this study. The bulk density of the fine and medium/coarse crushed limestone aggregates was 1575 kg/m^3 and 1450 kg/m^3 respectively, and their absorptions were 0.45% and 0.63% respectively. The grading curves of EAF slag, fine, medium/coarse and recycled aggregates are shown in Figure 1.

Table 2 Characteristics of the cement and mineral admixture

	Cement	Fly ash
Blaine fineness (cm^2/g)	4975	2870
Loss of ignition (%)	1.64	1.78
SO_3 (%)	3.41	0.49
Cl- (%)	0.0173	-
2-days compressive strength (Mpa)	41.03	-
28-days compressive strength (Mpa)	60.61	-

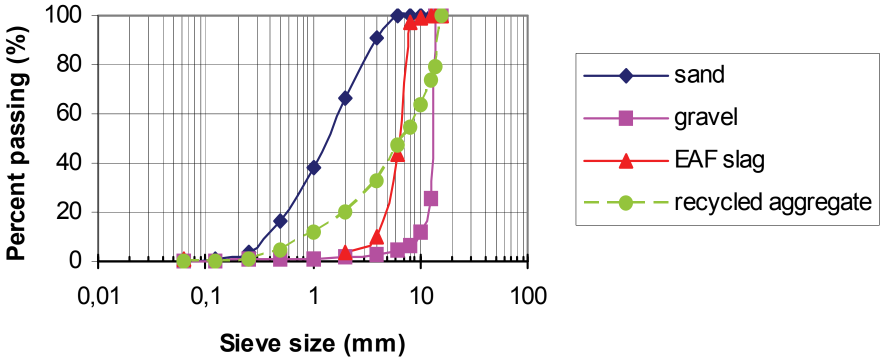

Fig. 1 Grading Curves

In this study a polycarboxylate based superplasticizer was used, allowing a high reduction of water, shrinkage, porosity (and consequently carbonation).

2.2 Mix compositions

The basic components for the mix composition of SCC are the same as used in conventional concrete, but to obtain the requested properties of fresh concrete in SCC, a higher proportion of ultra-fine materials and the incorporation of chemical admixtures, in particular a superplasticiser, are necessary. Ordinary and approved filler materials are fly ash, limestone powder, blast-furnace slag, silica fume and quartzite powder.

The mixture proportions were based on Okamura's method, with improvements made on the methods of selecting the fine aggregate content. The sand–mortar, the water–powder and the superplasticiser–powder ratios were selected by a simple evaluation test for assessing the stress transferability of fresh mortar [14]

Five tests on mortar have been carried out for a water/cement (W/C) ratio of 0.37-0.4: Table 3 shows the mix compositions. SCC normally requires a more efficient mixing, longer mixing time, to make sure that all constituents have been mixed thoroughly [15]. In this work, the mixing procedure consisted in mixing the aggregates with cement together for half a minute before adding the necessary water and superplasticizer during about a minute.

Table 3 Mix compositions

(kg/m^3 or l)	SCC1	SCC2	SCC3	SCC4	SCC5
CEM I 52.5 R	400	400	400	400	400
Limestone filler	130	0	150	0	0
Sand (0-4 mm)	1070	1070	1070	1070	1070
Gravel (4-8 mm)	570	570	400	400	400
Gravel (6-12 mm)	170	170	170	170	136
EAF slag (4-8 mm)	0	0	170	170	170
Fly ash	0	130	0	130	130
Recycled aggregate (5-16 mm)	0	0	0	0	34
Water	150	160	150	160	160
Superplasticizer	6	8	6	6	6

2.3. Fresh concrete consistence test methods

Some methods have been developed in recent years for SCC. They are not covered by standards but have proved effective in practice. In fact, none of the test methods in the current EN 12350 series "Testing fresh concrete" are suitable for assessment of the key properties of fresh SCC. Appropriate test methods for SCC are given in Annex B of [16]. Some test methods in common use are briefly described below (see also Figure 2).

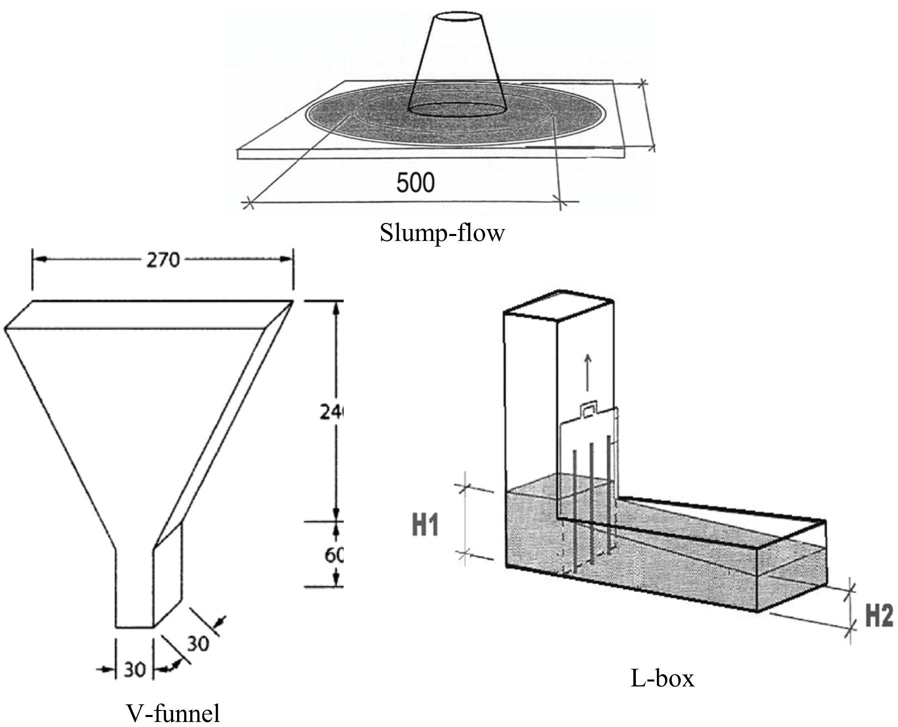

Fig. 2 Some fresh properties tests

The Slump-Flow Method

This method is a combination of slump (the same form is used) and flow diameter. The slump cone is filled with concrete on the flow plate, levelled and then slowly lifted. The usual measurement is the time in seconds to reach a flow diameter normally of 500 mm (this time can give additional information on the segregation resistance) named T_{50} flow time and then the maximum flow diameter at the end of its motion. Further obstacles can be added by placing a ring of steel with serrated steel in the centre (J-Ring test), to simulate the flow behaviour around a reinforcement. The typical slump-flow classes vary from a 550 mm to a 850 mm diameter, for many normal applications one can refer to values between 650 and 750 mm.

The L-box

The L-box is suitable for analysis of the flow behaviour from the vertical to the horizontal. Here again, the usual measurement is the time taken to reach the first 500 mm horizontally and also to reach the opposite side of the channel and the depth of the concrete at the outlet and on the opposite side. The discharge channels often have reinforcing steel at the outlet.

The V-funnel

The concrete is poured in with the base flap closed, then the flap is opened and the outflow time is measured, e.g. until the first break in the flow.
In this work, slump flow diameter and V-funnel time was determined to measure the filling ability; J-Ring and L-Box tests was carried out to measure the passing ability.

2.4 Compressive strength

An important property of hardened concrete is the compressive strength: it is determined by a compression test on specially produced specimens. The main factors influencing compressive strength are the type of cement, the W/C ratio and the degree of hydration which is affected mainly by the curing time and method.

High early strength means the compressive strength of the concrete in the first 24 hours after production.

High early strength is often very important for precast structures, since it means earlier striking, faster turnaround of the formwork, earlier handling of the precast structures, more economic use of cement, less heat energy.

The hardened concrete tests are regulated in the EN 12390 standards; requirements for specimens and moulds are contained in EN 12390-1; cubes with 150 mm size were used. Moulds must be water proof and non-absorbent; joints may be sealed with suitable material; calibrated moulds should be made of steel or cast iron.

For making and curing specimens one has to refer to EN 12390-2. The test equipment for the compressive strength of test specimens is given by a compressive testing machine according to EN 12390-4.

Cube samples should be tested perpendicular to the direction of pouring. At the end of the test, the type of break should be assessed. If it is unusual, it must be recorded with the type number.

3. Results and Discussion

In this work, the EAF slag replaced 30% of the crushed limestone aggregate with size 4-8 mm. The mixes SCC1 and SCC2 in Table 3 do not contain slag, they contain limestone filler and fly ash respectively; their equivalent with EAF slag are the mixes SCC3 and SCC4, whereas the mix SCC5 differs from SCC4 since the recycled aggregates replaced 20% of the crushed limestone aggregate with size 6-12 mm, i.e. 2.1% of all the natural aggregates (the Italian law, according to UNI EN 12620-2002, prescribes 5% of all the natural aggregates for precast structures). It is just the case to observe that SCC2, containing fly ash, requires a slightly higher quantity of superplasticizer, confirming existing results [17]; by adding EAF slag this quantity diminishes.
All the results will increase the data for a functional network in order to obtain other mixes with the required characteristics [18].

3.1 Workability

No segregation and no bleeding was observed for the mixes in Table 3. Table 4 summarises the fresh concrete tests results. All the tests give acceptable results. The effect of slag addition on the slump-flow and J-Ring tests is depicted in Figure 3. It is noticed that in any case values of slump flow without J-Ring are higher than those with the J-Ring as this reflects the passing ability. A decrease in both values can be observed for SCC4. The highest values are registered for SCC5. With regard to the V-funnel and L-box test results, by adding EAF slag, one has in any case an increase and a decrease in the values respectively.

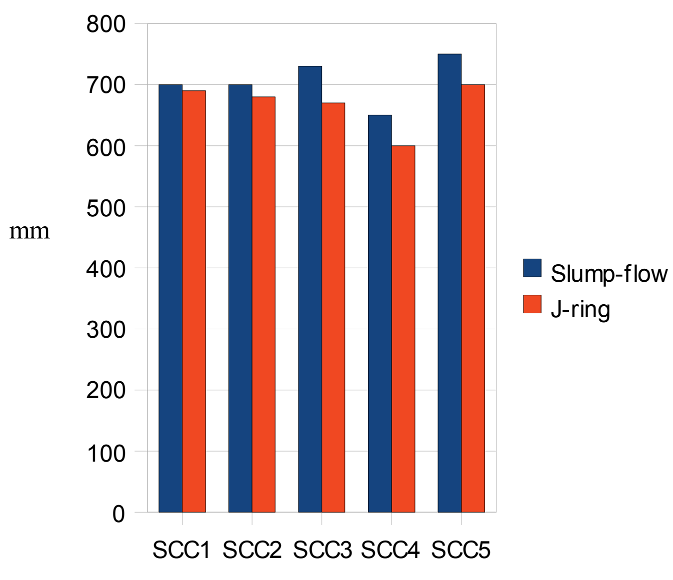

Fig. 3 The slump-flow and J-ring tests results

Table 4 Hardened and fresh properties of the concrete mixtures

	SCC1	SCC2	SCC3	SCC4	SCC5
24-hours compressive strength (MPa)	41	39	40	37.5	35
28-days compressive strength (MPa)	65	69	70	68	64
Slump-flow (mm)	700	700	730	650	750
J-ring (mm)	690	680	670	600	700
V-funnel (sec)	8	10	12	11	12
L-box	0.86	0.85	0.8	0.8	0.7
Bulk density (kg/m^3)	2550	2548	2640	2610	2520

3.2 Strength

Whereas a decrease in compressive strength at all ages is observed by adding fine EAF slag in SCC [9], an increase in compressive strength at all ages is observed by using EAF slag as coarse aggregate in ordinary concretes [12], particularly for a high content of EAF slag [13]. Here, the content of EAF slag is not high, in order to not increase the weight significantly. As one can see (Table 4), by adding the EAF slag in any case the 24-hours compressive strength is slightly decreased. By comparing the results for SCC1 with those for SCC3, one can see that in presence of EAF slag the 28-days compressive strength is increased. Instead, by comparing the results for SCC2 with those for SCC4, one can see that the 28-days compressive strength is slightly decreased, while by using recycled aggregates (SCC5) this value is further decreased.

4. CONCLUSIONS

In this work the use of EAF slag as by-product in EAF plants for continuous steel production was preliminarily studied to investigate the possibility of replacing the traditional aggregates to produce self-compacting concretes. Fresh properties and compressive strength of SCC containing EAF slag as medium aggregate were experimentally investigated. The results encourage further investigations.

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EAF ŠLJAKA U SAMOUGRAĐUJUĆEM BETONU

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Samougrađujući beton (SCC)postaje sve interesantniji zbog nekoliko prednosti u tehničkom, ekonomskom i ekološkom pogledu. Posebna pažnja posvećena na aspektu životne sredine pokreće istraživanja u pravcu reciklaže industrijskih otpadnih proizvoda kao što je leteći pepeo i šljaka čelika. Konkretno, postoji nekoliko eksperimenata o upotrebi EAF šljake u SCC. Ovaj rad sumira prve rezultate tekućeg eksperimentalnog rada koji istražuje upotrebu EAF šljake u SCC kao materijala agregata srednje veličine.

Ključne reči: *samougrađujući beton, EAF šljaka, srednje/krupan agregat, čvrstoća na pritisak*