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HIGH PERFORMANCES CONCRETE WITH EAF SLAG AS COARSE AGGREGATES

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Introduction

During the last decades, concrete technology has evolved to provide the structures with better mechanical and durability performances. This resulted in the development of high-performances concrete (HPC), characterized by a significant improvement of many properties with respect to ordinary concrete (OC), i.e. higher mechanical strength, better workability and durability. HPC are generally designed with reduced water content and high cement dosage, optimizing grains size distribution, using super-plasticizer, and possibly including mineral additions with pozzolanic activity. The quality of the aggregates also significantly influences concrete properties; hence, the use of recycled aggregates is mostly not recommended in HPC design, due to their high absorption capacity, unstable properties and weak strength (1). However, the promotion of recycling in concrete industry represents a valid route for sustainable development, because it will prevent natural resources consumption. Therefore, the utilization of recycled aggregates should be considered also for HPC design, as it is becoming more and more diffused.

In this work, the use of Electric Arc Furnace (EAF) steel slag as coarse aggregate in HPC has been investigated. EAF slag is a by-product of steel production, currently partially reused in asphalt concrete. However, huge quantitates of this material are still landfilled. Different from other recycled aggregates, EAF slag has very good mechanical properties: it is a crushed product with black color stone appearance and a rough surface texture. It has high abrasion resistance, low crushing value and excellent resistance to fragmentation. Those properties make EAF slag particularly suitable in concrete application, also for structural purposes (2), leading to an improvement of mechanical strength of the hardened concretes.

This study makes part of a wider research program aiming to improve the knowledge about EAF slag concretes, leading to a sustainable valorization of this material in the civil engineering field. Mechanical properties of HPC containing EAF slag are investigated. A microstructural characterization was also performed to observe the cementitious matrix-EAF slag transition zone.

Materials and Methods

Steel slag used in this experimental investigation is obtained from a local steel factory in the Northeastern part of Italy. Before its use, the slag is pretreated by exposing it to outdoor weather and regular spraying it for 90 days. Natural calcareous sand and limestone were used. Aggregates main physical properties are listed in Table 1. Ordinary Portland Cement type I 52.5R class, as defined in UNI EN 197-1 was used. A super-plasticizing (SP) sulphonated naphtalene admixture was used to allow the mixes to reach the required workability. In one mix, condensed silica fume (SF) obtained from BASF was used.

Table 1: Main physical properties of the aggregates.

	EAF slag	NA - sand	NA -gravel
Size (mm)	4-16	0-4	4-16
Apparent density (kg/m^3)	3854	2704	2700
Water absorption (%)	0.95	1.18	1.04
Shape	sharp-pointed	roundish	roundish

Three types of concretes were analyzed: the reference/control containing only natural aggregates (NA); the EAF slag concrete, where the whole coarse aggregates were substituted with EAF slag; and the EAF-SF concrete, with SF addition (15 % on cement weight). The minimum performance required to the mixes is to reach a concrete strength class between C50/60 and C60/75, with an S4 consistency class, as defined in EN 206-1. Aggregate grading curves were obtained according to Bolomey curve. Table 2 shows the details of the mixes.

After mixing, specimens were properly compacted, covered to limit evaporation, demolded 24 hours after casting, and then cured in standard temperature (20 ± 2 °C) and humidity (RH ≥ 95 %) conditions until the time of testing. Compressive strength was measured after 7, and 28 days on cubic specimens with 150 mm side. Cylindrical specimens with 100 mm diameter and 200 mm length were used for measuring tensile strength by means of splitting test, and to evaluate the secant modulus of elasticity by means of cyclic load test. After compressive test, specimens' surfaces were examined by Scanning Electron Microscope (SEM) aiming to analyze matrix-coarse aggregate interfacial regions.

Table 2: Mixture details.

	Control	EAF 1	EAF 2	EAF-SF
Cement (kg/m^3)	400	400	350	400
SF (kg/m^3)	-	-	-	60
W/(C+SF)	0.4	0.4	0.4	0.4
Coarse NA (kg/m^3)	1008	-	-	-
Coarse EAF (kg/m^3)	-	1408	1476	1370
Fine NA (kg/m^3)	832	832	872	810
SP (%)	1.2	1.2	1.2	1.2

Results and Discussion

The concretes produced in this experimental campaign belong to the S4 consistency class. Fresh concrete properties are listed in Table 3 together with the results of mechanical strength tests, including compressive, tensile strength and elastic modulus evaluated at 28 days. The use of EAF slag in general decreases concrete fresh concrete workability, as obtained also in OC mixtures (3). However, there is a relevant improvement of compressive and tensile strength, and of elastic modulus. As expected, also concrete density is higher, due to the higher specific weight of the slag. The use of SF lowers the density of the mix, but it does not improve mechanical strength. This result may be explained by the relative high w/(c+SF) ratio used in this work: generally SF incorporation results in significant improvement of the resistance only with w/(c+SF) ratio lower than 0.3. Furthermore, it is possible to observe that the reduction of 50 kg/m^3 in the cement content of Mix EAF2 does not affect mechanical strength with respect to EAF1 performances.

Table 3: Fresh concrete properties and mechanical strength at 7 and 28 days.

	Control	EAF 1	EAF 2	EAF-SF
Fresh concrete properties				
Density (kg/m^3)	2477	2935	3007	2777
Slump (mm)	210	170	160	210
Hardened concrete properties - 7 days				
Density (kg/m^3)	2470	2890	2982	2765
$f_{cm,cube}$ (MPa)	45.7	69.05	60.6	54.6

Hardened concrete properties - 28 days				
Density (kg/m^3)	2510	2930	2967	2790
$f_{cm,cube}$ (MPa)	56.4	76.4	73.9	65.0
f_{ctm} (MPa)	4.50	5.65	5.37	4.65
E_{cm} (GPa)	38.5	49.5	49.2	45.5

In the control mix, failure after compressive test at 28 days occurred both in the paste and in the NA, as it is shown in Figure 1. The EAF concretes showed higher compressive strength, due to the higher resistance of the slag with respect to the natural gravel: at 28 days failure occurred mainly for cracking of the paste. Furthermore, the interface zone between the EAF aggregates and the binder appears to be dense, and it cannot be easily distinguished. Any granular whisker-like hydrates or flake-like crystals could not be found (Figure 2).

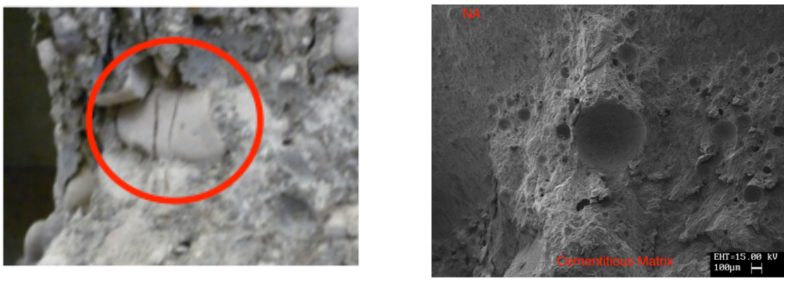

Figure 1: Macro-crack in the NA (left); SE-SEM image, micro-cracks at the ITZ.

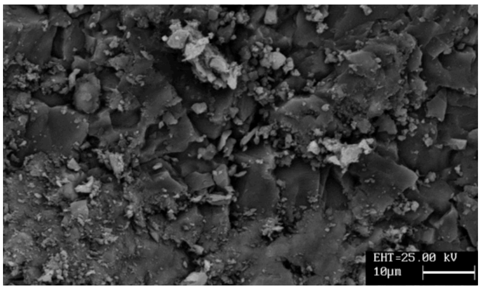

Figure 2: SE-SEM image, morphology of EAF2 concrete.

Conclusions

The experimental campaign conducted in this work has demonstrated that the use of EAF slag can be suitable in designing HPC concrete, with relevant increase of compressive strength (more than 25 %). According to Faleshini et al.[4], 1 ton of EAF slag determines a reduction of 65 % of CO_2 emissions with respect to 1 ton of NA, leading also to a significant improvement of sustainability in HPC production.

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