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High performance concrete with electric arc furnace slag as aggregate: Mechanical and durability properties

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HIGHLIGHTS

- The properties of conventional and EAF concretes are experimentally investigated.
- High strength concrete with EAF slag can be produced with relatively high w/c.
- The high density of EAF-HSC suggests a potential application as nuclear shielding.
- Chloride ingress in the concrete matrix is evaluated through $AgNO_3$ spray tests.
- EAF slag use in concrete promotes chlorides diffusion coefficient reduction.

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ABSTRACT

This paper investigates the feasibility of using Black/Oxidizing Electric Arc Furnace slag (EAF) as coarse aggregate to produce High Performance Concrete (HPC). Various experimental mixes have been produced, fully replacing natural coarse aggregates with EAF slag, varying the cement dosages and the water/cement ratios, and they have been characterized through a mechanical and microstructural campaign. For some mixtures also durability has been evaluated, through a study about chloride ingress into concrete matrix. Results indicate that the use of EAF slag improves concrete strength and durability, reaching C60/75 strength class without using any mineral additions and maintaining relatively high water/cement ratio.

1. Introduction

High Performance Concrete (HPC) is conventionally defined as a concrete with improved performances in terms of strength, workability and durability, which cannot be obtained with ordinary materials through routinely mixing, placing and curing operations [1]. Several Codes and Guidelines establish the design rules for the use of HPC in the construction of important civil engineering works, e.g. ACI-318 [1] and *fib Bulletin 42* [2].

Generally HPC mixtures have higher quantities of binders than normal concrete, containing one or more supplementary materials (e.g. fly ash, silica fume and granulated blast furnace slag). They are characterized by low water/cement ratio (usually ranging from 0.2 to 0.4), and large doses of superplasticizer are used to achieve the required workability. The aggregates should be strong and durable, and compatible with the cement paste in terms of stiffness and strength.

HPC has lead to important advances in the field of civil engineering, especially in the construction of high-rise buildings and long-span bridges. HPC performances allow engineers to reduce columns and beams size (increasing the available space and reducing the costs in formwork, reinforcing steel, etc.) and to extend structures' service life. However, behind these advantages, progress of concrete industry has also determined a series of drawbacks, mainly related to the sustainability of this industrial sector. Concrete industry is in fact responsible of a relevant environmental footprint on our planet [3], with an increasing trend associated to the actual and future growth of developing economies, demanding

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increasing quantities of natural raw bulk materials. The main sources of these environmental burdens lie into the productive chain of Portland cement, together with water and Natural Aggregates (NA) consumption, and lastly to the generation of Construction and Demolition Wastes (C&DW).

Among the several possible solutions to reduce environmental impacts of concrete industry, the use of coarse Recycled Concrete Aggregates (RCA) is one of the most discussed options that one may take. Several studies have analyzed the implications of partially or totally substituting NA with RCA on concrete mechanical properties [4–6]. Typically the full replacement of NA with RCA through Direct Volume or Weight Replacement (DVR, DWR) methods leads to a reduction of 20–25% in 28-days compressive strength, with respect to conventional mixtures. An increase of cement content may be useful to achieve the same strength of the control concretes, but it is considered nor cost- nor environmental-effective [4,7]. Additionally, the reduction in the elastic modulus can reach 45% when the RCA replacement is

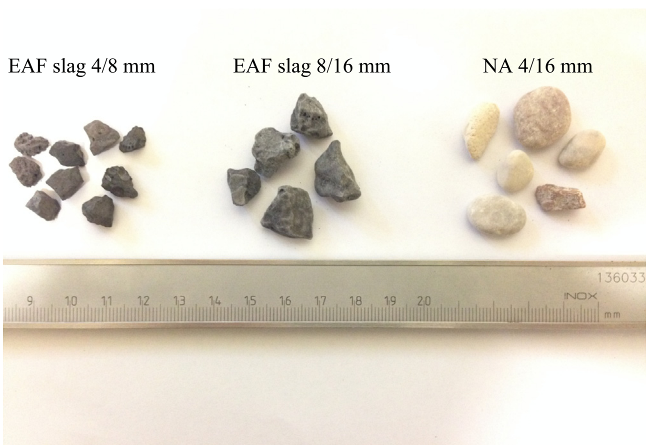

Fig. 1. Appearance of Electric Arc Furnace (EAF) slag compared with Natural Aggregates (NA).

Table 1
Main aggregates physical characteristics.

	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
Los Angeles loss (%)	<20	–	18

100% [5], and the durability of Recycled Aggregate Concrete (RAC) decreases too due to the higher porosity of RCA [8]. In general terms, it can be said that a full replacement of NA with RCA can be used in concretes with low-medium compressive strength, i.e. until 20–40 MPa [4]. Some studies have been carried out also to study the feasibility of using RCA in HPC [9–11], obtaining in most cases that high replacement ratios (more than 30%) significantly affect concrete strength and density. With the increase of the RCA content, water absorption, shrinkage and creep strains increase keeping constant the other values or the other magnitudes. However the source of RCA is very important with respect to RAC properties [10].

Another solution may be used to achieve the sustainability goals asked to the concrete industry, namely using recycled aggregates coming from metallurgical industry. Previous studies of some of the authors have demonstrated the feasibility to produce structural concrete including Black/Oxidizing Electric Arc Furnace slag (EAF slag), fully replacing the coarse aggregates and improving concrete compressive and tensile strength, and also elastic modulus [12,13]. The use of EAF slag is also beneficial against detrimental environmental conditions [14], and it is responsible of lower environmental emissions if compared to NA in a life cycle perspective [15].

This study is based on the cited previous experience of some of the authors introducing, other than a mechanical and microstructural characterization, the use of EAF slag as aggregate in HPC, and the evaluation of chloride ingress into the concrete matrix, with the objective of improving the knowledge about EAF concrete durability. Particularly, the mechanical properties of this new HPC with EAF slag as aggregate (HPC-EAF) are evaluated through compressive and tensile tests and with the determination of the Young's modulus. Durability is evaluated through the study of the chloride ingress using a $AgNO_3$-based colorimetric test, performed both on conventional and EAF concretes. Finally, the morphology and microstructure of each type of concrete is analyzed via Scanning Electron Microscopy (SEM).

2. Materials and experimental methods

2.1. Materials and mix proportions

Black/Oxidizing EAF slag is a by-product of steel production in electric arc furnaces plants, which stands for more than 40% of the global production of steel, yielding to more than 10 millions tons of this type of slag every year in Europe [16]. The EAF slag used in this study is obtained from a local steel factory located in the North-Eastern part of Italy: it is a crushed product, with a black color stone-like appearance, constituted by particles with a hard, dense and angular shape (Fig. 1). It has low water absorption, high

Table 2
Mix details referring to 1 m^3 of concrete.

	w/c	Water (kg)	Cement (kg)	NA sand (kg)	NA gravel (kg)	EAF slag (kg)	WRA[a] (%)
Conventional concretes							
C400-0.4	0.4	160	400	836	1020	–	1.2
C400-0.45	0.45	180	400	812	992	–	1.0
C400-0.5	0.5	200	400	789	963	–	0.8
EAF-concretes							
E400-0.4	0.4	160	400	1020	–	1190	1.45
E400-0.45	0.45	180	400	994	–	1148	1.2
E400-0.5	0.5	200	400	965	–	1115	1.0
E350-0.4	0.4	140	350	1067	–	1245	1.2
E350-0.45	0.45	157.5	350	1029	–	1200	1.0
E350-0.5	0.5	175	350	1014	–	1171	0.8

[a] Expressed in cement weight percentage.