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Mechanical and durability characteristics of concrete containing EAF slag as aggregate

Carlo Pellegrino *, Vittorio Gaddo

Department of Structural and Transportation Engineering, University of Padova, Via Marzolo 9, 35131 Padova, Italy

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ABSTRACT

The present study aims to investigate the opportunity to largely substitute natural aggregates of traditional concrete with Black/Oxidizing Electric Arc Furnace (EAF) slag. Compressive and tensile strength, elastic modulus and durability characteristics (accelerated aging, freezing and thawing, wetting and drying) of concrete containing EAF slag as aggregate according to Fuller's ideal grading curve were experimentally investigated. This study aims to improve the scarce database of mechanical and durability tests on this type of concrete and give some insights to improve durability properties of concrete made with EAF slag, not only using modern agents and additives, but also working on the actual grading curve of aggregates used, closely connected to the overall durability for any kind of concrete. Concrete made with EAF slag as aggregate showed good strength characteristics since, in normal environmental conditions, strength properties of the conglomerate containing EAF slag are totally comparable (or even better) than those observed for traditional concrete. Conversely, the typical chemical and physical properties of EAF slag, such as the high content in calcium and magnesium oxides inclined to hydration, may be a limit for the durability of the resulting concrete: on one hand the durability can be strongly improved even in critical freezing/thawing environmental conditions by a small amount of air-entraining agent, on the other hand, this conglomerate still remains rather vulnerable to repeated cycles of wetting and drying.

1. Introduction

The energetic/environmental impact [1] related to the use of natural aggregates in traditional concrete cannot be imputed to the real production process but to the huge amount of natural materials used in building industry and high transportation costs; moreover, although pit aggregates are mostly used at present, serious environmental problems formerly originated from unrestrained sand and gravel taken from rivers. Fortunately it has been considered for some decades the chance to use different recycled materials as concrete aggregates, even if just in partial replacement of natural counterparts. At present, two are the most commonly adopted solutions: using recycled conglomerate coming from building demolitions, properly fragmented and sieved, to substitute for up to 50% of natural aggregate, and the use of slag originating from metallurgical industrial production (metals melting and refining plants), as shown to be suitable as concrete aggregates.

Nowadays more than 40% global steel production in the world takes place in Electric Arc Furnaces (EAF) plants [2], which, differently from older Basic Oxygen Furnace (BOF) plants, are used for scrap metal recycling aiming to a more economical and sustainable production. More than 10 millions tons of slag are currently produced every year in Electric Arc Furnaces (EAF) all over Europe for steel making; this amount is destined to grow together with the need for their disposal or feasible recycling.

Steelworks based on EAF plants are already numerous also in Veneto (North-East of Italy), yielding a considerable quantity of Black/Oxidizing slag (also called EAF slag) during continuous steel production. In this framework, the present study aims to investigate the opportunity to largely substitute natural aggregates of traditional concrete with EAF slag.

Few researches (e.g. [3,4]) have been developed to test both mechanical properties and durability of concrete containing EAF slag. In particular, some relevant characteristics such as the modulus of elasticity seem less investigated. The few studies actually found in the literature (see e.g. [3]) generally showed good results regarding strength of the conglomerate made with EAF slag (compared to traditional concrete) in absence of critical weather conditions, but very poor performances of EAF concrete after heavy accelerated aging tests. Moreover, when any high density conglomerate is needed (such as for marine blocks or retaining walls), the typically high density of EAF slag would suggest the use of only the coarse fraction, eventually discarding most of the medium/fine size fraction.

Compressive and tensile strength, elastic modulus and durability characteristics (due to accelerated aging, freezing and thawing,

* Corresponding author. Tel./fax: +39 049 8275618.
E-mail address: carlo.pellegrino@unipd.it (C. Pellegrino).

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wetting and drying) of concrete containing EAF slag as aggregate according to Fuller's ideal grading curve were experimentally investigated. This study aims to improve the scarce database of mechanical and durability tests on this type of concrete and give some insights to improve durability properties of concrete made with EAF slag, not only by use of modern agents and additives, but also working on the actual grading curve of aggregates used, closely connected to the overall durability for any kind of concrete.

The present experimental study was conceived following the general purpose of testing new sustainable building processes and modern production systems, aimed not only at saving natural raw materials and reducing energy consumption, but also to recycle industrial by-products.

2. Chemical and physical properties of EAF slag

Steel slag, originated in Electric Arc Furnaces (EAF) for continuous steel production, have stone-like appearance, black colour with small white agglomerations of calcium carbonate and high roughness; they can be generally classified into two different kinds [5]: (1) Black basic slag, with a lime content lower than 40%, resulting from the cold loading of scrap and showing a high density (about 3.4 t/m^3), low water absorption (about 1.5%) and low porosity; (2) Black and White basic slags, with a lime content higher than 40%, generated during fining, when more lime is added to remove sulphur and phosphorus, showing a lower density (about 3.1 t/m^3), higher water absorption (about 4.2%) and higher porosity. EAF slag have generally excellent stone-like mechanical properties, however the most critical characteristic is their potential expansiveness that can reach 5% [4]. This study deals with a particular type of black EAF slag with high density and low water absorption (the main properties are described in Table 1).

Black/Oxidizing slag is mainly formed by oxides: about 70% is a set of iron, calcium, and silicon oxides, plus minor amounts of magnesium, aluminium and manganese oxides. The presence of free calcium and magnesium oxides is mainly responsible for both hydration and expansion phenomena typical of such slag: once in contact with water, calcium oxide hydrates very fast causing a rapid volumetric expansion, whereas magnesium oxide hydrates more slowly causing an expansion spread over a longer time. It was shown [4,6] 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.

Leaching tests have been developed on the slag in order to verify that the potential toxic compounds are under the limit values reported in the Italian standard. Table 2 shows a detailed list of all potential toxic compounds, the resulting range of the quantities obtained for the slag used in this experimental investigation and the corresponding limit values according to the Italian standard DM 186 5/04/2006 [7]. From the chemical point of view, the tested slag is fully admissible for use as concrete aggregates [8,9].

Table 1
Main characteristics of EAF slag aggregate.

	Medium/coarse size EAF slag
Size (mm)	2.0 ÷ 22.4
Apparent specific gravity (t/m^3)	3.64 ÷ 3.97
Water absorption (%)	0.18 ÷ 0.45
Los Angeles loss (%)	<20
FeO (%)	37.2 ÷ 44.8
SiO_2 (%)	10.1 ÷ 14.7
CaO (%)	24.2 ÷ 29.5
Al_2O_3 (%)	5.7 ÷ 7.2
MgO (%)	1.9 ÷ 4.6
MnO (%)	5.1 ÷ 5.7
Cr_2O_3 (%)	2.5 ÷ 4.1

Table 2
Results of leaching tests on the slag.

	Limits	Resulting range
Nitrates (mg/l)	50	<50 (<1)
Fluorides (mg/l)	1.5	<1.5
Sulphates (mg/l)	250	15 ÷ 50
Chlorides (mg/l)	100	5 ÷ 75
Cyanides (μg/l)	50	<50
Barium (mg/l)	1	<1 (<0.14)
Copper (mg/l)	0.05	<0.05
Zinc (mg/l)	3	<3 (<0.059)
Beryllium (μg/l)	10	<10
Cobalt (μg/l)	250	<250
Nickel (μg/l)	10	<10
Vanadium (μg/l)	250	<250
Arsenic (μg/l)	50	<50
Cadmium (μg/l)	5	<5
Total chromium (μg/l)	50	<50
Lead (μg/l)	50	<50
Selenium (μg/l)	10	<10
Mercury (μg/l)	1	<1
Amianthus (μg/l)	30	–
Chemical Oxygen Demand (COD) (mg/l)	30	<30
pH	5.5 ÷ 12.0	9.6 ÷ 11.25

3. Mix design for experimental and traditional/reference conglomerates

In the present investigation a cementitious conglomerate containing fine natural sand/filler plus medium and coarse EAF slag (maximum dimension of the aggregate D_{max} = 22.4 mm) and a control cementitious conglomerate containing only traditional natural aggregates (D_{max} = 31.5 mm) were designed. For each conglomerate all the size fractions corresponding to two different Fuller's ideal grading curves were calculated:

$$P = [100(d/D_{max})^{0.5} - C]/(100 - C) \quad \text{(Fuller's ideal grading curve)} \tag{1}$$

where

$$C = V_{cement}/V_{solids} = V_{cement}/(V_{cement} + V_i) \quad \text{(percentage value of the cement content)} \tag{2}$$

$$V_i = 1000 - V_{water} - V_{cement} - V_{air} \quad \text{(total aggregate volume per 1000 l of conglomerate)} \tag{3}$$

As defined in EN 206-1 (2006) [10] and UNI 11104 (2004) [11], a S4 slump class concrete (defined as "fluid", i.e. showing a 16–21 cm lowering of fresh concrete by a Slump Cone) generally suitable for medium steel-reinforced structures and asking for a short vibration time (about 10–15 s) was prepared. A concrete with higher class (S5) was not considered both for economical reasons and minimizing the risk of bleeding and heavy slag separation favoured by the high water content; for the same reasons it was planned to use a fluidifying agent (0.4% of cement weight) in place of the corresponding water necessary to achieve a S4 class concrete. An aerating additive (0.016% of cement weight) was also used to support the fluidifying agent in bleeding prevention, and especially to improve the resulting conglomerate durability when exposed to freezing/thawing cycles.

Therefore, planning to realize a S4 class (fluid) concrete for both experimental and traditional conglomerate, having slump = 185 mm, and being D_{max} = 31.5 mm for traditional natural aggregate and D_{max} = 22.4 mm for EAF slag, it would require about 220 kg of water per 1000 l of conglomerate with EAF slag and about 210 kg of water per 1000 l of traditional conglomerate; nevertheless a 10 kg water reduction is also computed since traditional conglomerate aggregates are naturally roundish [10]. For both conglomerates, the fluidifying agent allows a 20% water reduction plus a further 5% reduction due to the aerating additive [10]. As a result, it takes about 220 · 75% = 165 kg of water per 1000 l of conglomerate with EAF slag and about (210−10) · 75% = 150 kg of water per 1000 l of traditional conglomerate.

Table 3
Resulting mix design data for both experimental and traditional conglomerates.

	Conglomerate with EAF slag	Traditional conglomerate
D_{max} (mm)	22.4	31.5
V_i (l)	683	707
C (%)	13.02	11.61
$\rho_{(5\%\ air)}$ (t/m^3)	2.950	2.325
Cement CEM II-A/L 42.5R (kg)	317	288
Water (kg)	165	150
Total EAF slag s.s.d. fractions (kg)	2111	–
Total natural aggregate s.s.d. fractions (kg)	361	1888
Fluidifying agent (kg)	1.268	1.152
Aerating additive (g)	51	46

A cement mixture type CEM II-A/L 42.5R (with high percentage of clinker) is adopted for both conglomerates taking into account the versatility of a medium class quick-setting cement (such as 42.5R) and considering the wide spread availability in Italy of Portland cement with limestone. Moreover, planning to subject both conglomerates to various and severe accelerated aging tests, it is considered to satisfy basic requirements for medium exposure class corresponding to a fairly good durability, by reducing water/cement ratio to 0.52; however, the ratio is not reduced both for economical reasons (cement saving) and to remain within a common water/cement ratio. Therefore, it requires about 165/0.52 = 317 kg of cement per 1000 l of conglomerate with EAF slag and about 150/0.52 = 288 kg of cement per 1000 l of traditional conglomerate. According to EN 206-1 Standard [10], both the conglomerates (when properly compacted, aged in standard temperature and humidity conditions – $T = 20$ °C, RH $\geqslant$ 95% – for at least 3–7 days, and with proper cover) fit the following exposure classes: XC3 (carbonation, medium class), XD2 (non-marine chlorides, medium class), XF2 (freezing/thawing and thawing salts, medium class), XA1 (aggressive ground and water, minimum class), thus being able to show a fairly good durability even without adding other chemical additives (such as corrosion inhibitors) or minerals (such as silica fume).

Hence the following values are considered for both conglomerates: slump = 185 mm; water/cement ratio = 0.52; fluidifying agent = 0.4% of cement weight; aerating additive = 0.016% of

Table 4
Fuller's ideal grading curve calculus for the conglomerate made with EAF slag.

Sieve size (mm)	Ideal passing according to Fuller (1), D_{max} = 22.4 mm; C = 13.02 %	Fraction retained (%)	Partial vol. per m^3 of conglom. (l)	Dry volume mass (t/m^3)	Dry EAF slag (kg/m^3)	Dry natural aggregates (kg/m^3)	Water absorption (%)	Absorbed water (l)	s.s.d. weight (kg/m^3)
31.5	100.00								
22.4	100.00								
16	82.20	17.80	121.59	3.97	482.72		0.18	0.87	483.58
11.2	66.33	15.87	108.40	3.87	419.51		0.27	1.13	420.64
8	53.74	12.59	85.98	3.83	329.29		0.34	1.12	330.41
5.6	42.52	11.22	76.65	3.81	292.04		0.38	1.11	293.15
4	33.61	8.90	60.80	3.73	226.77		0.42	0.95	227.72
2	19.38	14.23	97.19	3.64	353.77		0.45	1.59	355.36
1	9.32	10.06	68.72	2.70		185.55	0.91	1.69	187.24
0.5	2.21	7.11	48.59	2.70		131.20	0.92	1.21	132.41
0.25	0.00	2.21	15.08	2.70		40.71	0.92	0.37	41.09
0.125	0.00	0.00	0.00						
0.063	0.00	0.00	0.00						
Totals		100.00	683.00		2104.09	357.47		10.05	2471.61

Table 5
Fuller's ideal grading curve calculus for the traditional conglomerate.

Sieve size (mm)	Ideal passing according to Fuller (1), D_{max} = 31.5 mm; C = 11.61 %	Fraction retained (%)	Partial vol. per m^3 of conglom. (l)	Dry volume mass (t/m^3)	Dry EAF slag (kg/m^3)	Dry natural aggregates (kg/m^3)	Water absorption (%)	Absorbed water (l)	s.s.d. weight (kg/m^3)
31.5	100.00								
22.4	82.27	17.73	125.36	2.58		323.43	0.78	2.52	325.95
16	67.50	14.77	104.44	2.61		272.60	0.82	2.24	274.83
11.2	54.33	13.17	93.11	2.64		245.82	0.85	2.09	247.91
8	43.88	10.45	73.85	2.65		195.71	0.87	1.70	197.41
5.6	34.57	9.31	65.84	2.65		174.48	0.88	1.54	176.01
4	27.18	7.39	52.22	2.70		141.00	0.90	1.27	142.27
2	15.37	11.81	83.48	2.70		225.41	0.90	2.03	227.43
1	7.02	8.35	59.03	2.70		159.39	0.91	1.45	160.84
0.5	1.12	5.90	41.74	2.70		112.70	0.92	1.04	113.74
0.25	0.00	1.12	7.91	2.70		21.35	0.92	0.20	21.55
0.125	0.00	0.00	0.00						
0.063	0.00	0.00	0.00						
Totals		100.00%	707.00		0.00	1871.89		16.07	1887.95

cement weight; cement specific weight = 3.1 kg/l; flat air volume mainly due to aerating additive = 5%.

Table 3 shows the values of D_{max}, V_i (Eq. (3)), C (Eq. (2)), the expected final density $\rho_{(5\%\ air)}$, and the resulting composition (per 1000 l of conglomerate) of both conglomerate containing fine natural aggregates plus medium and coarse EAF slag and traditional conglomerate containing only natural aggregates.

Tables 4 and 5 show the Fuller's ideal grading curve data for the conglomerate made with EAF slag and the traditional conglomerate, respectively.

After mixing the conglomerate with EAF slag, 30 standard cubic specimens (side 150 mm), five cylindrical specimens (diameter = 160 mm; height = 480 mm) for Young's modulus calculation and five cylindrical specimens (diameter = 160 mm; height = 320 mm) for splitting tests were prepared. Similarly, 18 standard cubic specimens (side 150 mm), three cylindrical specimens (diameter = 160 mm; height = 480 mm) for Young's modulus calculation and three cylindrical specimens (diameter = 160 mm; height = 320 mm) for splitting tests were prepared with the traditional/reference conglomerate.

4. Measured compressive and tensile strength and Young's modulus' calculation after 28 days

Compressive tests have been developed on the cubic specimens after 7 days (three specimens), 28 days (nine specimens) and 74 days (four specimens). The typical failure mode of the cubic specimen made with traditional aggregates and EAF slag was similar. In Table 6 the specimens properties and compressive strength values after 7, 28 and 74 days are listed (natural aging). It is significant to observe that compressive strength stabilizes, as expected, after the first 28 days for traditional conglomerate whereas it continues to improve for the EAF slag one; thus EAF slag conglomerate aging appears to develop on a longer time than traditional conglomerate.

In Table 7 the calculation of the theoretical tensile strength and Young modulus for both conglomerates starting from experimental cubic compressive strength is reported. In Tables 8 and 9 the comparison between theoretical and experimental properties, after 28 days, for both conglomerates is shown. Theoretical values are computed starting from the experimental cubic compressive strength values (see Table 7) according to the well-known Eurocode 2 formulas [12]:

$$f_{ck} = f_{cm} - 8 \ (\text{MPa}) \tag{4}$$

$$f_{ctm} = 0.3 f_{ck}^{2/3} \tag{5}$$

$$E_{cm} = 22 (f_{cm}/10)^{0.3} \quad (f_{cm} \text{ in MPa}) \tag{6}$$

$$f_{ctm,ax} = 0.9 f_{ctm,sp} \tag{7}$$

where f_{ck} = characteristic cylindrical compressive strength; f_{cm} = mean cylindrical compressive strength; f_{ctm} = mean tensile strength; E_{cm} = mean elastic modulus; $f_{ctm,ax}$ = mean tensile strength derived from axial tests; $f_{ctm,sp}$ = mean tensile strength derived from splitting tests.

Table 6
Average specimens properties and compressive strength variations during 74 days – natural aging.

Mix type	Aerating additive (cem. weight %)	Fluidifying			7 days		28 days		74 days	
		Agent (cem. weight %)	Slump (mm)	Density after jet (t/m^3)	Density (t/m^3)	Cubic compr. strength (MPa)	Density (t/m^3)	Cubic compr. strength (MPa)	Density (t/m^3)	Cubic compr. strength (MPa)
Traditional	0.021	0.27	150	2.365	2.335	25.3	2.312	32.5	2.334	30.4
with EAF slag	0.024	0.57	150	2.951	2.943	37.2	2.972	42.3	2.960	44.4

Table 7
Calculation of the theoretical tensile strength and Young modulus for both conglomerates starting from experimental cubic compressive strength and according to Eurocode 2 [12] (see Eqs. (4)–(8)); discarded values are set in parentheses.

Compressive strength test after 28 days			Calculation of theoretical tensile strength and Young modulus				
Mix type	Volume mass (t/m^3)	$f_{c,cube}$ (MPa)	$f_{cm,cube}$ (MPa)	Eq. (8), f_{cm} (MPa)	Eq. (4), f_{ck} (MPa)	Eq. (5), $f_{ctm,EC2}$ (MPa)	Eq. (6), $E_{cm,EC2}$ (MPa)
With EAF slag	2.976	43.7	42.3	35.1	27.1	2.71	32,077
With EAF slag	2.976	44.8					
With EAF slag	2.985	41.9					
With EAF slag	2.981	40.8					
With EAF slag	2.976	40.6					
With EAF slag	(2.940)	(34.0)					
Traditional	(2.264)	(26.8)	32.5	27.0	19.0	2.13	29,624
Traditional	2.345	32.5					
Traditional	2.329	32.5					

Table 8
Comparison between theoretical (EC2) and experimental tensile strength for both conglomerates.

Indirect tensile strength test by splitting after 28 days						
Mix type	Volume mass (t/m^3)	$f_{ct,sp}$ (MPa)	$f_{ctm,sp}$ (MPa)	Eq. (7), $f_{ctm,ax} = f_{ctm,exp}$ (MPa)	Eq. (5), $f_{ctm,EC2}$ (MPa)	Variation (%) = $(f_{ctm,exp} - f_{ctm,EC2})/f_{ctm,exp}$
With EAF slag	2.955	3.38	3.12	2.80	2.71	+3.4
With EAF slag	2.933	3.44				
With EAF slag	2.834	3.12				
With EAF slag	2.938	2.75				
With EAF slag	2.872	2.88				
Traditional	2.338	2.15	2.21	1.99	2.13	−7.3
Traditional	2.318	2.34				
Traditional	2.338	2.13				

Table 9
Comparison between theoretical (Eurocode 2 [12]) and experimental Young modulus for both conglomerates.

Compression Young's modulus test after 28 days				
Mix type	E_c (MPa)	$E_{cm,exp}$ (MPa)	Eq. (6), $E_{cm,EC2}$ (MPa)	Variation (%) = $(E_{cm,exp} - E_{cm,EC2})/E_{cm,exp}$
With EAF slag	29,419	30,693	32,077	−4.5
With EAF slag	30,290			
With EAF slag	30,077			
With EAF slag	31,918			
With EAF slag	31,761			
Traditional	23,941	24,065	29,624	−23.1
Traditional	24,280			
Traditional	23,974			

The cylindrical compressive strength was obtained from the cubic compressive strength with the following formula:

$$f_c = 0.83 f_{c,cube} \quad (8)$$

where f_c = cylindrical compressive strength; $f_{c,cube}$ = cubic compressive strength.

The notation is the same of the Eurocode 2 [12].

Since two specimens (one for each kind of conglomerate) showed values for volumetric mass and compressive strength presenting an excessive deviation from the average value, according to the usual statistic calculations, such data have been properly discarded in the calculations (see Table 7).

A reasonable difference was observed between experimental and theoretical values of the tensile strength for both conglomerates, being about 3.4% for concrete made with EAF slag and 7.3% for traditional concrete. A significant difference between experimental and theoretical values was surprisingly observed for the elastic modulus of the traditional concrete (23.1%), whereas this difference was minimal for concrete made with EAF slag (4.5%). The theoretical elastic modulus was higher than the experimental one for both conglomerates.

The higher global compressive strength for the conglomerate with EAF slag than that of the traditional one is not likely due to different strength properties of the aggregate, but rather to the different quality of cement matrix–aggregate contact surface. In most cases, splitting occurred within the cement matrix–aggregate for specimens with EAF slag, showing a strong link between binder and aggregate, favoured by the typical surface porosity and roughness of Black (Oxidizing) slag; the splitting surfaces in the traditional conglomerate instead showed a plain separation between aggregates and cement matrix, probably due to the smooth round shape of natural fluvial aggregate: this may have reduced the global strength of traditional conglomerate with respect to the experimental one. In Fig. 1, cylindrical specimen failures due to splitting test for EAF slag and traditional conglomerate are, respectively, shown. In Fig. 2 stress vs. strain diagrams for specimens tested with the aim of calculating the Young modulus, according to UNI EN 6556 [13], are shown. In Table 9 the average values of the compression secant Young modulus are listed. An average compression secant Young modulus of about 30693 MPa is obtained for EAF slag concrete and about 24065 MPa for traditional concrete specimens. A correlation between the higher stiffness of EAF slag conglomerate and density of EAF slag – considerably higher than that of natural aggregates – is possible; moreover higher cohesion between aggregate and matrix, due to the high roughness of the slag, may produce a higher stiffness too.

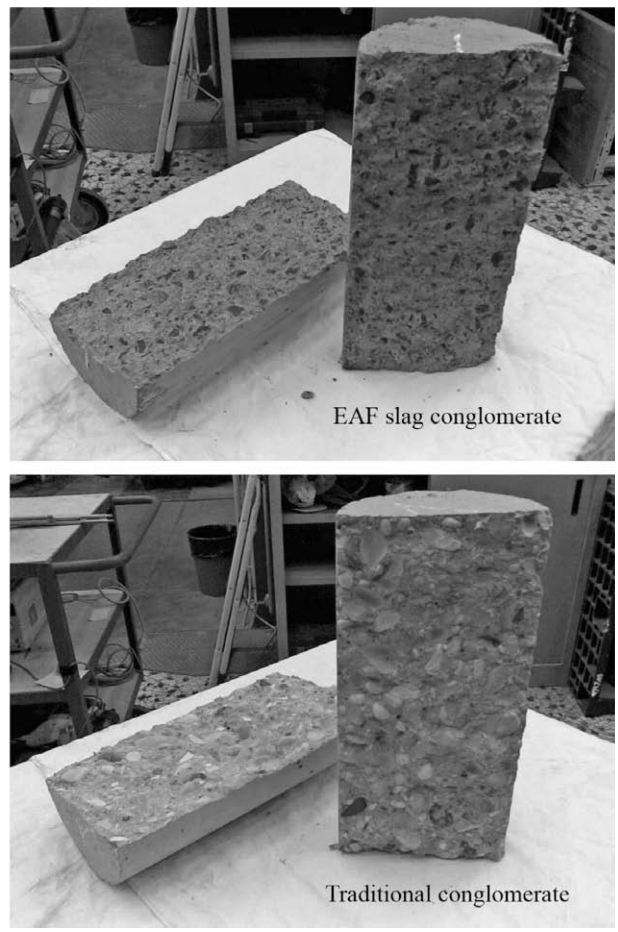

Fig. 1. Comparison between EAF slag and traditional conglomerate cylindrical specimen failures after the splitting test.

5. Durability tests

Both the conglomerate made with EAF slag and the traditional one, once aged for 28 days in standard conditions, have been subjected to three different kinds of accelerated aging, for periods of 25–32 days to obtain some information about the durability of the concrete containing EAF slag in place of traditional aggregates. In Fig. 3 the tests planning for standard and accelerated aging timeline is shown.

Referring to the accelerated aging method proposed in the ASTM D-4792 standard [14], five concrete specimens made with EAF slag and three traditional concrete specimens (both having a standard 28 days-aging) were completely dipped (below 5 cm) in a thermostatic tub containing 70 °C water and properly covered (to limit evaporation) for a total duration of 32 days. The main purpose of this procedure is to cause hydration of the free lime (CaO) and periclase (MgO) still contained in most slags used as aggregates, possibly shown by exterior signs and expansion. After the treatment, all the specimens – particularly those made with

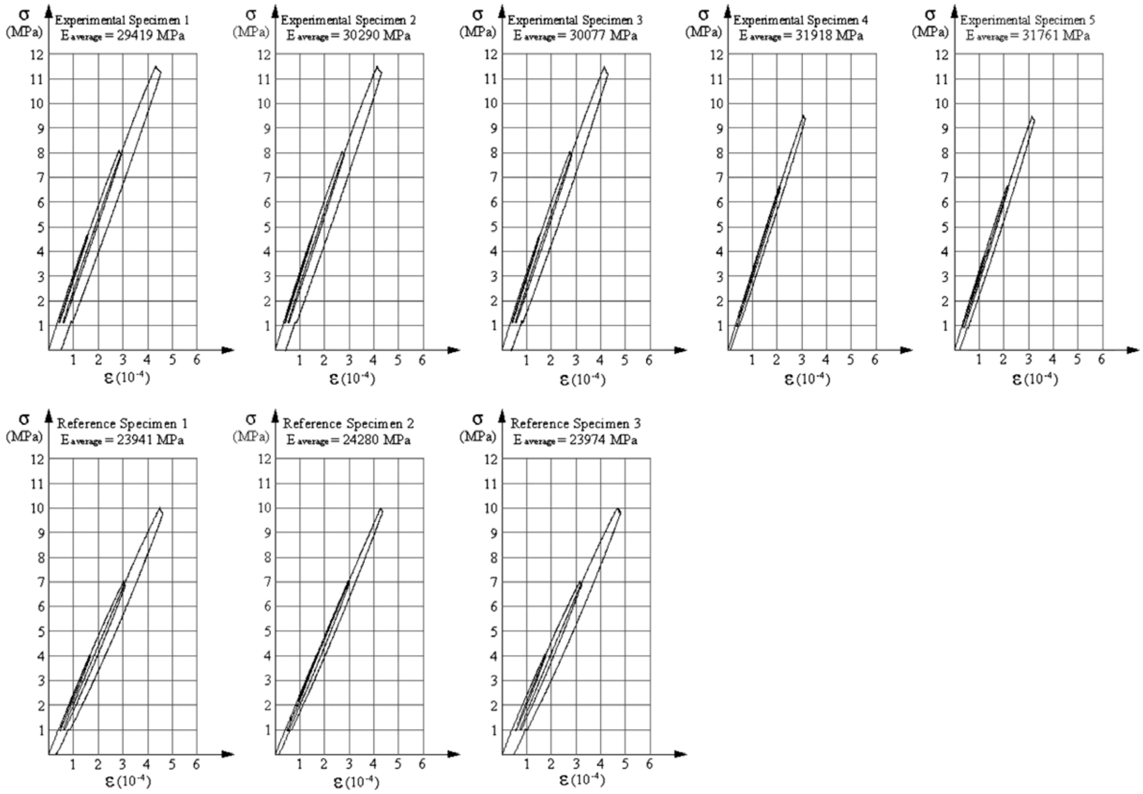

Fig. 2. Stress vs. strain diagrams for the calculation of the experimental Young modulus of the specimens with EAF slag and traditional ones.

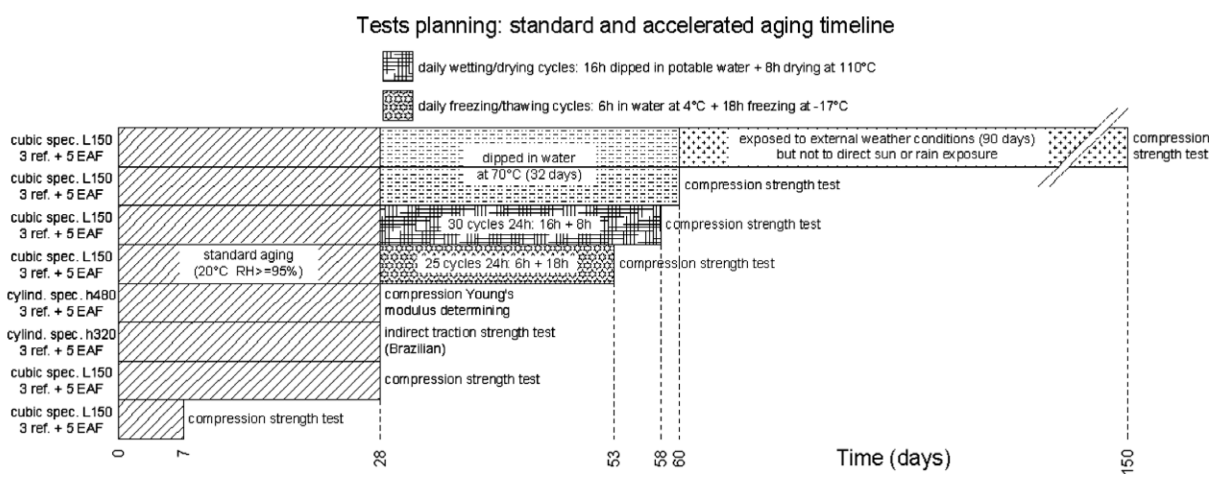

Fig. 3. Tests planning: standard and accelerated aging timeline.

slag – showed noticeable surface white powder outcrops, clearly recognizable as the respective calcium and magnesium hydroxides. In Fig. 4 noticeable surfaces white powder outcrops consisting of Ca and Mg hydroxides are shown for two specimens.

In Table 10 the variations of the basic properties in specimens dipped in warm water at 70 °C for 32 days are listed. Traditional concrete specimens subjected to such accelerated aging and showing the least amount of efflorescence, showed a final compressive strength about 9% higher than specimens that were not subjected to such treatment, prevailing here the aging/improving effect over the worsening effect on concrete specimens dipped in hot water; this is also in agreement with other experimental investigations reported in the recent literature [3]. On the other hand concrete specimens made with EAF slag, which were strongly subjected to free oxides hydration and to subsequent inner differential micro-expansions, lost more than 5% of their compressive strength. Basically the global density was not subjected to great variations, as the absorption of oxides hydration water slightly increased (just about 2%) the weight of all specimens.

A further set of four concrete specimens made with EAF slag plus one traditional concrete specimen was subjected to the same treatment (dipped in warm water at 70 °C for 32 days) and subsequently it was exposed to outdoor weathering for 90 days under moist atmospheric conditions, without direct sun or rain exposure, to allow any aging effect being fully extended inside the concrete. Such long-term test showed a sort of stabilization of the measured

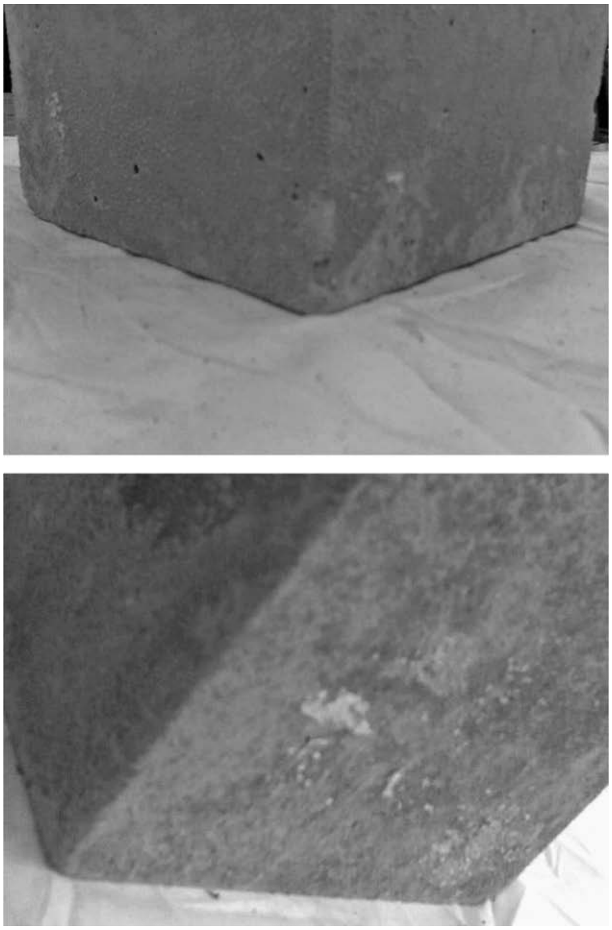

Fig. 4. Noticeable surface white powder outcrops consisting in Ca and Mg hydroxides observed for two specimens.

properties along time in specimens left outdoor for 3 months: both values of global density and compressive strength are similar to those tested without outdoor weathering and closer to the reference (natural aging) conditions. Long outdoor weathering seems to soften the effects of accelerated aging, allowing a spread of the consequent physical modifications all along the depth of the specimens. The strength increase due to natural aging is even predominant for concrete made with EAF slag (comparing Tables 10 and 11 EAF slag concrete shows a compressive strength of 41.9 MPa before weathering and 43.4 MPa after 3 months of outdoor weathering). Moreover, the release of hydration water during the first phase of such accelerated aging yields a noticeable loss in global density in both kinds of concrete (again compare Tables 10 and 11).

The second accelerated aging tests, aimed to simulate a continuous alternation of freezing and thawing critical weather conditions, were planned according to similar procedures already tested in past experimental investigations: five concrete specimens made with EAF slag plus three traditional concrete specimens, with standard 28 days aging, were subjected to 25 daily freezing–thawing cycles. The cycles consisted of a first phase with specimens dipped in 4 °C water for 6 h, followed by a second phase during which specimens were frozen at −17 °C for the remaining 18 h.

In Table 12 the basic properties variations in specimens subject to freezing and thawing cycles for 25 days are listed. All the specimens passed this test with excellent results without showing significant surface deterioration, despite the severity of the test. The large amount of closed porosity caused by the air-entraining agent yielded a marked resistance to freezing conditions and produced a minimization of the relevant thermal/expansive stress. After this test, the traditional conglomerate even shows a compressive strength slightly higher than before (about 3 MPa), probably caused by further cement hydration due to the direct contact with water pushed through the frozen saturated surface micro-porosity. As already noticed in other experimental programs on concrete made with EAF slag [3], this kind of concrete specimen showed less tolerance to freezing and thawing cycles than the traditional ones since specimens made with EAF slag showed a reduction of about 7% of their compressive strength after the treatment. However this reduction is more acceptable than the 40% loss obtained in [4] for specimens without an air-entraining agent. The worse response of EAF slag concrete subjected to critical freezing/thawing conditions, in this case, could be due more to the free oxides hydration during the thawing phase and, secondly, to the EAF slag/cement matrix interface porosity (due to the high roughness typical of such slag) than to the open surface porosity of the aggregate itself.

The third type of durability tests were done on five concrete specimens made with EAF slag plus three traditional concrete specimens with standard 28 days aging and aimed to investigate the response of conglomerates in critical environmental conditions with intense moist/wetting phases alternated to drying phases. The specimens were subjected to 30 daily wetting and drying cycles developed keeping the specimens in potable water at room temperature for 16 h and then drying them in a electric oven at 110 °C for the remaining 8 h.

In Table 13 basic properties variations in specimens subject to wetting and drying cycles for 30 days are listed. It was supposed that such treatment could be highly harmful for the physical/resistance properties of both conglomerates because of the combined effect of expansion and contraction due to thermal variation plus that due to inner and surface humidity variation. For this reason, as a result of such test, both traditional and EAF slag specimens showed a strength loss. This strength loss was more significant (about 26%) for the conglomerate made with EAF slag. Although surface damages were not observed in any specimen, it is probable that the higher expansion propensity, typical of black slag (produced in EAF plants) mainly due to the high amount of Calcium and Magnesium oxides, caused more serious degradation in EAF

Table 10
Basic properties variations in specimens dipped in warm water at 70 °C for 32 days.

Mix type	Density (t/m^3)	Cubic compressive strength (MPa)	Mix type	Density (t/m^3)			Compressive strength (MPa)		
				Without aging (average value)	With aging (average value)	Variation with aging (%)	Without aging (average value)	With aging (average value)	Variation with aging (%)
Traditional	2.385	31.1	Traditional	2.334	2.396	+2.63	30.4	33.1	+9.07
Traditional	2.424	35.3	with EAF slag	2.960	3.022	+2.08	44.4	41.9	−5.65
Traditional	2.379	32.9							
With EAF slag	3.003	44.0							
With EAF slag	3.026	46.2							
With EAF slag	3.036	38.2							
With EAF slag	3.015	40.8							
With EAF slag	3.028	40.4							

Table 11
Basic properties variations in specimens dipped in warm water at 70 °C for 32 days and then exposed to external weathering for 90 days.

Mix type	Density (t/m^3)	Cubic compressive strength (MPa)	Mix type	Density (t/m^3)			Compressive strength (MPa)		
				Without aging (average value)	With aging (average value)	Variation with aging (%)	Without aging (average value)	With aging (average value)	Variation with aging (%)
Traditional	2.344	32.9	Traditional	2.334	2.344	+0.41	30.4	32.9	+8.35
With EAF slag	2.937	46.7	with EAF slag	2.960	2.968	+0.26	44.4	43.4	−2.37
With EAF slag	3.010	45.2							
With EAF slag	2.969	41.4							
With EAF slag	2.955	40.3							

Table 12
Basic properties variations in specimens subjected to freezing and thawing cycles for 25 days.

Mix type	Density (t/m^3)	Compressive strength (MPa)	Mix type	Density (t/m^3)			Compressive strength (MPa)		
				Without aging (average value)	With aging (average value)	Variation with aging (%)	Without aging (average value)	With aging (average value)	Variation with aging (%)
Traditional	2.392	33.4	Traditional	2.334	2.384	+2.15	30.4	33.9	+11.53
Traditional	2.382	32.3	with EAF slag	2.960	3.001	+1.37	44.4	41.2	−7.28
Traditional	2.379	36.0							
With EAF slag	3.009	38.7							
With EAF slag	3.010	40.4							
With EAF slag	2.918	37.7							
With EAF slag	2.991	43.9							
With EAF slag	3.076	45.3							

Table 13
Basic properties variations in specimens subjected to wetting and drying cycles for 30 days.

Mix type	Density (t/m^3)	Compressive strength (MPa)	Mix type	Density (t/m^3)			Compressive strength (MPa)		
				Without aging (average value)	With aging (average value)	Variation with aging (%)	Without aging (average value)	With aging (average value)	Variation with aging (%)
Traditional	2.400	27.8	Traditional	2.334	2.401	+2.85	30.4	28.7	−5.68
Traditional	2.368	29.4	With EAF slag	2.960	2.983	+0.79	44.4	32.7	−26.52
Traditional	2.435	28.7							
With EAF slag	2.997	30.7							
With EAF slag	2.989	34.2							
With EAF slag	2.991	31.6							
With EAF slag	2.983	33.4							
With EAF slag	2.958	33.4							

slag conglomerate specimens than in traditional ones. A higher expansiveness in EAF slag conglomerate subjected to wetting and drying cycles seems confirmed by the density values observed: whereas traditional concrete specimens show a small weight/density increase corresponding to a certain absorption of hydration water, in specimens made with EAF slag it is probably balanced by a concomitant expansion, thus showing an almost constant density.

6. Conclusions

In this work the use of Black/Oxidizing slag (also called EAF slag) as by-product in EAF plants for continuous steel production was studied to investigate the possibility of replacing the traditional aggregates for concrete production. Compressive and tensile strength, elastic modulus and durability characteristics (accelerated aging, freezing and thawing, wetting and drying) of concrete containing EAF slag as aggregate according to Fuller's ideal grading curve were experimentally investigated. The main result was that EAF slag is basically suitable to replace traditional natural aggregates in conglomerates, even in high percentages and for medium sizes (to 2–4 mm size). However it should be considered that such slag have to be stored and aged outdoors in advance and exposed to natural moisture or forced spraying for various weeks, in order to allow any feasible expansion and breaking up for both short and long term hydration and achieve the chemical/physical stabilization necessary for safe use in concrete production. If, on one hand, concrete made with EAF slag as aggregate showed good strength characteristics in ordinary environmental conditions since its strength properties are totally comparable (or even better) than those observed for traditional concrete, on the other hand, free oxides hydration and EAF slag/cement matrix interface porosity seem to represent a limit for the durability of the resulting concrete. In fact, although it was shown that the durability can be strongly improved even in critical freezing/thawing environmental conditions by a small amount of air-entraining agent, such conglomerates still remain rather vulnerable to repeated cycles of wetting and drying.

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