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# Properties of concretes with Black/Oxidizing Electric Arc Furnace slag aggregate

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ABSTRACT

The aim of this work is to comprehensively investigate the possibility of partially substituting natural aggregates with Black/Oxidizing Electric Arc Furnace (EAF) slag in concrete production. Five recycled and one traditional mixes were produced to identify a convenient substitution ratio for the concrete. Main physical and mechanical properties of concrete containing EAF slag as aggregate according to Fuller's grading curve were experimentally investigated. Chemical and durability tests were performed to study the microstructure and analyse the behaviour of the conglomerate exposed to detrimental agents. Results showed that high substitution ratios of coarse natural aggregates are possible without decreasing mechanical properties of concrete. Conversely, replacement of fine natural aggregates with recycled ones seems feasible at lower substitution ratios only. Presence of calcium and magnesium oxides in the slag does not seem to represent a limit for the durability of concrete, due to their stabilization in crystalline lattice.



## 1. Introduction

Recycled material use in building industry represents an attractive alternative to landfill disposal of waste, reduce natural resources depletion and limit the high energetic/environmental impacts in traditional concrete production. Moreover, disposal costs and potential pollution problems could be reduced along with the achievement of resources conservation. Construction materials are very significant, representing the 3–4% of the total product in Europe [1], and their environmental impact could be limited using a series of alternative solutions. Nowadays, there are, among others, two significant possibilities: using recycled concrete coming from building demolition [2–4], and the use of slag from metallurgical industrial production [5–9].

Steel production takes place in two types of plants: Basic Oxygen Furnace (BOF) and Electric Arc Furnace (EAF) plants. The last ones produce more than 40% of the whole global steel, allowing the manufacture of steel from scrap metal and aiming to a more competitive and sustainable production. Black/Oxidizing EAF slag are the main by-product of steel manufacture, and their production in Europe is about 20 million tons every year. In 2009 steel production in Italy represented about 14% of total Europe steel industry, yielding a considerable quantity of EAF slag during production cycle [10]. Differently from slag produced in blast furnaces, which has been recycled as active addition in the manufacture of commercial blended Portland cement, EAF slag have major problems in recycling and reuse, even if applications in asphalt mixes and concrete production are growing up in the last decade [11].

The growing interest in identifying sustainable materials for concrete production, the necessity of establishing a correct management of this kind of slags and the lack of a thorough study on the substitution ratio slag/natural aggregate, induce to deepen this field by means of a comprehensive experimental approach which includes chemical and microstructural analysis of materials, evaluation of durability behaviour and mechanical tests on concrete with various percentages of EAF slag as coarse and fine aggregate.

In this work five recycled and one traditional mixes for concrete were produced with the aim of comprehensively study, from a mechanical and chemical point of view and with a particular attention to durability, the possibility of partially substituting natural aggregates with EAF slag and obtain some elements for identifying a convenient (coarse and fine) aggregate substitution ratio. Main physical properties, compressive and tensile strength, elastic modulus of concrete containing EAF slag as aggregate according to Fuller's ideal grading curve were experimentally investigated. Durability tests were performed to analyse the behaviour of the mixes exposed to detrimental agents, such as frost and moisture, in typical environmental conditions. Chemical and microstructural analysis were performed by means of four complementary techniques: leaching tests on the slag, Scanning Electroscope Imaging analyses, X-ray Diffraction analysis and Energy Dispersive X-ray Spectroscopy analysis on pulverized slag and concrete.

The present research work is a further stage of a previous research previously conducted, as a first step, by one of the authors [12], which was focused on a single mix design and where the

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wholeness of the coarse part was substituted by recycled aggregates. This wide experimental study has the aim of generalizing the previous pilot study [12] introducing, other than mechanical and durability characterization, a specific chemical and microstructural in-depth examination of various mixes with EAF slag. In particular, this work was conducted to assess the suitability of using both coarse and fine recycled aggregates in various replacement ratios, evaluate the effective stability of the material and estimate the effect of the slag/natural aggregate substitution ratio on concrete physical, chemical, mechanical and microstructural characteristics and its durability.

## 2. Materials and experimental methods

### 2.1. Materials

Steel slag used in this experimental investigation are obtained from a local steel factory in the North-Eastern part of Italy; they have a black colour stone-like appearance, a lime content lower than 40%, a high density and low water absorption and porosity. Two size ranges were used: a fine and a medium/coarse one, with physical characteristics listed in Table 1. Chemical composition is mainly formed by oxides: about 75% is a set of iron, calcium and silicon oxides, plus minor amount of magnesium, aluminium and manganese oxides. The presence of free calcium and magnesium oxides is mainly responsible for hydration and expansion phenomena: the firsts, when in contact with water, rapidly hydrate due to rapid volumetric expansion, whereas the seconds react slower, because the expansion spreads over a longer time [13]. Proper treatment, aimed to stabilize slag by exposing them to outdoor weather and regular spraying for 90 days, was applied to the slag used in this work, allowing to a safer use of the same slag as aggregate in concrete production [14]. A specific chemical analysis was performed at the end of the experimental work, to ensure that expansion phenomena will not occur. Leaching tests have been also developed on the slag to verify that the potential toxic compounds were under the limit values reported in the Italian standards, DM 186 [15]. Table 2 shows the resulting range of obtained quantities; according to the above Italian standards, tested slag is fully admissible.

Natural aggregates used in this experimentation have carbonate origin, their shape was mainly roundish and the main physical properties are listed in Table 3.

A commonly used, in Italy, cement mixture type CEM II-A/L 42.5R was adopted for the conglomerates (with high percentage content of clinker and limestone). In order to reach a S4 slump class concrete, as defined in EN 206-1 [16], it was planned to use a super-plasticizer admixture at 0.4% on cement weight, and an aerating additive at 0.016% on cement weight was introduced to improve durability against freezing/thawing cycles, allowing a 5% percentage of air on the total volume [12].

### 2.2. Mix proportions and experimental methods

One traditional and five experimental mixes with EAF slag were produced, varying the percentage of recycled material on total aggregates. Concerning the concrete production process, the preparation of the mixes was performed to satisfy some specific parameters, such as workability with slump 160–210 mm (S4 slump class), water/cement ratio less or equal than 0.55, and cylindrical compressive strength after 28 days greater than 30 MPa. After the mixing, the specimens were properly compacted and aged in standard temperature and humidity conditions $T = 20\,°C$, RH $\geqslant$ 95% until the time of testing. The mix designs are described in Table 4. Aggregate grading curves were obtained according to Fuller ideal curve and are shown in Fig. 1. Water/cement ratio slightly varies in the produced mixes, due to the necessity of reaching S4 slump class concrete for all the mixes. Since fine EAF aggregates have higher absorption capacity than natural sand, it was necessary to slightly increase w/c ratio when the quantity of recycled fine aggregates increases. Moreover w/c slightly increased in EAF conglomerates with respect to traditional ones also because traditional conglomerate has roundish aggregates whereas EAF slag is more angular and, as a consequence, implies less workability for the related mixes [12]. During production of Mix 5 (containing only recycled aggregates) some difficulties were experienced, because the paste showed a high water demand, due to the particular smooth and sharp shape of the material. Moreover, the aerating additive did not seem to work well in this case, causing the development of great diameter bubbles during concrete placement. It should to be noted that, in literature, there are works showing the strong difficulty to produce conglomerates with recycled aggregates only [17,18].

Mechanical tests and durability analyses were performed on 108 cubic specimens with 150 mm side, 18 cylindrical specimens with 160 mm diameter and 320 mm length for splitting test, according to European Standard EN 12390-1 [19], and 18 cylindrical specimens with 160 mm diameter and 480 mm length for Young modulus calculation, according to UNI EN 6556 [20]. Test plan is illustrated in Fig. 2: the first phase consists in standard

**Table 1**
Main physical characteristics of EAF slag.

| | Medium/coarse size EAF slag | Fine size EAF slag |
|---|---|---|
| Size (mm) | 4–22.4 | 0–4 |
| Apparent specific gravity (t/m$^3$) | 3.850 | 3.780 |
| Water absorption (%) | 0.53 | 1.613 |
| Los angeles loss (%) | <20 | – |

**Table 2**
Leaching test results.

| Parameter | Concentration (mg/l) | Limits |
|---|---|---|
| Nitrates | <40 | 50 |
| Fluorides | <1.5 | 1.5 |
| Sulphates | <200 | 250 |
| Chlorides | <75 | 100 |
| Cyanides | <0.03 | 0.050 |
| Barium | 0.0125 | 1 |
| Copper | <0.001 | 0.05 |
| Zinc | <0.03 | 3 |
| Beryllium | <0.005 | 0.01 |
| Cobalt | <0.01 | 0.25 |
| Nickel | <0.005 | 0.01 |
| Vanadium | 0.103 | 0.25 |
| Arsenic | <0.02 | 0.05 |
| Cadmium | <0.003 | 0.005 |
| Total chromium | <0.002 | 0.05 |
| Lead | <0.04 | 0.05 |
| Selenium | <0.010 | 0.01 |
| Mercury | <0.001 | 0.001 |
| Amianthus | <10 | 30 |
| COD | <25 | 30 |
| pH | 10.78 | 5.5–12.0 |

**Table 3**
Main physical characteristics of natural aggregate.

| | Medium/coarse size gravel | Sand |
|---|---|---|
| Size (mm) | 4–22.4 | 0–4 |
| Apparent specific gravity (t/m$^3$) | 2.732 | 2.724 |
| Water absorption (%) | 0.75 | 0.8 |
| Los angeles loss (%) | 18 | – |

**Table 4**
Mix design of conglomerates. Quantities are referred to 1 $m^3$ of concrete.

| | Traditional | Mix 1 | Mix 2 | Mix 3 | Mix 4 | Mix 5 |
|---|---|---|---|---|---|---|
| Natural gravel (%) | 100 | 100 | 100 | 50 | – | – |
| Natural sand (%) | 100 | 50 | – | 50 | 50 | – |
| Medium/coarse EAF slag (%) | – | – | – | 50 | 100 | 100 |
| Fine EAF slag (%) | – | 50 | 100 | 50 | 50 | 100 |
| D max (mm) | 22.4 | 22.4 | 22.4 | 22.4 | 22.4 | 22.4 |
| Cement (kg) | 330 | 335 | 340 | 340 | 350 | 355 |
| Water (l) | 155 | 158 | 167 | 180 | 185 | 195 |
| w/c | 0.47 | 0.47 | 0.49 | 0.53 | 0.53 | 0.55 |
| V aggregates (l) | 682 | 678 | 673 | 675 | 662 | 658 |
| Total EAF slag s.s.d. fraction (kg) | – | 514 | 1019 | 1278 | 1894 | 2508 |
| Total natural aggregates s.s.d. fraction (kg) | 1861 | 1480 | 1102 | 920 | 456 | – |
| Fluidifying admixture (kg) | 1.31 | 1.33 | 1.36 | 1.36 | 1.39 | 1.42 |
| Aerating additive (g) | 56 | 56 | 56 | 56 | 56 | 56 |

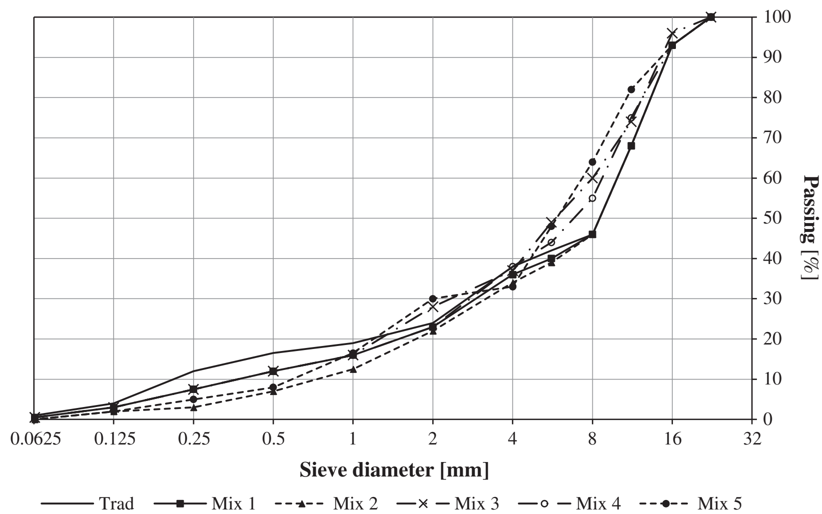


**Fig. 1.** Aggregate grading curves for experimental conglomerates.

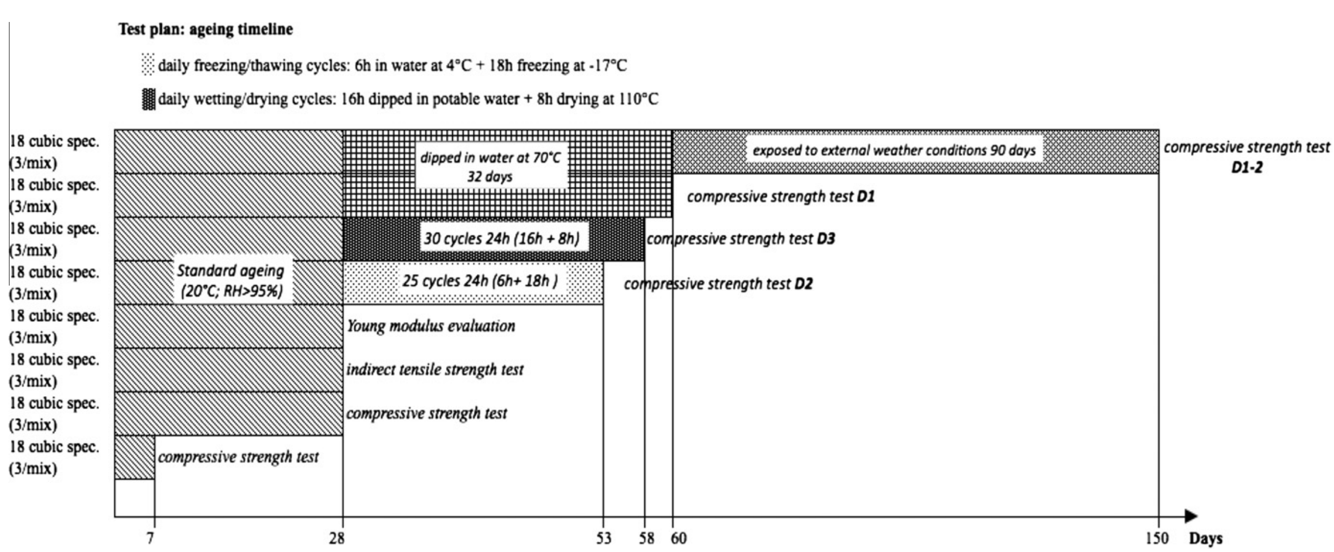


**Fig. 2.** Test plan: mechanical and durability analyses.

ageing, which concluded after 28 days. Compressive tests have been developed after seven (three specimens for each mix) and 28 days (three specimens for each mix), following the European Standard EN 12390-4 [21]. Indirect tensile strength was measured after 28 days by splitting test, following European Standard EN 12390-6 [22], and Young modulus was experimentally evaluated according to UNI EN 6556 [20]. In the second phase three different types of accelerated ageing (including wetting/drying and freezing/thawing cycles) were developed. The first durability test (D1) follows ASTM D-4792 standard [23]: specimens were completely dipped in a thermostatic tub containing 70 °C water and properly covered to limit evaporation for a total duration of 32 days. A further set of three specimens for each mix was subjected to the same treatment described above, and then exposed to outdoor weathering for 90 days under atmospheric conditions (D1-2), with direct sun and rain exposure. The second accelerated ageing test (D2) concerns the investigation of durability of concrete with an alternation of freezing and thawing conditions. Three specimens for each mix were subjected to 25 daily cycles consisting in a first phase with a duration of 18 h in which specimens were frozen at the temperature of −17 °C and a second phase with a duration of 6 h in which they were dipped in 4 °C water. The last durability test (D3) was done on three specimens for each mix; they were subjected to 30 wetting/drying daily cycles. Specimens were dipped for 16 h in potable water at room temperature, and then dried for 8 h in a electric oven at 110 °C. The main objective of these tests is to obtain some elements about the durability of the various mixes, comparing compressive strength after standard and accelerated ageing, and individuating the conditions that mainly affect the mechanical characteristics of concrete containing such recycled aggregates in time.

## 3. Results and discussion

### 3.1. Compressive and tensile strength and Young's modulus after 28 days

The results of compressive and tensile strength tests are listed in Table 5. Concerning compressive strength tests, as already obtained in [12], observed mean compressive strengths are similar for traditional and recycled conglomerates, and for some replacement ratios, they result higher than in traditional concrete. The failure mode was similar for specimens made with traditional and recycled aggregates, with exception of Mix 2 and, above all, Mix 5, which showed a more brittle behaviour. Results show that the tensile strength in concrete with EAF slag is generally higher than those in traditional concrete; this is probably due to the different cement matrix-aggregate contact surface, which is more rough in recycled concrete and may allow a stronger link between binder and aggregate. Splitting surfaces in concrete containing EAF slag are less regular than in the traditional mix, in particular when the coarse aggregates are substituted. On the other hand, substitution of fine aggregates may cause a decrease of the mechanical strength, because cementitious matrix becomes less cohesive.

As for the other measured mechanical properties, the obtained values of the Young modulus are similar and, in most cases, recycled concrete showed greater moduli.

However, the fluctuation in experimental values is more evident for the mixes containing high percentage of EAF slag, in particular for the conglomerates with the whole fine part as recycled aggregate, than for traditional concrete. This is mainly due to the higher heterogeneity of the slag with respect to natural aggregates.

### 3.2. Durability tests

Once aged for 28 days in standard conditions, three specimens for each conglomerate have been subjected to three kinds of accelerated ageing for periods varying from 25 to 32 days.

The first durability test D1 investigates the potential expansion of dense graded compacted aggregates, which could induce hydration of free lime (CaO) and periclase (MgO) generally contained in most slag used, leading to consequent volume increase. After the test, all the specimens, including the traditional ones, showed white powder outcrops, as shown in Fig. 3. The formation of this type of efflorescence could be assigned to the cementitious matrix hydration, which leads to the formation of a calcium carbonate powder on specimen surfaces. Specific chemical and microstructural analyses were performed to understand the nature of this phenomenon, revealing a composition mainly consisting in calcium, silicon, magnesium, and aluminium oxides. Iron presence was null, indicating that this material is not connected with EAF slag use, but that it was composed by dissolved salts transported on specimen surface through water evaporation.

Table 6 shows the values of mean compressive strength measured after the above durability test for each mix, compared to the strength after 28 days of natural ageing. All the specimens increased their mechanical strength, even if the treatment in hot water has a worse effect on conglomerates with high content of EAF slag, which were strongly subjected to free oxides hydration and subsequent inner differential micro-expansion. There are no significant differences in specific weight due to this durability test, since the absorption of oxides hydration water only slightly increased the weight of the specimens (the maximum variation is +2.3%).

**Fig. 3.** White powder outcrops on specimens after accelerated ageing treatment.

**Table 5**
Mean specific weight, slump, compressive and tensile strength and Young modulus (after 7 and 28 days).

| Mix type | Specific weight (t/m$^3$) | Slump (mm) | 7 days | | | 28 days | | |
|---|---|---|---|---|---|---|---|---|
| | | | Specific weight (t/m$^3$) | $f_{cm,\ cube}$ (MPa) | Specific weight (t/m$^3$) | $f_{cm,\ cube}$ (MPa) | $f_{ctm}$ (MPa) | $E_{cm}$ (GPa) |
| Traditional | 2.53 | 20.0 | 2.38 | 37.8 | 2.49 | 44.63 | 3.54 | 37.51 |
| Mix 1 | 2.66 | 19.0 | 2.53 | 35.3 | 2.61 | 45.42 | 3.73 | 37.36 |
| Mix 2 | 2.85 | 20.5 | 2.71 | 33.1 | 2.78 | 44.00 | 3.62 | 38.68 |
| Mix 3 | 2.83 | 19.5 | 2.83 | 37.5 | 2.79 | 45.23 | 3.56 | 40.39 |
| Mix 4 | 3.00 | 19.5 | 2.90 | 36.0 | 2.94 | 45.10 | 4.01 | 40.04 |
| Mix 5 | 3.19 | 18.0 | 3.12 | 33.9 | 3.13 | 41.40 | 3.76 | 38.47 |

**Table 6**
Basic properties in specimens after accelerated ageing for 32 days and variation with respect to the same properties before accelerated ageing.

| Mix type | Mean specific weight | | | Mean compressive cubic strength | | |
|---|---|---|---|---|---|---|
| | After ageing (t/m$^3$) | Before ageing (t/m$^3$) | Variation (%) | After ageing (MPa) | Before ageing (MPa) | Variation (%) |
| Traditional | 2.49 | 2.49 | −0.07 | 51.59 | 44.63 | +13.49 |
| Mix 1 | 2.61 | 2.61 | −0.19 | 47.02 | 45.42 | +3.39 |
| Mix 2 | 2.80 | 2.78 | +0.68 | 44.76 | 44.00 | +1.70 |
| Mix 3 | 2.85 | 2.79 | +2.29 | 50.79 | 45.23 | +10.95 |
| Mix 4 | 2.95 | 2.94 | +0.38 | 47.52 | 45.10 | +5.10 |
| Mix 5 | 3.13 | 3.13 | −0.29 | 42.36 | 41.40 | +2.28 |

**Table 7**
Basic properties in specimens after accelerated ageing for 32 days plus weathering for 90 days and variation with respect to the same properties before accelerated ageing/weathering.

| Mix type | Mean specific weight | | | Mean compressive cubic strength | | |
|---|---|---|---|---|---|---|
| | After ageing (t/m$^3$) | Before ageing (t/m$^3$) | Variation (%) | After ageing (MPa) | Before ageing (MPa) | Variation (%)SS |
| Traditional | 2.49 | 2.49 | −0.17 | 54.50 | 44.63 | +18.10 |
| Mix 1 | 2.57 | 2.61 | −1.56 | 53.85 | 45.42 | +15.65 |
| Mix 2 | 2.78 | 2.78 | +0.13 | 51.08 | 44.00 | +13.87 |
| Mix 3 | 2.82 | 2.79 | +0.97 | 56.24 | 45.23 | +19.58 |
| Mix 4 | 2.93 | 2.94 | −0.29 | 53.19 | 45.10 | +15.21 |
| Mix 5 | 3.12 | 3.13 | −0.50 | 48.32 | 41.40 | +14.33 |

A further set of three specimens for each mix produced was subjected to the durability test D1-2. Results are reported in Table 7: long outdoor weathering is predominant and mitigates the effects of the previous accelerated ageing, allowing a further increase in compressive strength, both in the traditional and experimental conglomerates.

The second accelerated ageing tests D2 concern the investigation of durability of concrete with an alternation of freezing and thawing conditions. All the specimens passed this test without showing significant surface deteriorations. This suggests that the air-entering admixture contributed to form an air bubble system preventing that a great quantity of water penetrates in concrete pores, and limiting thermal expansion. After the freezing and thawing cycles, measured compressive strength values increase with respect to the corresponding before cycles both for traditional specimens and specimens with EAF slag (Table 8) probably due to further cement hydration occurred by direct contact with water pushed through the frozen saturated surface micro-porosity, and the natural ageing of the material. Mix 3 and Mix 4 showed a reduced increase in compressive strength with respect to Mix 1 and Mix 2, probably due to their higher water/cement ratio. On the other hand, Mix 5, the one containing recycled material only, showed a significant increase in strength after the cycles. All the specimens showed the same failure mode, with the exception of Mix 2 and Mix 5, showing a more brittle failure than the others (particularly for Mix 5).

The last durability tests D3 have the objective of simulating the behaviour of concrete under critical environmental conditions, with intense moisture conditions alternated to drying ones. Mean compressive strength was evaluated at the end of the treatment, and the results are listed in Table 9. All the mixes (both traditional and recycled) showed a significant decrease in strength, due to the

**Table 8**
Basic properties in specimens after freezing/thawing cycles for 25 days and variation with respect to the same properties before freezing/thawing cycles.

| Mix type | Mean specific weight | | | Mean compressive cubic strength | | |
|---|---|---|---|---|---|---|
| | After ageing (t/m$^3$) | Before ageing (t/m$^3$) | Variation (%) | After ageing (MPa) | Before ageing (MPa) | Variation (%) |
| Traditional | 2.50 | 2.49 | +0.22 | 50.14 | 44.63 | +10.98 |
| Mix 1 | 2.60 | 2.61 | −0.32 | 51.74 | 45.42 | +12.21 |
| Mix 2 | 2.80 | 2.78 | +0.70 | 50.36 | 44.00 | +12.63 |
| Mix 3 | 2.82 | 2.79 | +1.14 | 49.63 | 45.23 | +8.86 |
| Mix 4 | 2.96 | 2.94 | +0.51 | 48.83 | 45.10 | +7.64 |
| Mix 5 | 3.14 | 3.13 | +0.05 | 50.50 | 41.40 | +18.03 |

**Table 9**
Basic properties in specimens after wetting/drying cycles for 30 days and variation with respect to the same properties before wetting/drying cycles.

| Mix type | Mean specific weight | | | Mean compressive cubic strength | | |
|---|---|---|---|---|---|---|
| | After ageing (t/m$^3$) | Before ageing (t/m$^3$) | Variation (%) | After ageing (MPa) | Before ageing (MPa) | Variation (%) |
| Traditional | 2.50 | 2.49 | +0.33 | 39.24 | 44.63 | −13.74 |
| Mix 1 | 2.61 | 2.61 | 0.00 | 42.80 | 45.42 | −6.12 |
| Mix 2 | 2.83 | 2.78 | +1.66 | 41.35 | 44.00 | −6.42 |
| Mix 3 | 2.85 | 2.79 | +2.06 | 37.86 | 45.23 | −19.48 |
| Mix 4 | 3.01 | 2.94 | +2.23 | 36.91 | 45.10 | −22.17 |
| Mix 5 | 3.19 | 3.13 | +1.65 | 37.35 | 41.40 | −10.84 |

highly harmful conditions of the test combining both the alternating effect of expansion and contraction due to thermal variation plus that due to inner and surface humidity variation. Any goethite type was detected by diffraction test (the results of this test are shown in the following section) and surface damages were not observed in any specimens. Nevertheless strength loss could be assigned to some expansion phenomena occurred during the test. Moreover, the small increase in specific weight in all the conglomerates with respect to that measured before the test, could be due to absorption of hydration water, which probably balances the concomitant expansion, as already obtained in [12,24]. Failure mode was similar for all the specimens tested, with the exception of Mix 2 and Mix 5, which showed a more brittle failure, revealing a less cohesive matrix.

Fig. 4 summarizes the outcomes of durability analyses in terms of mean compressive strength, showing that Mix 2 and Mix 5 had lower values in almost all the environmental conditions simulated than those of traditional concrete. The complete substitution of coarse and fine aggregates generated the worst conglomerate having the lowest values of compressive strength both in standard conditions and after environmental cycles. On the other hand, partial substitution of natural aggregates with EAF slag does not seem to induce negative effects on the conglomerates, whose behaviour remains quite similar to the reference concrete. Specific weight remains almost constant in all the conditions simulated for each conglomerate. As expected, the concrete with EAF slag as aggregate has higher specific weight than traditional concrete and this becomes more evident when the substitution percentage increases.

### 3.3. Physical–chemical and mineralogical composition

Three complementary techniques were used to investigate the stability of recycled concrete produced and understand the nature of the variation of the main properties detected after durability tests (specific weight, compressive strength, formation of white powder outcrops): Scanning Electroscope Imaging analyses on concrete samples, X-ray Diffraction analyses and Energy Dispersive

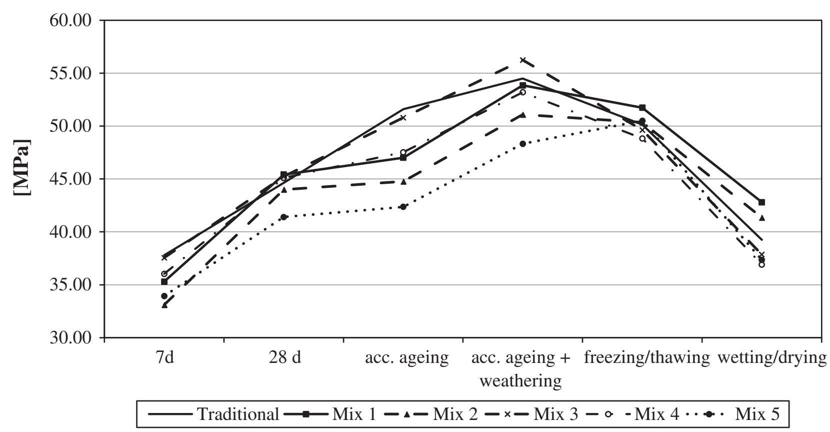


**Fig. 4.** Mean compressive strength observed after natural ageing and various durability tests.

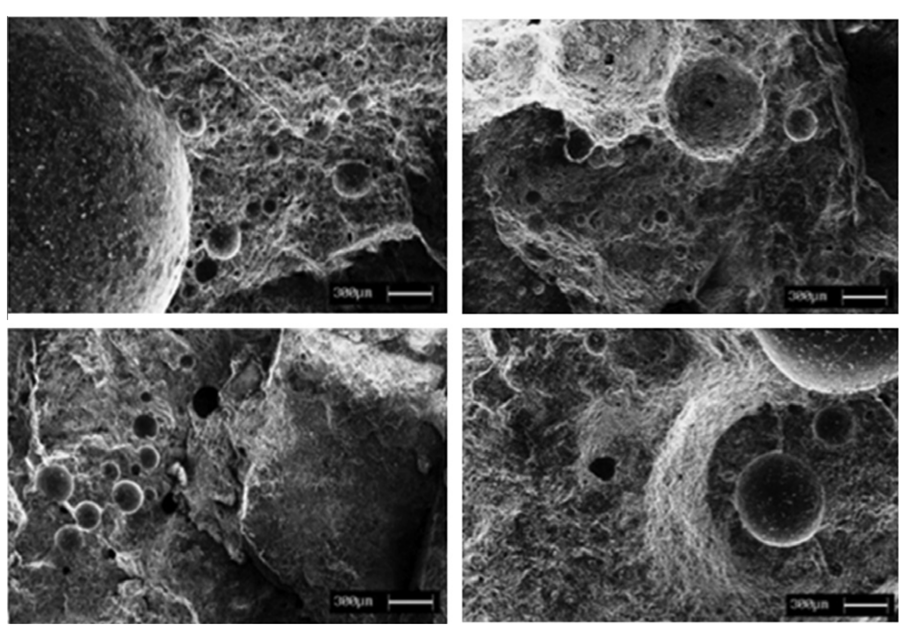

**Fig. 5.** SEM images at 70× magnification. Upper left: traditional concrete; upper right: Mix 2; lower left: Mix 4; lower right: Mix 5. All the samples were extracted from specimens subjected to accelerated ageing.

X-ray spectroscopy analyses on pulverized slag extracted by concrete specimens.

A Stereoscan Cambridge 440 Scanning Electron Microscopy (SEM) was used to investigate the morphology of the material, applying Secondary Electrons (SE) acquisition technique on samples of concrete extracted from concrete specimens subjected to durability tests and from naturally aged specimens (without environmental cycles). SEM images were taken at 70× magnification aiming at identifying, for traditional and recycled concrete, the development of air bubble systems and analysing the cementitious matrix appearance. Fig. 5 shows that there are not significant microstructural differences between traditional and recycled concrete for almost all the mixes, with the exception of Mix 5, containing only EAF slag as aggregate. In this last case the number of developed micro-bubbles seems fewer than the other mixes, and micro-pores seem to remain empty, increasing the probability of

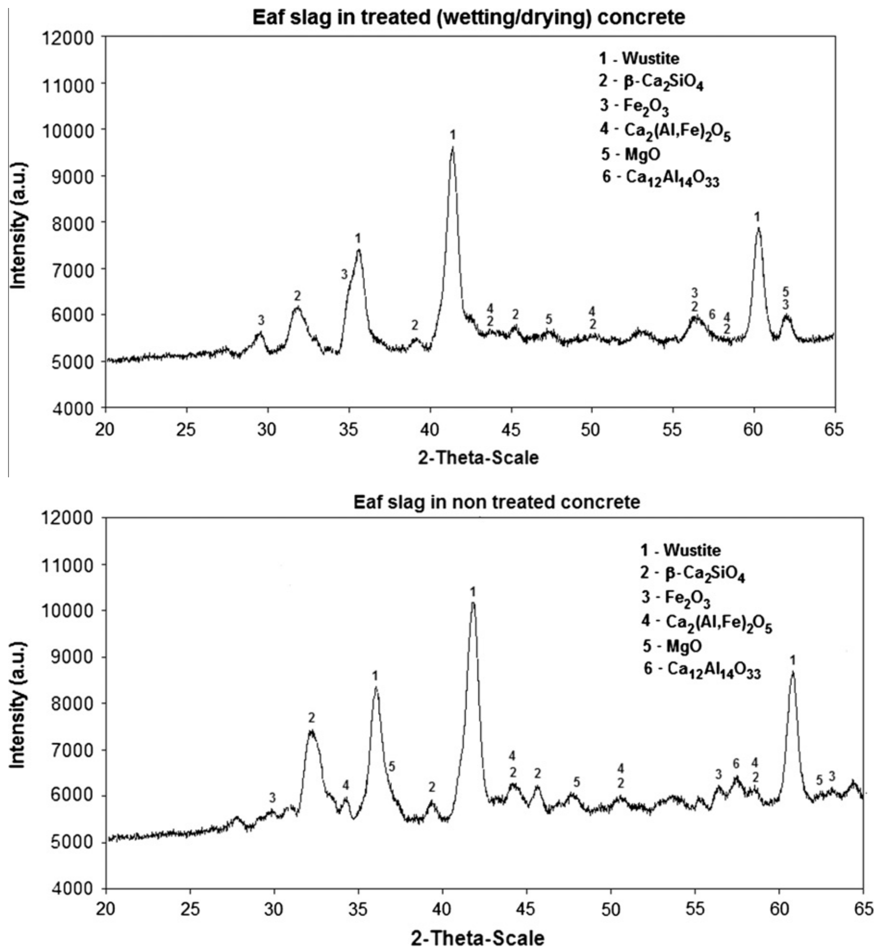


**Fig. 6.** XRD patterns of EAF slag extracted from concrete before and after wetting/drying cycles.

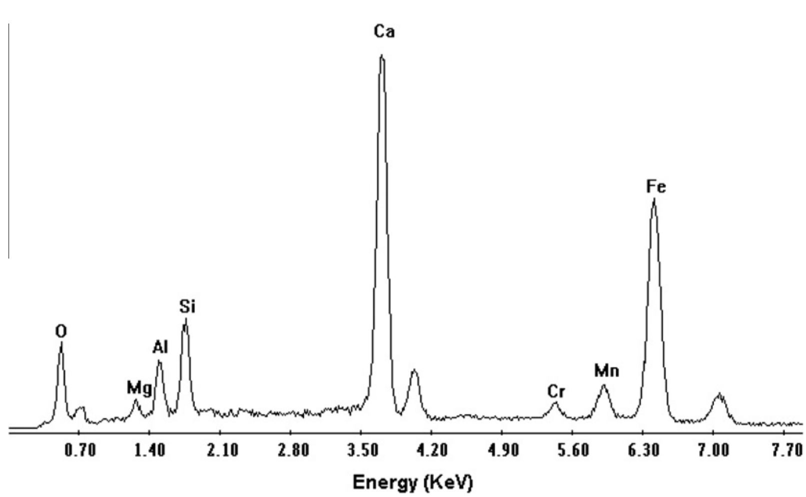


**Fig. 7.** EDS spectrum on EAF slag extracted from concrete after accelerated ageing treatment.

**Table 10**
Oxides weight percentage content in EAF slag, detected after EDS-EDAX analysis.

| Oxide | Wt% |
|---|---|
| MgO | 4.02 |
| $Al_2O_3$ | 10.99 |
| $SiO_2$ | 16.61 |
| CaO | 27.79 |
| $Cr_2O_3$ | 2.17 |
| MnO | 4.67 |
| FeO/$Fe_2O_3$ | 33.75 |
| Total | 100.00 |

having expansion phenomena and reduced strength with respect to the other conglomerates. This result is in agreement with the observed failure mode of Mix 5 that was more brittle probably due to less cohesion in the matrix with respect to the others.

The mineralogy of slag phases was established on pulverized slag extracted from the surface of concrete specimens subjected to durability tests, using Siemens D500 diffractometer, with a stepped and continuous scanning device, with (Cu K$\alpha$) radiation emission. The analyses were performed on samples extracted from Mix 4 concrete specimens, before and after accelerated ageing (D1) and wetting/drying cycles (D3). In both cases any differences were detected in the crystallographic structure. Fig. 6 shows the complex mineralogical system, which is mainly formed by crystalline material, as identified by the graphs. Main crystalline solids are wustite (FeO), calcium silicate ($\beta$-$Ca_2SiO_4$), hematite ($Fe_2O_3$) and brownmillerite ($Ca_2(Al, Fe)_2O_5$); unassimilated MgO was detected in limited quantities. The high crystalline nature of the examined slag indicates a quite stable material and limits further possibilities of expansion phenomena [25].

Chemical composition and detection of oxides was obtained analysing polished thin samples extracted from the superficial zone of concrete specimens of Mix 4, subjected to accelerated ageing (D2), using Philips PV 9800 SEM, with energy dispersive analysis (EDS). Produced spectra applying this analytical technique are similar for all the samples tested, obtaining a maximum fluctuation in quantitative estimation of elements of ±2%, mainly due to the nature of scrap materials in the furnace, during steel production. Fig. 7 and Table 10 illustrate results of the analyses, firstly defining a qualitative indication of the elements detected inside the slag, and then, after results processing through standardless EDAX ZAF quantification, a quantitative definition of weight percentage of oxides in the material, whose results are similar to those present in [11].

## 4. Conclusions

This work deals with a comprehensive assessment of the suitability of using both coarse and fine recycled EAF slag aggregates in various replacement ratios for concrete production and the estimation of the effect of the slag/natural aggregate substitution on concrete chemical, physical and mechanical characteristics, durability and microstructure, evaluating the effective stability of the material. According to the results presented in this research work, the following conclusions can be drawn:

(1) The use of EAF slag has a negative impact on the workability of the mixes when substitution ratio becomes high (more than 50%). It is recommended to maintain at least 50% of fine natural aggregates content, to prevent difficulties in mix preparations.
(2) Other than increasing the specific weight of the concrete, the use of EAF slag as a coarse aggregate contributes to increase compressive and tensile strength, and elastic modulus. On the other hand, the effect of EAF slag, when it replaced the wholeness of the fine aggregates (e.g. Mix 2 and Mix 5), has a negative influence on compressive strength, causing, in this case, losses until 7% compared to the traditional mix.
(3) The influence of environmental cycles on compressive strength is generally similar for traditional and recycled concrete. Accelerated ageing showed that specimens containing EAF slag as fine aggregates had less significant increase in compressive strength than specimens with EAF slag only as coarse aggregates (average variation of compressive strength in Mix 2 and Mix 5 about +2%; average variation of compressive strength in Mix 3 and Mix 4 about +8%). Both traditional and recycled mixes showed a significant decrease in strength when subjected to wetting and drying cycles: losses were about 15% for traditional concrete and until about 22% for concrete with recycled aggregates.
(4) SEM images highlighted a difference between the matrix of Mix 5 (for which both coarse and fine natural aggregates have been replaced by EAF slag) and the other conglomerates in which the use of air-entering admixture allowed a well-developed air bubble system and a compact matrix with regular cracks. Mix 5, with recycled materials only, seemed to develop less bubbles with small diameter, showing that the admixture could behave in a different way when EAF fine particles are used and natural sand is not present.
(5) Crystalline lattice of EAF slag showed complex mineralogical structures, which seem to improve the stability of the material. Free oxides quantity is limited, and possible further expansion phenomena seemed to be substantially prevented. Furthermore, no significant difference was observed on chemical and mineralogical structure in specimens before and after durability tests.

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