Concrete with EAF steel slag as aggregate: A comprehensive technical and environmental characterisation

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This paper concerns comprehensive experimental study to evaluate properties and environmental suitability of Electric Arc Furnace (EAF) steel slag as well as mechanical behaviour of concrete designed with 100% of EAF slag as aggregate.

Several tests were carried out on samples of fresh and aged slag, as required by standard specifications. In addition, the leaching behaviour and the volumetric stability were investigated. Concrete mixtures were designed with aged slag as aggregate having a diameter up to 31.5 mm. The concrete mechanical properties were then compared with the properties of reference mixtures having only natural aggregates. The concrete with EAF slag showed mechanical properties compatible with their use in civil constructions (compressive strength 35–45 MPa and modulus of elasticity up to 46 GPa).

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1. Introduction

Around 350 BC., Aristotle stated that “When iron is purified by fire, there forms a stone known as iron slag. It is wonderfully effective in drying out wounds and results in other benefits” [1], thus highlighting a first potential reuse of steelworks slags.

Steel slag is the waste product of the steel production process, which can be carried out by means of Basic Oxygen in a steelmaking Furnace (BOF) or by an Electric Arc Furnace (EAF) process.

Nowadays, the reuse or recovery of these slags is becoming a core content of sustainable development. In this direction, much more efforts have to be made in order to increase the recycling attitudes of the society and to reduce the waste landfill disposal [2].

Steel slag is generated during the steelmaking process in the amount of 15–20% the production of crude steel (weight/weight) [3–5]. In 2014, the production of steel in EU28 was equal to 169.2 million tons, whilst in Italy accounted for about 23.7 million tons [6]. This resulted in a steel slag production of about 29.6 and 4.1 million tons respectively. Furthermore, in 2020 the world steel production will be approximately 1781 million tons, with a huge amount of slag produced that will need to be managed [7]. Reusing steel slag as recycled material in constructions, instead, allows for a reduction of the amount of waste to dispose of and the consumption of natural aggregates. In 2012, in Italy, the quarrying activities caused the extraction of natural aggregates for about 130 million tons [8]. The overexploitation of quarries and the amount of industrial waste generated worldwide are becoming a serious environmental problem [2,9–12]. For these reasons, eco-friendly constructions are quickly establishing as a new global standard, certified by voluntary programs such as the LEED (Leadership in Energy and Environmental Design), which promotes an approach to sustainability even in terms of materials and resources used.

Despite the substitution of natural aggregates in constructions by the recovery of special wastes has been widely investigated and continues to be a focus topic for researchers [13–17], the investigation of the reuse of steel slag has been a matter of the last decade. The latter could be a substitute of natural aggregates (mostly regarding bituminous mixtures) [18–27] or a media for water treatment [28–30]. For instance, Tsakiridis et al. [21] demonstrated that the addition of steel slag by 10.5% in the raw meal did not affect either the sintering or the hydration process during Portland cement production. In an authors’ previous study [22], EAF slag demonstrated to be suitable for its recovery in bituminous mixtures (containing up to 40% of EAF slag as recycled aggregate). Steel slag did not determine any alteration in terms of release of pollutants or volumetric expansion phenomena and the mechanical characteristics of bituminous mixtures were more satisfactory than the mixtures
obtained using natural aggregates. Moreover, Jha et al. [30] highlighted that steel slag can produce sorbents, with a high capacity for removing phosphate and ammonium ions, that are extremely suitable for reducing environmental pollution caused by the presence of these common ionic contaminants of water.

Regarding the specific recovery of EAF slag in concrete mixtures, in 2003 Maslehuddin et al. [31] evaluated the mechanical properties and durability characteristics of concrete containing steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag provided better physical properties, durability characteristics and compressive strength, whilst comparable results were obtained for the flexural strength. Lun et al. [32] investigated the possibility of enhancing the volume stability of steel slag used as fine aggregate in concrete. Other authors studied the EAF slag and blast furnace slag, enhancing the volume stability of steel slag used as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone. Concrete mixtures designed with steel slag as aggregate in comparison with a traditional concrete containing crushed limestone.

Other studies investigated the release of pollutants, by leaching tests [2,9,12,33–36], and the volumetric stability [33,35,37] of steel slag, which are two considerable unsafe factors for its recovery as aggregate in the construction sector.

Aim of this study is the production of an eco-friendly concrete obtained only with industrial by-products, thus minimizing the use of natural resources. In particular, this research aimed at investigating the possibility of using 100% EAF slag as recycled aggregate in concrete, by means of a comprehensive characterisation (technical and environmental) covering both the EAF slag and the concrete mixtures containing slag. The geometrical, physical, mechanical and chemical characteristics of both fresh and aged slag were evaluated. Finally, the leaching behaviour and the volumetric stability of steel slag were carefully investigated. Concrete mixtures produced by replacing 100% of the natural aggregate with slag were designed and tested in order to study their properties.

2. Materials

2.1. Steel slag

The fusion slag of the steel production process was provided by a factory located in Brescia (northern Italy). The steel is produced by an EAF process with direct fusion of ferrous scraps, reclaimed body parts of vehicles and the addition of lime, iron alloys, coal and oxygen.

Both fresh and aged slags were sampled and subjected to a crushing treatment (only for the aged slag) and a sieving process in order to obtain a particle diameter smaller than 31.5 mm. The fresh slag was sampled immediately after the slagging, whilst the aged slag was sampled after a period of 3–4 months of ageing of the fresh slag in an unprotected open area. After these preliminary treatments, the fresh (hereinafter called “FS”) and aged slag (hereinafter called “ASZ”) were analysed.

The properties of the slag were also compared with the results of a previous characterisation of an aged slag (called “AS1”), coming from the same steel factory but with a different grain size (0–63 mm). A further comparison was made with a natural gravel of different grain size fractions (respectively: 2–14 mm diameter, named “G1”; 0–16 mm diameter, named “G2”; 11–22 mm diameter, named “G3”), and a recycled aggregate coming from construction and demolition waste with a particle size of 0–80 mm (called “C&D”).

2.2. Concrete mixtures

Concrete mixtures were designed with 100% of EAF slag as aggregate, in order to maximise the reuse of the slag and to test the concrete mechanical behaviour in the most adverse conditions (absence of natural aggregates). A typical concrete class C25/30 was adopted, whose composition is shown in Table 1.

The grain size distribution of concrete was chosen according to the Bolomey curve. The water/cement (w/c) ratio was equal to 0.43, slightly lower than the usual value of 0.5. This reduced w/c ratio was probably due to chemical reactions amongst cement, water and slag. The final concrete mix was made without plasticisers because of an unexpected segregation of the steel slag that occurred during the preliminary tests.

The mass density of slag concrete was about 3100 kg/m³, approximately 25% more the mass density of concrete with natural aggregates.

3. Tests for material characterisation

3.1. Steel slag

The properties of both fresh and aged steel slags (geometrical, physical, mechanical and chemical) were determined in accordance with EN 12620 [38] and its Italian accomplishments UNI 8520-1 [39] and UNI 8520-2 [40]. Since 2004, these standards had to be adopted for the CE mark of natural or recycled aggregates for concrete production.

The chemical composition of steel slags and their leaching behaviour were evaluated according to the Italian legislation, the Legislative Decree 2006/152 [41], which regulates the waste characterisation, reuse and recovery, and the Ministerial Decree 2006/186 [42], which specifically regulates the recovery and reuse of special waste as steel slag.

Geometrical requirements, as prescribed by EN 12620, include granulometric composition, flakiness and shape indices, fine particle quality (by means of sand equivalent and methylene blue test) and content. The most relevant property is the particle size, owing to its influence over the concrete mix-design definition.

Regarding the physical requirements, the following parameters were determined: 1) resistance to fragmentation (Los Angeles coefficient, as specified in EN 1097-2 [43]), 2) resistance to wear (micro-Deval coefficient, as specified in EN 1097-1 [44]), 3) particle density, 4) water absorption, 5) resistance to freezing (by means of freeze-thaw resistance or magnesium sulphate soundness), 6) drying shrinkage and 7) alkali-silica reactivity. Each testing method is defined in the EN 12620 and refers to specific technical standards.

According to EN 12620, water-soluble chloride and acid-soluble sulphate ion content, total sulphur content, organic contaminants content and slag expansion were investigated. The test for determining the content of organic contaminants (EN 1744-1 [45]) required the preparation of mortar samples (40 × 40 × 160 mm) with slag pre-treated and not treated at 480 °C for 4 h (respectively named “pre-treated” and “untreated” in the session 5 “Results and discussion”), and the measurement of the initial setting time and the compressive strength. The aim of this test was to verify the possible presence of organic materials that could influence the mechanical properties of concrete.

The slag expansion test allowed to evaluate the volume stability due to hydration phenomena of free CaO and MgO. According to EN

<table>
<thead>
<tr>
<th>Component</th>
<th>(kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland cement CEM II/A-LL 32.5R</td>
<td>380</td>
</tr>
<tr>
<td>Water/cement ratio</td>
<td>0.43</td>
</tr>
<tr>
<td>Steel slag</td>
<td>2580</td>
</tr>
<tr>
<td>Mass density</td>
<td>3125</td>
</tr>
</tbody>
</table>
1744-1, the testing time is 7 days. Results obtained were compared with the limit value proposed by ASTM D 2940-98 [46], due to the absence of a reference value in the European and Italian standards.

The release of pollutants was evaluated in compliance with the method provided by the Italian Ministerial Decree 2006/186 and EN 12457-2 [47]. The leaching test was carried out on grain size fraction 0–4 mm of both slag samples (FS and AS2), according to EN 12457-2. As suggested by EN 12620, the leaching test was even carried out on a 16–32 mm size fraction of FS and AS2, according to testing method provided by EN 1744-3 [48].

Table 2 highlights all the results from the characterisation of steel slags and other natural or recycled aggregates used as reference.

### 3.2. Concrete mixtures

Mechanical characterisation of concrete containing steel slag was carried out both in the fresh state and in the hardened one. Workability was measured by means of slump tests according to EN 12350-2 [49].

Uniaxial compression tests on cubic samples with a side of 150 mm were carried out according to EN 12390-3 [50] at different curing times.

The shrinkage was studied on specimens with a square base of 100 × 100 mm and a length of 500 mm, stored at 20 °C with a 50% relative humidity, according to UNI 11207 [51].

Tensile strength was measured after 28 days of curing by means of uniaxial tests on cylindrical samples, according to UNI 6135 [52]. Finally, the elastic modulus was determined on cylindrical specimens according to EN 12390-13 [53]. All concrete samples were casted in a temperature and humidity controlled room. The day after casting the specimens were stored in water at 20 °C until the time of the tests.

### 4. Results and discussion

#### 4.1. Steel slag characterisation

##### 4.1.1. Geometrical properties

Fig. 1 shows the curves of the particle size distribution of the adopted aggregates as compared to the Bolomey curve.

Results from the geometrical properties evaluation are shown in Table 3.

The values of flakiness and shape indices indicate that the percentage of flat or non-polygonal elements was lower in steel slags (1–2%) as compared to the other aggregates, contributing to ensure higher stability characteristics of concrete. The fine quality (expressed as sand equivalent and methylene blue value) showed a limited content of particles potentially reactive. The sand equivalent provided to be acceptable for all the samples tested, although the value obtained by AS2 was slightly below the minimum allowable value of 70% (UNI 8520-2), owning to the pre-crushing treatment. The recycled aggregate C&D provided a value equal to 16%, considerably below the limit set by UNI 8520-2.

#### 4.1.2. Physical properties

The results of the physical characterisation of the steel slag are summarized in Table 4.

Particle density was approximately 3.8 ton/m³, much higher than the natural aggregate values. Particle water absorption was between 0.9 and 2.4%, providing higher values than the natural aggregate but still lower than the absorption of the “C&D” samples (5.9%). Since water absorption was higher than the limit value (1%) in FS and AS2 samples, the resistance to freezing has to be determined according to the EN 12620 and declared in the CE mark. The values of resistance to freezing of 22 and 23%, for FS and AS2 respectively, were in accordance with the standard requirement (lower than 25%), therefore water absorption does not represent a constraint for slag recovery. Los Angeles test (resistance to fragmentation) showed values of about 18–23%, whilst micro-Deval test (resistance to wear) resulted in the range 7–8%, showing that steel slag had a fair resistance to fragmentation and wear and could be used as recycled aggregate even for concrete classes higher than C50/60. Similar results were obtained even in other experimental works reported in literature [10,20,22,54]. Regarding the alkali-

<table>
<thead>
<tr>
<th>Test requirements</th>
<th>Slag samples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UNI EN 12620:</strong> Grain size distribution (EN 933-1); Flakiness index (EN 933-3); Shape index (EN 933-4); Fine content (EN 933-1); Sand equivalent (EN 933-8); Methylene blue value (EN 933-9); Particle density (EN 1097-6); Particle water absorption (EN 1097-6); Resistance to fragmentation (EN 1097-2); Resistance to wear (EN 1097-1); Acid-soluble sulphate (EN 1744-1); Total sulphur (EN 1744-1).</td>
<td>✓</td>
</tr>
<tr>
<td><strong>UNI EN 12620:</strong> Magnesium sulphate soundness (EN 1367-2); Alkali-silica reactivity (UNI 8520-22); Drying shrinkage (EN 1367-4); Water-soluble chloride (EN 1744-1); Acid-soluble chloride (EN 1744-5); Water-soluble sulphate (EN 1744-1); Carbonate content (EN 1744-1); Water solubility (EN 1744-1); Free lime (EN 1744-1); Dicalcium silicate disintegration (EN 1744-1); Dicalcium silicate disintegration (EN 1744-1); Iron disintegration (EN 1744-1); Volumetric expansion (EN 1744-1); Fulvo acid content (EN 1744-1); Lightweight contaminants (EN 1744-1); Content of organic contaminants (EN 1744-1).</td>
<td>✓</td>
</tr>
<tr>
<td><strong>UNI EN 12620:</strong> Freeze-thaw resistance (EN 1267-1).</td>
<td>X</td>
</tr>
</tbody>
</table>

✓: property investigated; X: property not investigated.
significantly below the reference value (0.075% of shrinkage).

4.1.3. Chemical properties

Significant concentrations of Fe, Ca, Si, Al, Mg and Mn were detected in the slag (Table 5).

Moreover, referring to potential environmental impact, high concentrations of total chromium, vanadium and barium were observed; all the other elements investigated had negligible concentrations or were absent (i.e. asbestos).

Table 6 summarises the other results obtained from the chemical characterisation.

Water-soluble chloride ion content was negligible in all the samples tested (<0.01%), thus preventing phenomena of corrosion if slag is employed in reinforced concrete. Acid-soluble sulphate and chloride, water-soluble sulphate, total sulphur, water solubility and free lime provided values under the detection limit. Carbonate content ranged between 0.1% (FS) and 4.3% (AS2); the higher value refers to the aged slag and is probably due to the ageing in an unprotected open area for several months that increased the content of carbonate. However, values are lower than carbonate content usually characterising natural aggregates (some of 10–40%), thus reducing the probability of corrosion in reinforced concrete. The presence of organic components was not detected in EAF slags (humus and fulvo acid content tests were performed), whilst a concentration of lightweight organic contaminants, equal to the limit (0.1%) set by UNI 8520-2, was detected from the FS sample.

Results of mechanical tests on mortar samples with EAF slag are presented in Fig. 2.

After 28 days of curing, the initial setting time and the flexural/compressive strength were measured. Initial setting time and flexural strength did not exhibit any relevant difference amongst the samples (untreated and pre-treated fresh and aged slag, according to the procedure described in Section 3.1), whilst the compressive strength was significantly different between FS and AS2. Both mortar specimens made with the aged slag (untreated and pre-treated) provided an average compressive strength of 60 MPa. Mortar samples made with the fresh slag provided an increase of about 20 MPa of compressive resistance from the specimen made with the untreated slag (38 MPa) to the one made with the pre-treated slag (55 MPa). Such a high variation (20 MPa) in the compressive strength between treated and untreated fresh slag was not expected. According to the test method and purpose [45], this difference should be justified by the presence of organic contaminants in the untreated fresh slag that altered the mechanical properties of the mortar (compared to the sample made with treated slag). However, this appears uncommon due to the heating at 1200°C that characterises the steelmaking process. Further analyses will investigate in more details this aspect.

By comparing the results of this test with a research reported in literature [36], it can be highlighted that, when employing an aged slag, the cement mortars provide higher values of compressive strength; in fact, this type of slag contributes mainly to the hardened properties of mortars. In the present study, a compressive strength of about 60 MPa was obtained with a cement to steel slag ratio of 20:80, whilst other authors [36] obtained an average value of 32 and 42 MPa of mortars with a ratio (cement to steel slag) equal to 50:50 and 70:30, respectively. The higher values provided by the present research could be justified by the lower w/c ratio (0.43) used for the cement mortars.

Table 3
Geometrical properties of steel slag, natural and recycled aggregates.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>FS</th>
<th>AS1</th>
<th>AS2</th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>C&amp;D</th>
<th>Limits of UNI 8520-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flakiness index (EN 933-3)</td>
<td>%</td>
<td>2.0</td>
<td>1.0</td>
<td>2.0</td>
<td>14.4</td>
<td>14.0</td>
<td>14.0</td>
<td>6.0</td>
<td>–</td>
</tr>
<tr>
<td>Shape index (EN 933-4)</td>
<td>%</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>11.0</td>
<td>13.0</td>
<td>12.3</td>
<td>21.0</td>
<td>–</td>
</tr>
<tr>
<td>Fine content (EN 933-1)</td>
<td>%</td>
<td>0.7</td>
<td>0.5</td>
<td>2.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&lt;3.0</td>
</tr>
<tr>
<td>Sand equivalent (EN 933-8)</td>
<td>%</td>
<td>92</td>
<td>89</td>
<td>66</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>16</td>
<td>&gt;70</td>
</tr>
<tr>
<td>Methylene blue value (EN 933-9)</td>
<td>g/kg</td>
<td>0.1</td>
<td>0.1</td>
<td>0.5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.4</td>
<td>&lt;1.2</td>
</tr>
</tbody>
</table>

Table 4
Physical properties of steel slag, natural and recycled aggregates.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>FS</th>
<th>AS1</th>
<th>AS2</th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>C&amp;D</th>
<th>Limits of UNI 8520-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle density (EN 1097-6)</td>
<td>kg/m³</td>
<td>3750</td>
<td>3810</td>
<td>3810</td>
<td>2700</td>
<td>2710</td>
<td>2720</td>
<td>2570</td>
<td>&gt;2300</td>
</tr>
<tr>
<td>Particle water absorption (EN 1097-6)</td>
<td>%</td>
<td>1.3</td>
<td>0.9</td>
<td>2.4</td>
<td>0.8</td>
<td>0.8</td>
<td>5.9</td>
<td>1.0</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Magnesium sulphate soundness (EN 1367-2)</td>
<td>%</td>
<td>22.0</td>
<td>–</td>
<td>23.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&lt;25.0</td>
</tr>
<tr>
<td>Resistance to fragmentation (EN 1097-2)</td>
<td>%</td>
<td>22.0</td>
<td>23.0</td>
<td>18.0</td>
<td>22.4</td>
<td>27.0</td>
<td>21.6</td>
<td>32.0</td>
<td>&lt;30.0</td>
</tr>
<tr>
<td>Resistance to wear (EN 1097-1)</td>
<td>%</td>
<td>7.0</td>
<td>8.0</td>
<td>8.0</td>
<td>10.5</td>
<td>10.0</td>
<td>9.5</td>
<td>38.0</td>
<td>–</td>
</tr>
<tr>
<td>Alkali-silica reactivity (UNI 8520-22)</td>
<td>%</td>
<td>0.05</td>
<td>–</td>
<td>0.03</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>Drying shrinkage (EN 1367-4)</td>
<td>%</td>
<td>0.023</td>
<td>–</td>
<td>0.030</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&lt;0.075</td>
</tr>
</tbody>
</table>

Note: in both samples tested, the following elements had concentrations lower than the detection limit: NO₃, F, Cl⁻, CN⁻, Be, Co, Ni, As, Cd, Se, Hg, Ti, Sn, Ag, Sb, Te, Li, Asbestos.
According to EN 12620, the volume stability of steel slag was analysed. Dicalcium silicate disintegration and iron disintegration tests (Table 6) did not show significant phenomena of cracking or crushing. Since it is essential to avoid expansion phenomena for a possible use of these aggregates in concrete, the volumetric expansion test was also carried out; Fig. 3 shows the results obtained from FS and AS2 samples. The volumetric expansion limit (0.5%) proposed by ASTM D 2940-98 was taken into account.

The aged slag provided a negligible expansion (with an average value of 0.02%), whilst the fresh slag had an average expansion of 0.25% with a peak of 0.4% in Test 2. These values are significantly lower when compared to the results obtained by Chunlin et al. [4], who carried out the same investigation by means of the testing methodology provided by ASTM D 2940-98. Indeed, this research [4] showed that the volumetric expansion of the coarse EAF slag (5–25 mm) reached a value of 3.9%, whilst the fine EAF slag (0–5 mm) provided an expansion up to 4.8%. These higher values, however, can be justified by the different quality of the material (e.g. ferrous scrap) fed into the furnace, which can give different characteristics to the final slag.

In order to guarantee the hydration phenomena depletion, a minimum ageing of 120 days is finally recommended, as even suggested by other researchers [20,22,54].

### 4.1.4. Leaching behaviour

The leaching test performed on different grain size fractions of EAF samples showed values below the limits set by the Ministerial Decree 2006/186 (Table 7).

The only exception was total chromium in sample AS2 (0–4 mm fraction) that provided a concentration of 73 µg/L, higher than the limit of 50 µg/L. On the contrary, other authors found concentrations below the detection limit [10] and close to the Italian reference limit [1]. Since the slag is used in concrete mixture, the compliance of the leaching test limits for the raw slag is not mandatory for the Italian legislation [42]. Regarding other parameters, barium and fluorides provided a concentration close to but lower than the reference limit. Vanadium was released with high concentrations (in the range 72–168 µg/L) even if lower than the limit value; similar values, lower than the limit of 250 µg/L but still consistent (103 µg/L), were observed by Pellegrino et al. [12]. As expected, results indicated that the release of pollutants was higher in the finest grain size fraction, due to the higher specific surface. Figs. 4–6 propose, for the most critical parameters (total chromium, vanadium and barium respectively), a comparison amongst the total content of pollutant in the slag and the release concentrations (from the two grain size fractions tested). All these results suggest an accurate selection of the materials fed into the steel-making process, in order to avoid a high variability on the slag composition and component concentrations beyond the accepted limits for leaching test.

### 4.2. Properties of concrete mixtures designed with steel slag

Tests on fresh and hardened concrete with “AS2” steel slag were carried out in order to characterize the mechanical behaviour. Workability of fresh concrete was measured according to the slump test [49] and resulted in class S2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>FS</th>
<th>AS1</th>
<th>AS2</th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>C&amp;D</th>
<th>Limits of UNI 8520-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-soluble chloride</td>
<td>%</td>
<td>&lt;0.01</td>
<td>---</td>
<td>---</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>---</td>
<td>&lt;0.03</td>
</tr>
<tr>
<td>Acid-soluble chloride</td>
<td>%</td>
<td>0.04</td>
<td>0.04</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
<td>---</td>
<td></td>
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<tr>
<td>Water-soluble sulphate</td>
<td>%</td>
<td>&lt;0.01</td>
<td>---</td>
<td>---</td>
<td>&lt;0.01</td>
<td>---</td>
<td></td>
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</tr>
<tr>
<td>Acid-soluble sulphate</td>
<td>%</td>
<td>&lt;0.20</td>
<td>0.18</td>
<td>&lt;0.20</td>
<td>&lt;0.20</td>
<td>&lt;0.20</td>
<td>&lt;0.20</td>
<td>0.50</td>
<td>&lt;0.20</td>
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<tr>
<td>Total sulphur</td>
<td>%</td>
<td>&lt;0.20</td>
<td>0.06</td>
<td>&lt;0.20</td>
<td>&lt;0.50</td>
<td>&lt;0.50</td>
<td>&lt;0.50</td>
<td>&lt;0.50</td>
<td>&lt;1.00</td>
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<tr>
<td>Carbonate content</td>
<td>%</td>
<td>0.1</td>
<td>---</td>
<td>4.3</td>
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<td></td>
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<tr>
<td>Water solubility</td>
<td>%</td>
<td>&lt;0.2</td>
<td>---</td>
<td>&lt;0.2</td>
<td></td>
<td></td>
<td></td>
<td>---</td>
<td></td>
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<tr>
<td>Free lime</td>
<td>%</td>
<td>&lt;0.1</td>
<td>---</td>
<td>&lt;0.1</td>
<td></td>
<td></td>
<td></td>
<td>---</td>
<td></td>
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<tr>
<td>Dicalcium silicate</td>
<td></td>
<td></td>
<td>---</td>
<td></td>
<td>No crack</td>
<td>No crack</td>
<td>No crack</td>
<td>No crack</td>
<td></td>
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<tr>
<td>disintegration</td>
<td></td>
<td></td>
<td>---</td>
<td></td>
<td>Colourless</td>
<td>Colourless</td>
<td>Colourless</td>
<td>Colourless</td>
<td></td>
</tr>
<tr>
<td>Iron disintegration</td>
<td></td>
<td></td>
<td>---</td>
<td></td>
<td>No crack</td>
<td>No crack</td>
<td>No crack</td>
<td>No crack</td>
<td></td>
</tr>
<tr>
<td>Presence of humus</td>
<td></td>
<td></td>
<td>---</td>
<td></td>
<td>Colourless</td>
<td>Colourless</td>
<td>Colourless</td>
<td>Colourless</td>
<td></td>
</tr>
<tr>
<td>Fulv acid content</td>
<td></td>
<td></td>
<td>---</td>
<td></td>
<td>Colourless</td>
<td>Colourless</td>
<td>Colourless</td>
<td>Colourless</td>
<td></td>
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<tr>
<td>Lightweight contaminants</td>
<td>%</td>
<td>0.1</td>
<td>---</td>
<td>&lt;0.1</td>
<td></td>
<td></td>
<td></td>
<td>---</td>
<td>&lt;0.1</td>
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</table>

![Fig. 2](image-url) Initial setting time, compressive and flexural strength of mortar samples made with EAF slag. a) mortars made with untreated slag; b) mortars made with pre-treated slag.

![Fig. 3](image-url) Volumetric expansion of steel slag samples.
The reduced workability is due to the coarser aggregate distribution, compared to the grain size distribution of a reference concrete made with natural aggregates. With the same w/c ratio and ordinary aggregate, the slump test would lead to a workable fresh concrete resulting in class S3 or S4.

Compression strength was measured on three cubic specimens (150 mm side), tested after 3, 7, 14, 28, 60, 120, 240 days of curing in order to investigate the early age and long-term strength. In particular, considering the 100% replacement of natural aggregates, it was necessary to control the evolution of the interaction cement/slags. Fig. 7 evidences that concrete reached its maximum strength capacity after 120 days of curing since tests performed later showed a negligible increase in resistance. After one year of curing, however, no strength decrease was detected.

The average tensile strength, as measured from uniaxial tensile strength, measured on three specimens with a diameter of 80 mm and a length of 240 mm, was 3.2 MPa; this result is in agreement with the behaviour of traditional concrete and underlines as steel slag did not affect the concrete tensile strength.

Drying shrinkage tests performed on two different prismatic samples confirmed the material reliability. Analysing the data obtained by means of a displacement transducer after 240 days of curing, the strain of both samples demonstrated to reach an asymptotic value of about 700 \(\mu\)m. Fig. 8 shows the comparison between experimental data and the reference curve proposed by Table 7.

Table 7

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Slag sample</th>
<th>Limits of M. D. 2006/186</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>FS 0−4</td>
<td>FS 16−32</td>
</tr>
<tr>
<td><strong>Fluorides</strong></td>
<td>mg/L</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Sulphates</strong></td>
<td>mg/L</td>
<td>1.7</td>
<td>7.4</td>
</tr>
<tr>
<td><strong>Barium</strong></td>
<td>mg/L</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Selenium</strong></td>
<td>µg/L</td>
<td>&lt;1</td>
<td>&lt;1</td>
</tr>
<tr>
<td><strong>Mercury</strong></td>
<td>µg/L</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td><strong>Vanadium</strong></td>
<td>µg/L</td>
<td>168</td>
<td>98</td>
</tr>
<tr>
<td><strong>Total chromium</strong></td>
<td>µg/L</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td><strong>DOC</strong></td>
<td>mg/L</td>
<td>10.5</td>
<td>10.1</td>
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</table>

Note: in all the samples tested, the following pollutants had concentration lower than the detection limit: NO\(_3\) -, Cl\(^-\), CN\(^-\), Cu, Zn, Be, Co, Ni, As, Cd, Pb.
The comprehensive characterisation (technical and environmental) of EAF steel slag and concrete produced with 100% slag as aggregate demonstrated the suitability of recycled concrete for a sustainable use as construction material. In particular, the recycled concrete seems mostly suitable also for applications as foundations and industrial pavements.

Acknowledgements

This study was conducted under the research agreement “Recovery of steel slags in concrete” between the University of Brescia and the company “Paterlini Costruzioni S.p.A.” (Brescia, Italy). Authors wish to thank all the “Paterlini Costruzioni” staff, and, in particular, Eng. Diego Gobbin and Eng. Paolo Braga for the collaboration in the research project. Luca Rondi did data collection and analysis on slag characterisation, and was responsible for the paper drafting; Guido Bregoli and Luca Cominoli were responsible for the experimental activities; Sabrina Sorlini planned and supervised the research activities and the paper drafting; Carlo Collivignarelli and Giovanni Plizzari were principal investigators for the agreement between University of Brescia and “Paterlini Costruzioni S.p.A.”.

References


Eurocode 2 [55]; a good fitting between experimental data and code provisions can be observed. The experimental shrinkage behaviour of slag concrete is comparable to that of a traditional concrete, confirming that the shrinkage phenomenon was substantially connected to the cementitious matrix behaviour and minimally to the aggregates behaviour.

Finally, the last test concerned the identification of the elastic modulus of concrete with aged steel slags determined according to EN 12390-13 [53]. Experimental results show that mean value (from three specimens) of elastic modulus was about 46 GPa; this value is considerably higher than the elastic modulus provided by Eurocode 2. This increase in the elastic modulus is due to the higher compression strength of the steel slag as compared to traditional natural aggregates.

5. Concluding remarks

According to the results presented in this research, the following concluding remarks can be drawn.

- The physical properties of EAF slag showed suitable results for both fresh and aged conditions. The fragmentation (18–23%) and wear (7–8%) resistance were comparable to the natural aggregates (21–27% for fragmentation and 9–10% for wear resistance).
- Chemical properties were acceptable according to UNI 8520-2. Moreover, water-soluble chloride ion content was negligible in both fresh and aged slags (<0.01%), thus reducing the risk of corrosion when used in reinforced concrete.
- Long term compressive tests confirmed the reliability of the concrete mixtures containing EAF slag. After a period of one year, the compressive strength showed a stable behaviour as it is expected from traditional concrete.
- Slag particle density (3700–3800 kg/m³) and water absorption (1.0–2.5%) were higher in comparison with natural aggregates (2700 kg/m³ and 0.8% respectively), and should be carefully considered during the mix design of concrete.
- The volumetric expansion of fresh slag resulted slightly lower than the 0.5% limit value. Therefore, in order to avoid cracking phenomena in concrete mixtures, a minimum ageing period of 3–4 months of the EAF slag is recommended.
- The release of pollutants measured from leaching tests on slag resulted acceptable, although presenting some variability regarding vanadium (in the range of 72–168 µg/L) and total chromium (in the range of 8–73 µg/L). A careful selection of the scraps fed into the EAF should be provided, in order to reduce the variability of such pollutants in the slag.


[38] EN 12457-2. Leaching: compliance test for leaching of granular waste mate-


[47] EN 12457-2. Leaching: compliance test for leaching of granular waste mate-


