

## Article

# Sustainable Recycling of Electric Arc Furnace Steel Slag as Aggregate in Concrete: Effects on the Environmental and Technical Performance

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**Abstract:** The aim of this research work was the evaluation of the feasibility to utilize industrial by-products, such as electric arc furnace steel slags, for sustainable concrete production. The paper evaluated the environmental and mechanical properties of steel slags and concrete, respectively. Specifically, the release of contaminants from steel slags was investigated by leaching test and the properties of fresh and hardened concrete were evaluated for a concrete mixture designed with a partial substitution (30%) of natural coarse aggregates with electric arc furnace steel slags. The results show that the concentrations of pollutants were lower than the legal limits imposed by the Ministerial Decree 186/2006 and the addition of steel slag can enhance the mechanical performance of concrete. The compressive strength of cubic specimens was also measured after different cycles of alternate wetting–drying. The steel slag incorporation results in a stiffness comparable to that of a traditional concrete. Overall, the mechanical and leaching characterization has shown that the reuse of electric arc furnace steel slags for sustainable concrete production is feasible and reliable.

**Keywords:** recycling; EAF steel slag; leaching behavior; concrete; mechanical properties



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## 1. Introduction

Sustainability can build value in construction and design of green buildings. A sustainable approach to construction brings environmental, social, and economic benefits to a construction project. From this perspective, several resources from industries and construction waste are used to manufacture sustainable green concretes. Steel slags, fly ash, granulated blast furnace slag, silica fumes, recycled aggregates from construction and demolition waste, and many other are nonbiodegradable materials used in concrete by replacing one of its components. Incorporating recycled materials in concrete prevents large land areas from being landfilled, reduces the extraction of virgin raw materials and the environmental pollution, and contributes to achieving a circular economy [1].

The steelmaking process contributes to a considerable production of industrial by-products, including steel slags. The reuse of these residues allows manufacturers to reduce the consumption of natural resources and minimize the production of wastes. According to the Directive (EU) 2018/851 (amending Directive 2008/98/EC) for the use of recycled materials in construction, the main purpose of this study was to favor the reuse of steel industry residues rather than landfill disposal. The use of slag in construction dates back to the Romans, who used crushed slags from the crude iron production to build their roads. Nowadays, slags are still used to build roads due to their excellent mechanical strength performance [2], but their use is not limited to roads anymore and slag aggregates are widely used in all kinds of civil works [3,4].

The steel is made in integrated steel plants using a basic oxygen furnace (BOF) or an electric arc furnace (EAF) process. The technology of the electric furnace has established itself due to the lower complexity of the production cycle, the increased availability of steel scrap, and the lower CO<sub>2</sub> emissions [5]. Steel slag is produced during the separation of molten steel from impurities in steel furnaces. The slag appears as a heterogeneous solution of silicon dioxide and calcium-iron oxides that solidify during cooling. These characteristics make it suitable for the substitution of aggregates in the construction sector, such as aggregate in road base or sub-base layers, asphalt mixtures, concrete production, or for soft clay stabilization. In 2018, the total production of crude steel in Europe was 167.1 million tons, of which 69.5 million tons derived from EAF process (41.5%) [6]. In the same period, the Italian crude steel production was 24.5 million tons, of which 20.0 million tons (81.6%) derived from EAF processes [7]. Liu Chunlin et al. [8], Subathra Devi et al. [9], and Rondi et al. [10] stated that steel slags, as the main by-products in the crude steel production process, represent 15–20% of the entire crude steel production (weight/weight). This resulted in an average EAF steel slag production of about 13.9 and 3.5 million tons in Europe and Italy in 2018, respectively.

In order to avoid landfilling and to reduce the depletion of natural resources due to the fast pace of construction activities, a correct management of EAF steel slags is required by evaluating the possible release of contaminants into the surrounding environment and the technical feasibility for their use in the construction sector [11]. Several studies have been performed on the properties and the use of EAF steel slags in concrete [12,13]. Many authors found that the release of pollutants from EAF slags is generally below the regulatory limits [14,15]. On the contrary, authors such as Mombelli et al. [16] and Rondi et al. [10] detected high concentrations of Ba, Cr, and V in EAF steel slags when subjected to leaching tests. Other authors, such as Ledesma et al. [17], evaluated the potential reuse of EAF dust in mortar. The results highlighted that Se, Mo, Cd, Pb, and Cl anion were the most conflictive elements; this phenomenon was particularly evident in the finest grain size fraction due to the higher specific surface [18,19]. Some studies have also been developed on the potential ecotoxicity and genotoxicity of steel slags [20]. The authors, by an integrated chemical–biological approach applied to plant, animal organisms, bacteria, and human cells, demonstrated the low toxicity of steel slags, ensuring the feasibility of their potential use as recycled material.

The possibility of using EAF positively in concrete has also been demonstrated by many authors [8,9,11,18,21–29]. For instance, Manso et al. [18] demonstrated that the definition of the optimal grading curve is a key parameter to improve the workability and the mechanical properties of the concrete produced. In particular, the authors suggested that the use of steel slags with a size of 0–20 mm and the addition of a suitable proportion of natural aggregates to adjust the grading curve may improve the concrete workability. This was also observed by other investigations [11]. On the other hand, the inclusion of EAF steel slags in concrete mixtures can sometimes lead to a decrease in workability due to the greater water absorption of the slag. In particular, EAF steel slags evidence higher water absorption (2–5%) when compared to the corresponding values of natural coarse aggregates [9,22,26,29]. This is due to their rough and porous surface, as demonstrated by Abu-Eishah et al. [11]. In this context, Subathra et al. [9] investigated the use of fine and coarse steel slag as aggregate in concrete. For a constant water/cement ratio ( $w/c$ ), the results showed a high water absorption by steel slag and a drastic reduction in the workability of the concrete mixtures. In particular, the replacement of 30% of coarse natural aggregates with steel slags (5% of water absorption) decreased the concrete workability by about 20%. This can be easily overcome by adding proper amount of superplasticizer in the mixture [26]. The studies also revealed improvement in mechanical properties of the hardened concrete [29]. In particular, the authors [23,26] observed that the compressive strength increased up to 45 MPa (50% more than a conventional concrete with the same characteristics) when the concrete mixture was realized, with 40% of steel slag replacement and 0.55 water/cement ratio. Other studies [10,24,27] generally showed good results

regarding tensile strength, hygrometric shrinkage, and elastic modulus of the conglomerate made with EAF steel slags. In particular, Santamaria et al. [21] highlighted that the addition of fly ash in concrete mixture can slightly increase the shrinkage values, a phenomenon that can be mitigated by the presence of steel slag (due to its volume expansion). Moreover, the drying shrinkage of steel slag concrete after the same curing time (90 days) presented values very close to reference concrete, indicating that steel slag has a small influence on the concrete shrinkage, as demonstrated by Qiang et al. [28]. The main problem concerns the durability of the EAF steel slag concrete [18,27]. Abu et al. [11] pointed out that water is one of the most frequent causes of concrete deterioration. In fact, when subjected to different wetting–drying cycles, an evident degradation of the samples was detected, as reported by Santamaria et al. [21]. The resulting compressive strength, following the aforementioned wetting–drying cycles, showed an evident loss of strength ranging from 2% to 40% of the initial compression strength. The authors also highlighted that, in terms of durability, a suitable fines content (amounting to 15–16% by aggregate volume) seems to be a key variable in this durability tests.

According to the studies available in the literature, the present study aimed to clarify and support the data obtained over the years. In particular, in order to evaluate the environmental performance of steel slag as a secondary raw material, the batch leaching test (UNI EN 12457-2) was applied, as well as the evaluation of the potential toxic and mutagenic effect on the ecosystem.

The aggregates, which represent about 70% of the volume of materials used for concrete production [9], usually derive from natural resources (gravel, sand, stone, etc.); they provide a rigid skeleton structure and reduce the space occupied by the cement paste in the conglomerate. Therefore, the aim of the study was to investigate the mechanical and durability properties of concrete mixtures, in which 30% of natural aggregates were replaced with EAF steel slags (weight/weight). The mixtures were then characterized both in the fresh (i.e., slump test) and hardened state (i.e., compression strength, indirect tensile strength, hygrometric shrinkage, elastic modulus).

## 2. Materials and Methods

### 2.1. Materials

#### 2.1.1. EAF Steel Slag

EAF is used for the steel production from metallic scraps. Scrap-based steel accounts for about 25% of the global steel production [6]. The scrap is melted by an electric arc constituted by three graphite electrodes that, through a violent thermal action, bring the scrap from the solid state to the liquid one. As the slags are lighter than the liquid metal, they float and can be easily removed. The EAF slag derive, therefore, from the rapid cooling of the oxidized and superficial liquid from about 1600 °C to room temperature, followed by a double crushing and sieving phase.

The slag from carbon steel production (EAF-C) used for the present research work was supplied by a steel plant located in Lombardy (Province of Brescia) and catalogued with EWC code 10 02 02 (i.e., solid waste of the untreated steel industry stored in open piles on a waterproofed surface) (Figure 1). Different sizes of slag were used depending on the type of mixture designed. Three different grain size fractions were adopted, respectively: 5–10 mm, 10–16 mm, and 16–20 mm. For the leaching test, the slag samples were further crushed and sieved up to a diameter <4 mm.



**Figure 1.** Electric arc furnace (EAF) steel slag used.

### 2.1.2. Concrete Mixtures Made with EAF Steel Slag

Conventional concrete is composed of aggregates (constituting 60–80% of the total volume), cement, water, air, and other chemical additives. The concrete mixtures herein considered were designed with 30% by weight of EAF steel slag as coarse aggregate ( $d \geq 5$  mm) in order to evaluate the concrete performance behavior with a partial substitution of natural aggregates. In particular, the steel slag had a maximum diameter of 20 mm.

The grain size distribution was chosen in order to better reproduce the distribution curve of Bolomey, which represents a compromise between minimization of voids and improvement of workability. The water/cement ratio ( $w/c$ ) was 0.48. Furthermore, an additive superplasticizer was used in the concrete mixture in order to guarantee the target workability by considering that part of the mixing water was absorbed by EAF steel slag. The concrete density was about  $2470 \text{ kg/m}^3$ , comparable to that of a traditional concrete. The mix composition is shown in Table 1.

**Table 1.** Composition of concrete with EAF steel slag.

Component	( $\text{kg/m}^3$ )	( $\text{L/m}^3$ )
Portland cement CEM II/A-LL 42.5R	400	127
Water	190	190
Aggregates	1879	659
Fluidifying additive	4.0	3.7
Mass density	2470 [ $\text{kg/m}^3$ ]	
Water/cement ratio ( $w/c$ )	0.48	
Steel slag replacement	30%	

## 2.2. Experimental Methods

### 2.2.1. EAF Steel Slag

In the environmental context, leaching tests simulate the process of transferring chemical constituents from a solid particle to an aqueous solution (demineralized water) in contact with the particle. The release of contaminants from the steel slag was evaluated according to the batch leaching test (UNI EN 12457-2) [30] and compared with natural aggregates. The eluate obtained was chemically characterized, detecting the parameters required by the Ministerial Decree 186/2006 (M.D. 186/2006) [31] for the recovery and reuse of special waste, in this case, steel slag.

Six liters of eluate were produced in 7 polyethylene bottles (PE) with a liquid/solid ratio of 10 L/kg and demineralized water at  $\text{pH} = 6.2$  and conductivity  $3.8 \mu\text{S}$ . The bottles have been placed in the Rotax, a device that keeps them rotating at a speed of 10 revolutions/minute for 24 h, according to the test procedure. The eluate obtained was filtered at  $0.45 \mu\text{m}$  using a vacuum filtration device and characterized from a chemical point of view, detecting the parameters required by the M.D 186/2006.

An ionic chromatography system (Dionex, model ICS 1000) was used to detect the concentrations of nitrates, fluorides, sulphates, and chlorides. The metal concentrations were instead measured using an optical plasma ICP spectrometer (PerkinElmer, Optima 2000 DV model). Finally, the analysis of cyanides was carried out using a colorimetric method (Nanocolor 400 D).

### 2.2.2. Concrete Mixtures Made with EAF Steel Slag

The experimental research deals with the mechanical characterization of fresh and hardened concrete. The experimental tests were carried out at the Materials Testing Laboratory of the University of Brescia. The fresh concrete was cast into the mold after mixing and was compacted by immersion vibrator up to the maximum level. After that, the samples were stored in a fog room at a temperature of 20 °C and 95% relative humidity. Workability was measured by slump test according to EN 12350-2 [32].

The uniaxial compression strength was evaluated on 18 cubic samples with a side of 150 mm at different curing times, according to the EN 12390-3 [33]. The tests were carried out with the Controls Autocomp machine (3000 kN). Four of the 18 cubic specimens were subjected to drying cycles in an oven at 110 °C for 8 h and hydration in water at room temperature for the remaining 16 h. Indirect tensile strength was studied on 3 cylindrical samples with diameter of 100 mm after 28 curing days, according to EN 12390-6 [34].

Accelerated ageing tests and hygrometric shrinkage tests were performed on 2 prismatic beams with a square base of 80 × 80 mm and a length of 285 mm, then stored in a moist room at 20 °C with 50% relative humidity, according to American ASTM C157/C 157M-08 standards [35]. The monitoring of the hygrometric shrinkage was performed day by day up to 50 days of samples curing.

Finally, the elastic modulus was measured on 3 cylindrical specimens, according to EN 12390-13 [36]. The machine used for the test was the Metrocom press model MI10-100 kN, equipped with manual load control. Table 2 summarizes the tests developed on concrete samples.

**Table 2.** Tests performed on fresh and hardened concrete samples.

Test	Number and Size of Samples
Workability	Cone of Abrams
Uniaxial compression	18 cubic samples (150 × 150 × 150 mm)
Indirect tensile strength	3 cylindrical samples (Ø100 mm; h = 200 mm)
Hygrometric shrinkage	2 prismatic beams (80 × 80 × 285 mm)
Elastic modulus	3 cylindrical samples (Ø100 mm; h = 200 mm)

## 3. Results and Discussion

### 3.1. EAF Steel Slag Characterisation

#### Leaching Behavior

The environmental behavior according to the leaching tests performed on the EAF steel slags showed release levels of pollutant elements below the limits imposed by the M.D. 186/2006, as shown in Table 3. Although the decree only concerns nonhazardous waste, and therefore does not affect quarry aggregates, it is necessary to include data from a natural material in order to establish the comparison between leaching levels recorded in the material in study (EAF steel slag) and the natural one (natural aggregate), since the type of unbound use could be the same for both tested aggregates.

**Table 3.** Leachate concentrations from EAF steel slag and natural aggregate.

Parameter	Unit	EAF Steel Slag	Natural Aggregate	Limits of M.D. 186/2006
pH	-	10.4	8.4	5.5–12
Nitrates	mg/L	<1	1.1	50
Fluorides	mg/L	0.15	<0.1	1.5
Sulphates	mg/L	5.7	0.86	250
Chloride	mg/L	1.6	1.6	100
Cyanide	µg/L	<5	<10	50
Barium	mg/L	0.29	0.021	1
Copper	mg/L	<0.01	<0.01	0.05
Zinc	mg/L	<0.01	<0.01	3
Berillium	µg/L	<0.01	<10	10
Cobalt	µg/L	<10	<10	250
Nickel	µg/L	<5	<10	10
Vanadium	µg/L	220	23	250
Arsenic	µg/L	<10	18	50
Cadmium	µg/L	<1	<4	5
Total chromium	µg/L	5	<10	50
Lead	µg/L	12	<10	50
Selenium	µg/L	<5	<10	10
Mercury	µg/L	<1	<1	1
Asbestos	mg/L	n.d. <sup>(1)</sup>	n.d. <sup>(1)</sup>	30
COD	mg/L	<15	<15	30

<sup>(1)</sup> n.d.: not detected.

Overall, compared to natural aggregate, the steel slag eluate had higher concentrations of constituents, except for nitrates and arsenic. For both materials the pH was alkaline, with a lower value in the eluate from natural aggregate.

According to leaching data obtained from eluates from granular samples of EAF steel slag and the natural sample used as control, concentrations of pollutants were lower than the legal limits indicated by the M.D. 186/2006. The measured levels (expressed in mg/L and µg/L) were close to the limit only for vanadium and barium (data consistent with previous works about leaching behavior on EAF steel slag [10]). Results prove that the tested material complies with current legislation and can be used for concrete manufacturing as a partial substitution of natural coarse aggregates contributing to a sustainable concrete production.

### 3.2. EAF Slag Concrete Characterisation

In order to evaluate the mechanical behavior of concrete mixtures made with EAF steel slag, several tests on fresh and hardened concrete were developed.

#### 3.2.1. Workability

At the end of the mixing process, the fresh concrete must have a homogeneous mass that is able to guarantee workability as well as mechanical resistance in its hardened state.

Fresh concrete had a slump of 140 mm, which identified it as a S3 consistency class (defined as “semi-fluid”) according to EN 206 [37]. It was found that the use of steel slag with a maximum diameter higher than 20 mm caused an undesired impact on workability. In particular, during the production of preliminary concrete mixtures, the use of steel slag with a maximum diameter of 31.5 mm caused a slag segregation in the concrete mixture. For this reason, the maximum particle size was reduced to 20 mm.

However, concrete with steel slag is suitable for usual reinforced concrete structures and requires an accurate vibration time.

#### 3.2.2. Compression Strength

Compression strength was measured on eighteen cubic specimens with a side of 150 mm (Figure 2). The samples were tested after 3, 7, 14, 21, 28, 70, and 90 days of curing in order to evaluate the compression strength variation over time. After 28 days a significant fraction of the final resistance was obtained.



**Figure 2.** Compression strength test on cubic samples.

All the failure modes of the cubic samples under uniaxial compression were satisfactory. The average compression strength values of both the 16 cubic samples and the four samples subjected to wetting and drying cycles (the strength for these samples was determined only at 28 and 90 curing days) are shown in Table 4. It is worth observing that compression strength continuously increases in the EAF slag concrete samples. This behavior is attributable to the strong bond between the cement paste and the steel slag used, characterized by rough surface and angular shape. A significant loss of strength was evident in all samples subjected to wetting and drying cycles, with a loss of about 25% after the treatment. The damage was produced by two combined effects: thermal dilation and contraction and shrinkage due to moisture variation, as demonstrated in [19]. In particular, after the process, all the samples showed a white powder outcrops on the surface, clearly identifiable as calcium and magnesium hydroxides. This efflorescence, composed by dissolved salts transported to the surface of the sample by water evaporation [38], showed no detrimental effects and did not affect the loss in compressive strength.

**Table 4.** Compression strength of cubic samples at different curing time.

Curing Days	Average Value (MPa)	
	Monotonic Loads	Wet-Dry Cyclic Loads
3	40.5	-
7	45.3	-
14	48.0	-
21	46.3	-
28	50.6	37.8
70	52.8	-
90	52.3	34.5

As stated by Pellegrino et al. [38], the influence of wetting and drying cycles on the compressive strength is generally similar for natural and steel slag concrete. In particular, a loss of strength of 15% was recorded for the traditional concrete, while a loss of strength of 22% was recorded for the steel slag concrete. These results are in line with those obtained from this study.

Figure 3 shows the development of the cubic compression strength vs. time and the comparison between experimental data and the reference curve proposed by Eurocode 2 [39] for normal concrete in standard conditions (temperature of 20 °C, relative humidity (RH) larger than 95%).

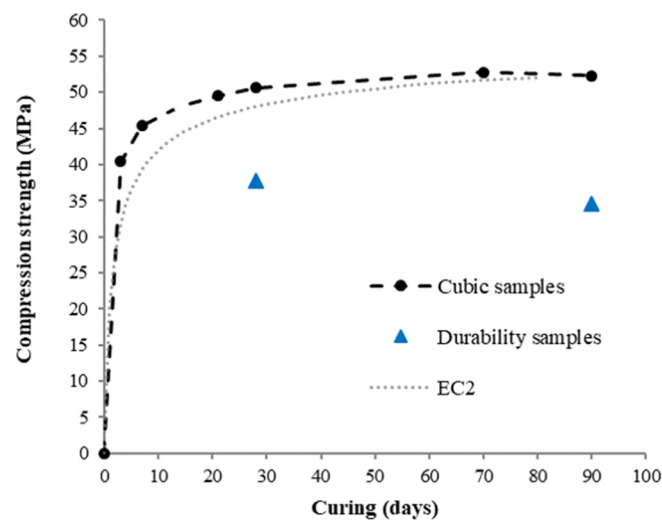


Figure 3. Results from compression tests at different curing time.

Since the number of tests after 28 days of curing was not sufficient to determine a statistical data, the characteristic strength ( $f_{ck}$ ) was evaluated as [40]:

$$f_{ck} = f_{cm} - 8 \text{ [MPa]}$$

where  $f_{ck}$  is the characteristic cylindrical compressive strength and  $f_{cm}$  is the mean cylindrical compressive strength of concrete. According to the experimental results obtained from the compression tests, concrete with EAF slags can be classified as C32/40.

### 3.2.3. Indirect Tensile Strength

Concrete structures are highly exposed to tensile cracking due to the applied loads. A cylindrical sample was loaded diametrically and uniformly across the circular cross section. To allow the uniform distribution of the applied load, plywood strips were placed between the sample and the load plates of the testing machine. The load caused a tensile deformation perpendicular to the loading direction, which produced a tensile failure. So, the concrete samples split into two halves due to the indirect tensile stress, as shown in Figure 4. The tensile load can be calculated from the formula as:

$$\sigma_c = 2P/(\pi h d),$$

where  $P$  = compressive load at failure,  $h$  = length of the cylinder, and  $d$  = diameter of the cylinder.



Figure 4. Sample failure mode.



Sample 1 showed lower resistance values, so it was considered as an anomalous sample. Table 5 shows the experimental results obtained; it can be noticed that the average tensile strength (i.e., 3.62 MPa) represented 7% of the compressive strength calculated at the same curing period.

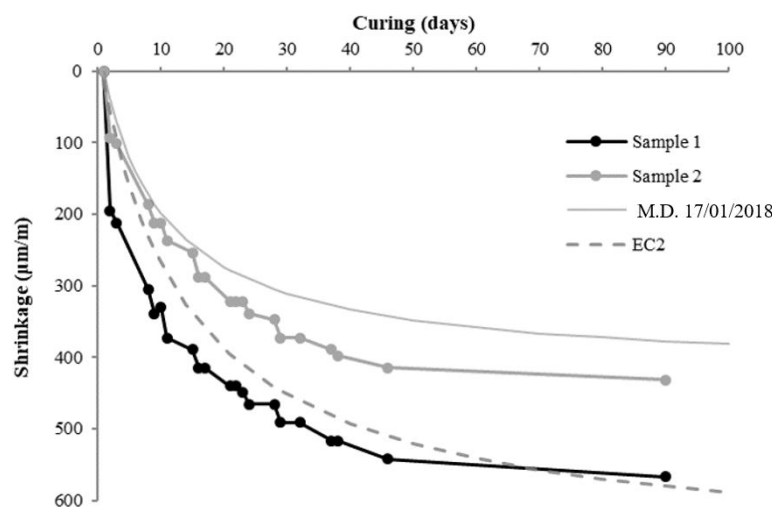
**Table 5.** Indirect tensile strength values of the analysed samples.

Sample	Failure Load (kN)	Indirect Tensile Strength at 28 Days (MPa)
1	76.5	2.43
2	121.6	3.87
3	105.9	3.37

### 3.2.4. Hygrometric Shrinkage

The test was performed to measure the axial dimensional shrinkage of concrete samples during the hardening process in a curing room. According to ASTM C157 standard [35], steel pins were glued on the head surfaces of the sample in order to measure the dimensional changes of samples properly stored in specified temperature and humidity conditions (20 °C and 50% relative humidity). The measurement of the variation of the specimen length allowed us to assess the volumetric expansion/contraction of concrete. The test device requires a reference bar made with nonabrasive and anti-absorbing material that does not vary its size over time.

Figure 5 shows the trend over time of the sample's deformation induced by the hygrometric shrinkage and the reference curves proposed by Ministerial Decree 17/01/2018 [41] and Eurocode 2 [40].



**Figure 5.** Shrinkage tests on prismatic specimens at different curing days.

Analyzing the data obtained during 90 days of curing, the two samples reached asymptotic values of about 400 µm/m and 550 µm/m, respectively, which are typical values for a normal concrete.

### 3.2.5. Elastic Modulus

The concrete elastic modulus is directly related to the elastic modulus of the aggregates and the cement matrix. In this study, the elastic modulus was determined according to EN 12390-13 [36]. Before the test, the samples were stabilized at room temperature and humidity; conditions that were maintained throughout the duration of the test. Each sample was subjected to three increasing loading/unloading cycles, the values of the stresses applied by the press varied from  $F/10$  to a maximum value equal to  $F/3$ , until instrumentation stabilization.

The different loading and unloading cycles performed for each sample as well as the stress-strain curves with the corresponding trend line for steel slag concrete are shown in Figure 6.

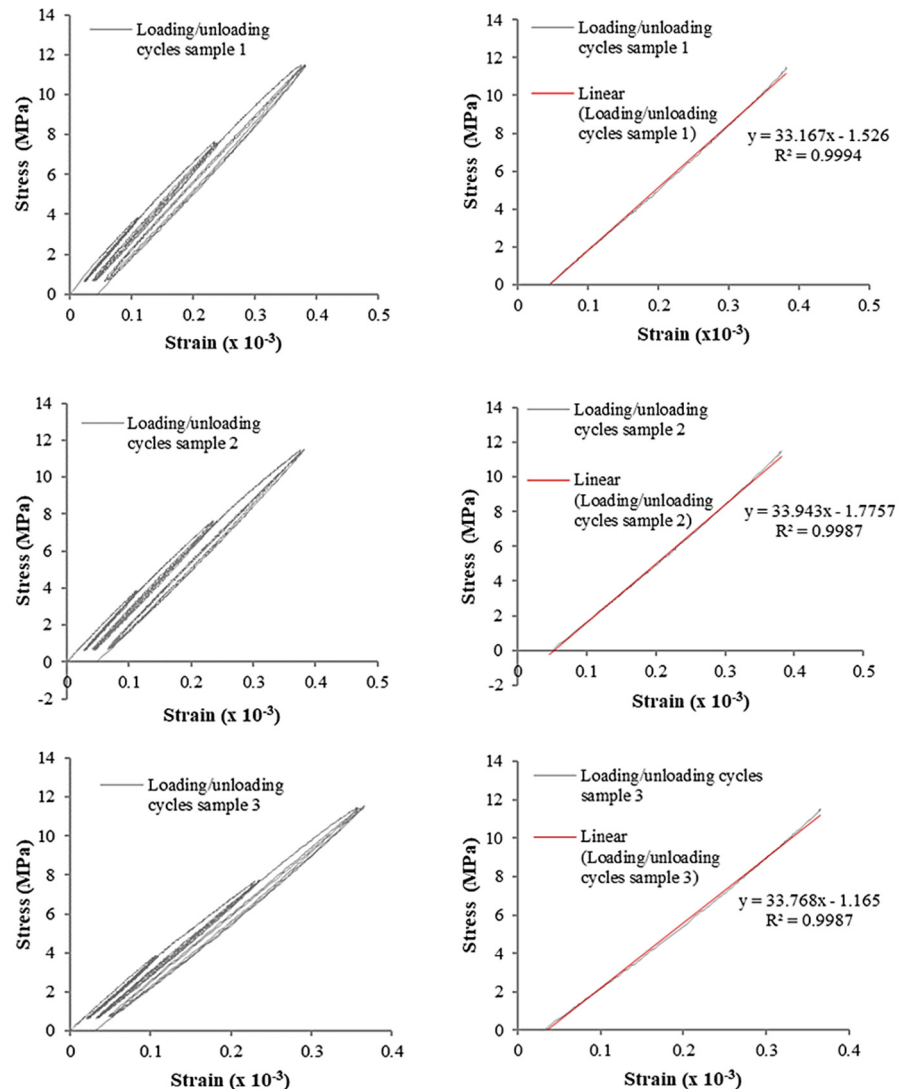


Figure 6. Load–unload cycles and values of the elastic modulus for the 3 different samples.

The experimental values show a mean elastic modulus value of about 34 GPa; this result shows that the stiffness contribution provided by the slag is compatible with that of a traditional concrete (about 35 GPa for a C35/45, according to Eurocode 2 [40]).

#### 4. Recycled Concrete as a Sustainable Building Material

The present research work focused on the evaluation of the environmental and technical feasibility of using an industrial by-product (EAF steel slag) as aggregate in concrete. Life-cycling is a concept that involves the environmental impacts during the entire life cycle of a product (as a construction material), from the extraction of resources for its manufacturing to their disposal phase. The green philosophy of the present research work was to contribute and promote waste prevention through the reuse and recovery of industrial by-products, with waste disposal as a last resort.

In addition to promoting material recovery, environmentally sustainable concrete from secondary materials also has the potential to save energy and CO<sub>2</sub> emissions compared to more traditional concrete [39]. Generally, Portland cement was found to be the main

source of CO<sub>2</sub> emissions produced by traditional concrete mixtures, being responsible for 74% to 81% of total CO<sub>2</sub> emissions. At the same time, coarse aggregates represented the second main source of CO<sub>2</sub> emissions and were responsible for 13% to 20% of the total CO<sub>2</sub> emissions produced by concrete production [42]. Otherwise, fine aggregates generated less equivalent CO<sub>2</sub> since they were not crushed.

In this context, the use of industrial by-products such as slags from steelworks as coarse aggregates in concrete production can, therefore, significantly contribute to increasing the environmental sustainability of the entire economic sector. At the same time, as also demonstrated by the experimental results obtained in this study, the use of EAF steel slags, in comparison with other recycled materials such as construction and demolition waste, is desirable in concrete structures to get better mechanical performance than traditional concrete.

However, regardless the analysis of the physical and mechanical properties of the recycled materials used in the concrete, it is essential to evaluate their pollutant potential due to the presence of hazardous compounds that may be released into the environment. The release level of these hazardous chemical elements must be evaluated according to the leaching test, which is a useful analytical tool [43]. In the present study, no element listed in the M.D. 186/2006 regulation exceeded the legal limit, so the environmental feasibility of EAF steel slag for being used for concrete was demonstrated. In that sense, in the research field on recycled building materials, combining the study of mechanical properties, which ensures the correct behavior of materials in structures, with the environmental assessment, which guarantees the environment safety and health, ensures to achieve the green policies that European Union promotes in key areas, as is the case of construction sector.

## 5. Conclusions

The present work investigated the influence of EAF steel slag as a partial substitute of natural coarse aggregate in concrete production. Based on the experimental results, the following conclusions can be drawn.

- The release of pollutants from steel slag was acceptable. The eluates produced widely respected all the standard limits established by M.D. 186/2006 [31]. Only vanadium showed a concentration value close to the limit (220 µg/L).
- The use of steel slag with a maximum diameter higher than 20 mm had an undesired impact on concrete workability (steel slag segregation). In light of this, it is recommended to use this maximum grain size to prevent any difficulties in the subsequent concrete mixing.
- The average compressive strength of concrete mixtures made with EAF steel slags increased up to 53 MPa at 90 days of curing. This can be ascribed to the strong bond between cement/mortar particles and EAF steel slags, as well as to the porous and rough surface of the steel slag. However, tests up to 1 year of curing are foreseen to prevent any unexpected decrease in load bearing capacity. Based on the results obtained, the concrete could be classified as C32/40.
- The concrete density was about 2470 kg/m<sup>3</sup>, which is comparable to the traditional concrete density.
- Samples subjected to wetting–drying cycles showed a significant compressive strength reduction due to the consecutive thermal variations. In particular, after 28 days of curing, the tested samples exhibit a loss of strength of about 25% (range from 51 MPa to 38 MPa).
- The concrete mixtures showed an average indirect tensile strength of 3.62 MPa, which represented about 7% of the relative compressive strength.
- Hygrometric shrinkage of steel slag concrete developed quickly during the first days due to the effect of the high water absorption of EAF steel slag, and slowly in the following days, until reaching a horizontal asymptote of about 500 µm/m.
- The elastic modulus of concrete mixtures was about 34 GPa. Although steel slag has internal pores, the elastic modulus of the concrete made with EAF steel slag was closer to

that of traditional concrete. Therefore, the effect of the aggregate type on these coefficients was negligible and these results agree with those obtained by most authors.

This experimentation showed good technical and environmental results for the use of EAF steel slag as coarse aggregate in concrete production. In particular, EAF steel slag can be successfully used to replace gravel in concrete without affecting the concrete properties. In fact, despite the increase in density, the use of steel slags as partial replacement of natural aggregates allows users to obtain concrete with good workability and mechanical properties.

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