

## Article

# Use of Iron and Steel Slags in Concrete: State of the Art and Future Perspectives

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**Abstract:** In the two last decades, world production of pig iron and steel has undergone a significant increase. In 2018, 1252.87 and 1806.46 million tons of pig iron and steel, respectively, were produced as compared to the 575.78 and 809.94 million tons of 2000. Consequently, the amount of the different types of slags deriving from these production processes has also increased considerably. In relation to the principles of sustainability and circular economy, the available literature suggests several possible reuses for these slags (bituminous conglomerates, hydraulic engineering, metallurgy, fertilizers, etc.). This paper aims to provide an overview of the iron and steel slags production and their reuse in concrete (for example as replacement of cement, fine or coarse aggregates). The characteristics of slags are analyzed in terms of chemical, physical, and mechanical properties. Mechanical and durability tests (both from material and structures point of view) carried out in the different studies and research are shown as well. Particular attention was devoted to electric arc furnace slags (EAF) since they are the most produced in Italy. Based on this deep literature review, the gaps that still require further studies have been identified and discussed.

**Keywords:** concrete; iron; slag; steel; sustainability



**Citation:** Piemonti, A.; Conforti, A.; Cominoli, L.; Sorlini, S.; Luciano, A.; Plizzari, G. Use of Iron and Steel Slags in Concrete: State of the Art and Future Perspectives. *Sustainability* **2021**, *13*, 556. <https://doi.org/10.3390/su13020556>

Received: 29 November 2020

Accepted: 5 January 2021

Published: 8 January 2021

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## 1. Introduction

The worldwide iron and steel production showed a rapid increase in the last twenty years. From 2000 to 2018, pig iron production increased from 575.78 to 1252.87 million tons, steel from basic oxygen furnace increased from 522.68 to 1282.54 million tons, and steel from electric arc furnaces increased from 287.26 to 523.92 million tons [1]. During the steel production process, a great amount of slag is inevitably generated. The sector forecast indicates an upward trend in future production and the quantity of slag to be managed is also expected to increase. Usually, iron and steelmaking slags can be divided into four main types, according to the considered production process:

- Blast furnace slag (BFS);
- Basic oxygen furnace slag (BOF);
- Electric arc furnace slag (EAF or “black slag”);
- Ladle furnace slag (LFS or “white slag”).

Based on the literature [2–12], each production process is characterized by different slag to steel output ratios: 250–300 kg of blast furnace slag per ton of pig iron produced, 120–180 kg of basic oxygen furnace and electric arc furnace slags per ton of steel produced, and 30–80 kg of ladle furnace slag per ton of steel treated with secondary metallurgy processes. Based on these slag to steel output ratios, it is clear that there are huge quantities of slag that must be properly managed in order to avoid different problems such as the

increase in landfill space and environmental problems related to a possible release of contaminants. Due to their characteristics, iron and steel slags can be reused in different fields such as bituminous mixtures for road construction, concrete and cement production, metallurgy, hydraulic engineering, internal recycling in iron and steel production processes, fertilizer, and soil stabilization [13].

Focusing on the construction sector and in particular on the production of cement, it has undergone a strong increase in recent years, reaching values around 4 billion tons in 2018 (+3% compared to 2017). The leader of this sector is China, which holds about 60% of the entire world cement production [14]. There are several favorable reasons for the reuse of iron and steel slags in this sector:

- The cement production industry is responsible of 7–9% of the CO<sub>2</sub> worldwide emissions: the use of iron and steel slags in partial or total replacement of cement would lead to a reduction in cement production, with a consequent reduction in CO<sub>2</sub> emissions [4,6];
- The raw materials extracted from quarries begin to be scarce and the demand for aggregates for concrete production is continuously growing: considering that the aggregate constitutes about 70–75% of the concrete weight, a reuse of the slag in partial or total replacement of natural aggregates would lead to a reduction in the demand for raw materials from quarries;
- A reuse of the slag would also bring benefits from the environmental point of view due to the lower quantities being destined for landfill, less space occupied by the landfill itself and lower risk of any contaminants which, if the slag is stored in the open air, could be harmful to the aquifer.

Many studies have been conducted on the possibilities of reuse of iron and steel slags in concrete and this paper aims to provide an overview on the state of the art of this topic, analyzing the slag generation processes, their characteristics, their reuses in concrete production and the results obtained from the various studies. Particular attention was devoted to EAF slag since they are the most produced in Italy (average production of 3 million tons per year [15,16]). The literature review was carried out by mainly consulting “Scopus” and “Web of Science” databases. In the case of blast furnace slag, the adopted keywords were: “blast furnace slag generation processes”, “blast furnace slag reuse”, “blast furnace slag reuse in concrete”, and “blast furnace slag properties”. Then, the same procedure was adopted for the other types of slags analyzed in this article, i.e., “basic oxygen furnace slag”, “electric arc furnace slag”, and “ladle furnace slag”. Finally, in the last two sections, the gaps that still require further studies have been identified and discussed.

## 2. Types of Slag

### 2.1. Blast Furnace Slag (BFS)

Pig iron production takes place in a blast furnace (Figure 1). It is a 30–40 m high structure made up of an external steel armor internally coated with refractory bricks able to withstand high temperatures. Near the blast furnace there are three or four Cowper’s towers which are used to collect and filter the fumes emitted (these fumes will then be reintroduced into the structure). The raw materials (iron ores, coke, and flux (mainly limestone)) are placed on the conveyor belts that take them to the highest part of the structure, where there is a special opening for their insertion. Simultaneously with the insertion of the raw materials from above, there is a blowing of hot air (called “hot wind”) from below, through special tubers. This hot wind comes from the previously mentioned Cowper’s towers. The oxygen contained in the hot wind (with a possible external enrichment) reacts with the carbon of the coke generating reducing gas, rich in CO (carbon monoxide), which invests the loaded material from below and exercises the reducing action against the iron oxides contained in minerals. The reduced part (Fe) melts and settles in the crucible where the carburization takes place (solution of carbon in the molten mass) generating the pig iron. Not all the carbon monoxide reacts in this way; a part will remain with the fumes that come

out, i.e., blast furnace gases. The calcination of the flux present in the charge gives rise to a calcium oxide which, together with the waste substances of the iron ores (called “gangue”) and the ashes of the coke, forms the blast furnace slag. This is collected in the crucible in a floating layer over the pig iron bath. In addition to neutralizing the acid component of the minerals, the slag allows the absorption of sulfur and other impurities contained in the raw materials and unwanted in the pig iron.

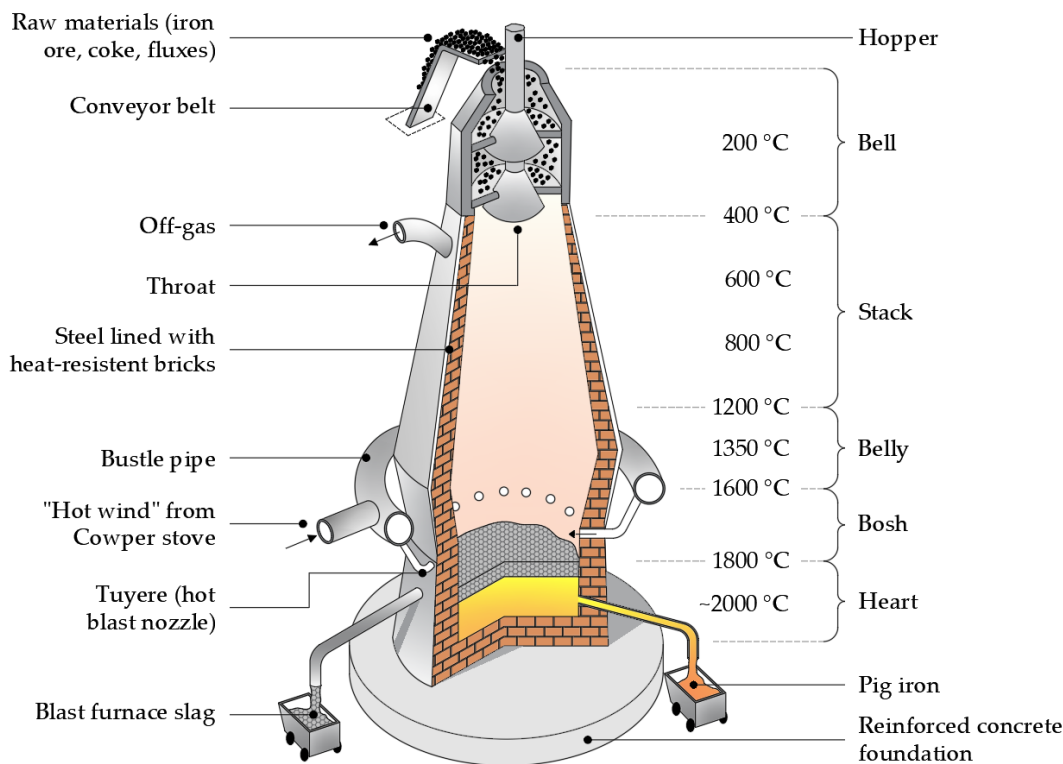


Figure 1. Schematic representation of the blast furnace.

This type of slag is divided in three main groups, which differ in cooling processes, treatments, and reuse fields (Table 1).

Table 1. Types of blast furnace slag (BFS) according to the cooling processes [17].

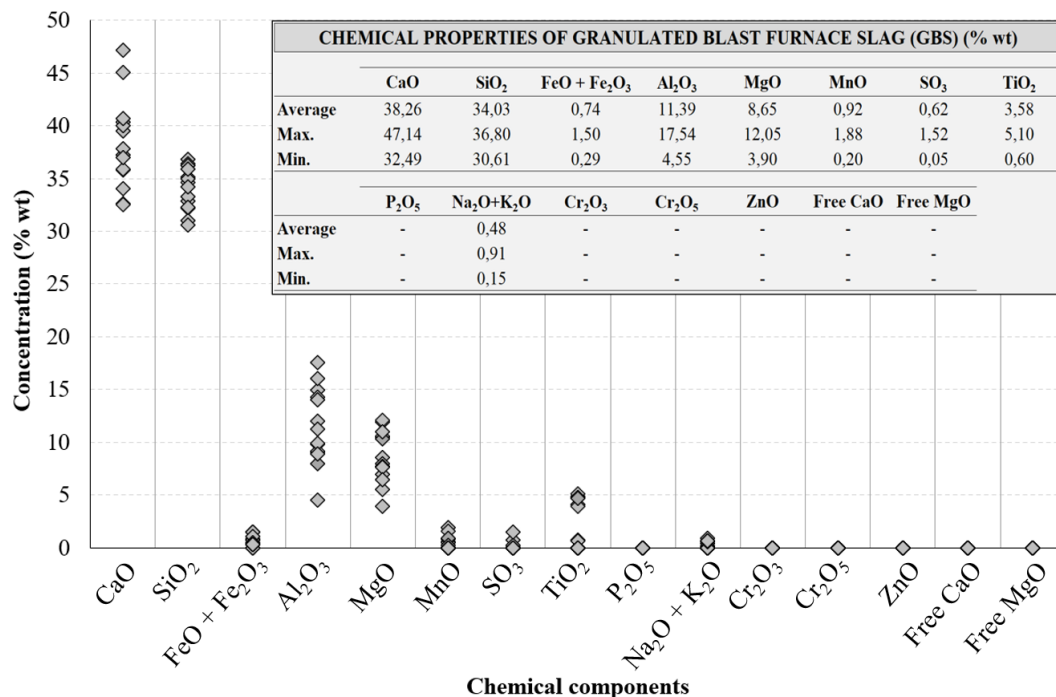
	<b>GBS—(Granulated Blast Furnace Slag)</b>	<b>ABS—(Air-Cooled Blast Furnace Slag)</b>	<b>PBS—(Pelletized Blast Furnace Slag)</b>
Cooling process	Quick cooling with water to produce vitrified granulates (0–5 mm)	Slow cooling with air in slag pits to produce crystalline material	Quick cooling with air to produce glassy or crystalline pellets (0–20 mm)
Common treatments	Grinding to powder (<100 μm) to produce GGBS (ground granulated blast furnace slag) or addition of ground Portland cement clinker	(a) Crushing, sieving, grading to produce aggregates (b) Grinding to powdered material (<300 μm)	(a) Material < 10 mm: grinding to powder, addition of ground Portland cement clinker (b) Material > 10 mm: crushing, sieving, grading to produce light aggregates
Common reuses	Portland slag cements and BFS cements	(a) Road construction and concrete (b) BFS lime	(a) Portland slag cements and BFS cements (b) Concrete

Table 2 summarizes the physical properties of the blast furnace slag (both GBS and ABS) from the literature. Given that around 80% of blast furnace slag production in Europe is made up of GBS and the remaining 20% of ABS (with a drop to about 13% in 2018 [13]), this document focuses mainly on GBS slag and Figure 2 shows its chemical composition from the literature and how the concentrations of the different chemical components are distributed. However, it should be underlined that the chemical composition of ABS slag is very similar to that of GBS slag [18].

**Table 2.** Physical properties of the blast furnace slag from the literature.

Physical Properties	Units	GBS		ABS	
		Values	References	Values	References
Dimension	mm	≤0.063	[10,19]	0–4.75	[20,21]
Density	kg/m <sup>3</sup>	2810–2955	[9,10,20,22,23]	2630	[20]
Surface area	cm <sup>2</sup> /g	4000–4720	[6,9,10,22,24]	-	
Fineness modulus	%	2.37–3.35	[20,23,25]	3.02; 3.1	[20,21]
Blaine fineness	cm <sup>2</sup> /g	3800–5502	[20,26]	-	
Porosity	%	-		41	[20]
Water absorption	%	2.1	[23]	3.45	[21]
Water content	%	-		0.35	[20]
Loss on ignition (LOI)	%	1.08; 1.11	[26]	-	

Note: PBS slag properties are not shown in this table due to the low quantity produced. Furthermore, PBS slag production in Europe is 0% of the total blast furnace slag since 2010 [13].



**Figure 2.** Chemical composition of the GBS slag from the literature (average, maximum and minimum values, and distribution of the concentration (in % of weight) of each chemical component) [8–10,22–24,26,27].

From X-ray diffraction (XRD) and X-ray fluorescence (XRF) analyses, the following mineralogical phases were found in the blast furnace slag: glassy phase, gehlenite (Ca<sub>2</sub>Al(AlSi)O<sub>7</sub>), akermanite (Ca<sub>2</sub>MgSi<sub>2</sub>O<sub>7</sub>) [27], belite (C<sub>2</sub>S), alite (C<sub>3</sub>S), dodecalcium hepta-aluminate (12CaO·7Al<sub>2</sub>O<sub>3</sub> or C<sub>12</sub>A<sub>7</sub>), and RO phase (i.e., a solid solution of CaO-FeO-MnO-MgO) [6].

## 2.2. Basic Oxygen Furnace Slag (BOF)

The basic oxygen furnace (Figure 3) is usually located in association with a blast furnace and is charged first with steel scraps, for maintaining the temperature at 1600–1650 °C for the chemical reactions, and then with molten iron produced in the blast furnace [28,29]. Then, a 99% pure oxygen flow is applied at supersonic speed through a lance lowered into the furnace, in order to allow oxidation reactions and the removal of impurities contained in the charge. Other fluxes (lime/dolomite) are added later and, once burned and combined with the impurities, they lead to the formation of the slag and the reduction of the unwanted chemical elements in the melt [28,29]. A small amount of molten steel is tapped and analyzed and, when its chemical composition meets the requirements, the oxygen blowing lance can be removed. The furnace is tilted on one side in order to tap the molten steel and then on the other side to allow the recovery of the slag (previously deposited in a layer over the molten steel bath) [28]. The slag produced in the basic oxygen furnace is called basic oxygen furnace slag (BOF) and there are numerous methods for cooling this type of slag, e.g., natural air cooling, air quenching, water spraying, and shallow box chilling. Depending on the cooling method used, the physical, chemical, mineralogical, and leaching characteristics of the BOF slag may change. Other physical processes can be applied to the BOF slag before their reuse (crushing, grinding, screening, sieving, magnetic separation, etc.) [29]. Table 3 shows the different cooling processes, common treatments, and reuses of the BOF slag.

**Table 3.** Cooling processes, common treatments, and reuses of the basic oxygen furnace (BOF) slag [30].

	BOF	BOF Treated with O <sub>2</sub> and SiO <sub>2</sub>	
Cooling process	Slow air-cooling in slag pits	Slow air-cooling in slag pits	Extreme slow air-cooling in special slag pits
Material obtained	Crystalline material with grain sizes < 100 mm	Crystalline and volume stable material with grain sizes < 100 mm	Crystalline and volume stable material with grain sizes < 300 mm
Common treatments	(a) Weathering to achieve volume stable material, crushing, sieving, and grading; (b) Sieving and grading < 3.15 mm; (c) Grinding to a powdered material (<300 µm)	Crushing, sieving, and grading	Crushing, sieving, and grading
Common reuses	(a) Aggregate for road construction; (b) Converter lime humid coarse (fertilizer); (c) Converter lime (fertilizer)	Aggregate for road construction	Aggregate for road construction and hydraulic structures

Table 4 summarizes the physical properties of the basic oxygen furnace slag from the literature. Table 5 shows the range of the physical properties of the materials commonly used as aggregates in concrete production (depending on the treatment they undergo before their use (crushing, grinding, sieving, etc.)). This allows a direct comparison between the BOF slag properties and those of standard aggregates.

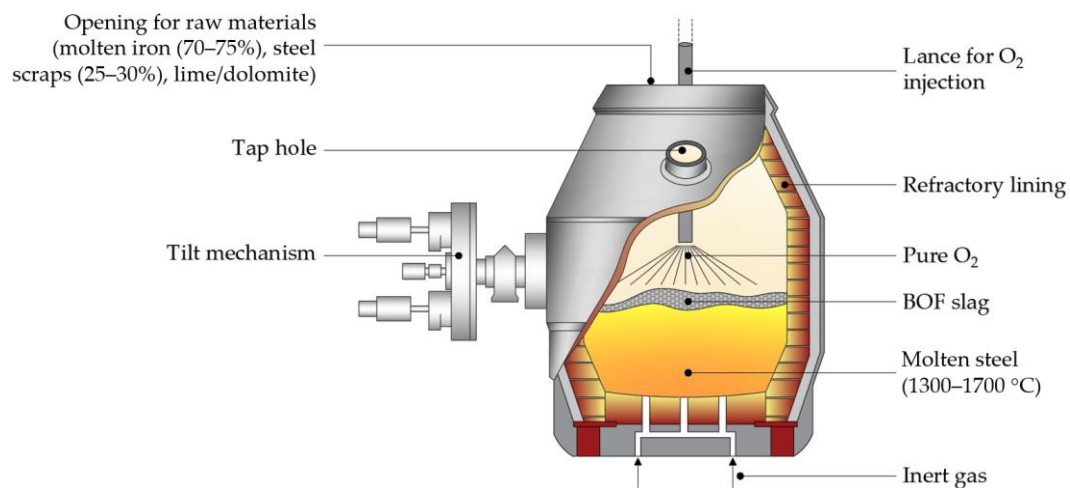


Figure 3. Simple schematic representation of the basic oxygen furnace.

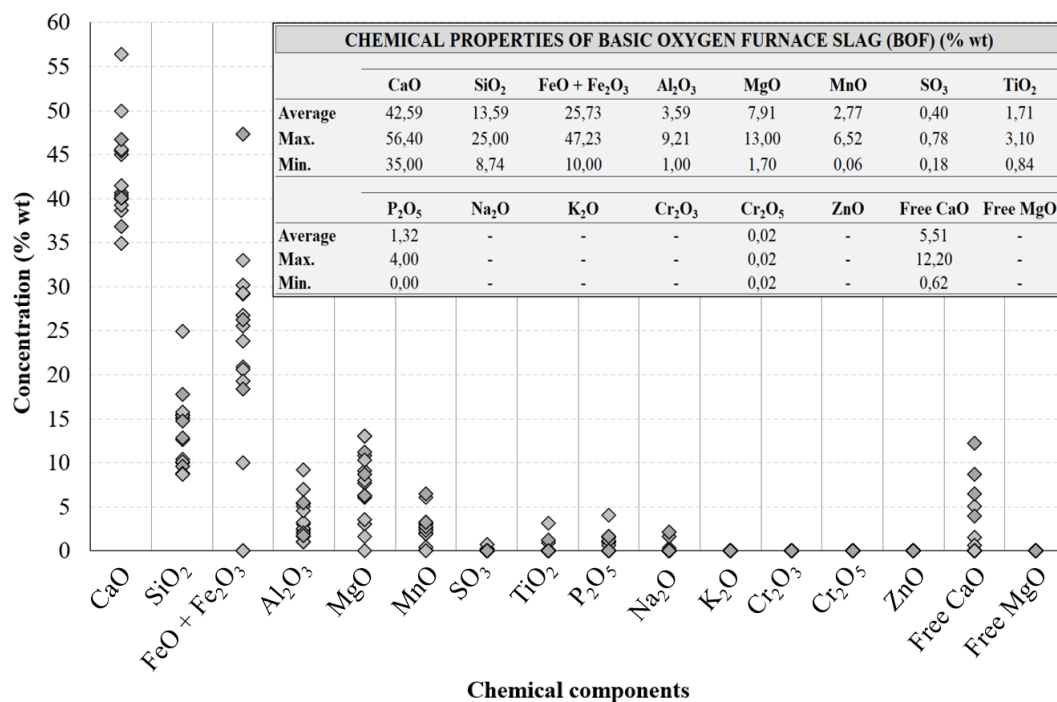
Table 4. Physical properties of the basic oxygen furnace slag from the literature.

Physical Properties	Units	BOF	
		Values	References
Dimension (fine)	mm	0.16–4.75	[8,31–34]
Dimension (coarse)	mm	4.75–22.00	[33,35,36]
Density	kg/m <sup>3</sup>	3100–3600	[32,37–39]
Specific weight	kg/m <sup>3</sup>	2980–3580	[29,36,40]
Specific surface	cm <sup>2</sup> /g	4510–4530	[32,35]
Fineness modulus	%	2.08–2.80	[8,31,35]
Color		Gray/Black	[33]
		Gray/Brown	[38] (Low basicity slag)
		Gray/White	[38] (High basicity slag)
		Brown	[32]
Water absorption	%	0.70–4.23	[29,33,39,40]
Water content	%	1.56–13	[33,38,40]
Los Angeles test	%	11–22	[29,39]
Grindability index	-	0.7	[37]
Crushing value	%	21	[29]
Impact value	%	16	[29]

Table 5. Physical properties of the common materials used as aggregates in concrete.

Physical Properties	Units	Sand	Limestone	Gravel	Granite	Refs.
Density	kg/m <sup>3</sup>	2520–2720	2490–2690	2650–2730	2510–2690	[29,41,42]
Fineness modulus	%	2.60–3.30	2.23–6.90	6.85	5.90–7.30	[29,41,42]
Water absorption	%	0.40–3.99	0.30–3.30	0.55–0.75	0.50–2.30	[29,41,42]
Los Angeles test	%	-	18–37	18	20–27	[29,42]
Crushing value	%	-	-	-	24	[29]
Impact value	%	-	-	-	21	[29]

Figure 4 shows the chemical composition of the basic oxygen furnace slag from the literature and how the concentrations of the different chemical components are distributed.



**Figure 4.** Chemical composition of the BOF slag from the literature (average, maximum and minimum values, and distribution of the concentration (in % of weight) of each chemical component) [8,27,31–35,37–40].

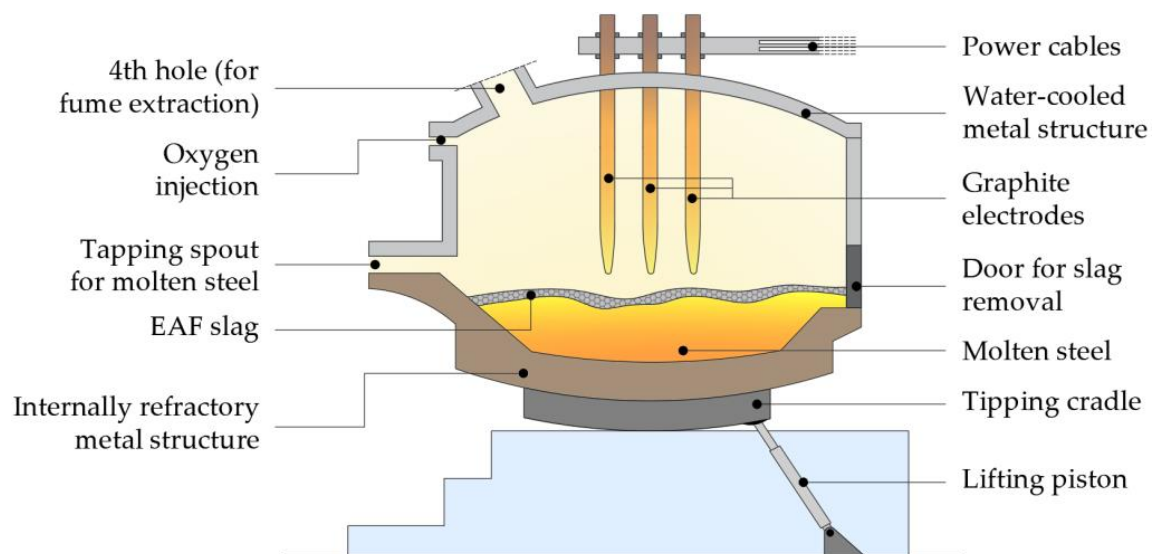
From XRD and XRF analyses, BOF slag is mainly characterized by the following mineralogical phases (depending on their basicity/alkalinity ( $\text{CaO}/\text{SiO}_2$ ): 0.9–2.7 (low hydraulic reactivity), >2.7 (high hydraulic reactivity) [32]): belite ( $\text{C}_2\text{S}$ ), alite ( $\text{C}_3\text{S}$ ), RO phase (i.e., a solid solution of  $\text{CaO}$ - $\text{FeO}$ - $\text{MnO}$ - $\text{MgO}$ ), dicalcium ferrite ( $\text{C}_2\text{F}$ ), gehlenite ( $\text{Ca}_2\text{Al}(\text{AlSi})\text{O}_7$ ), olivina ( $\text{Mg,Fe}_2\text{SiO}_4$ ), and merwinite ( $\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$ ) [27,31,32,35,37–39].

### 2.3. Electric Arc Furnace Slag (EAF)

The steel production with electric arc furnace (Figure 5) does not depend from the production of pig iron in the blast furnace; in fact, the charges are made up of steel scraps and other secondary materials in smaller quantities (first, pig iron and  $\text{CaO}$  in the form of burnt lime or dolomite; subsequently, small quantities of oxygen and carbon powder). These raw materials are loaded from the top of the furnace after being separated, graded, and sorted [28]. The quality, density, and size of the charged materials must be carefully chosen for two reasons: the melting and temperature conditions inside the furnace and the chemical composition of the finished steel must be in the required ranges. For the fusion, three graphite electrodes are lowered into the electric arc furnace; then, an arc transformer is struck and the electricity travels through the electrodes and the steel scraps, melting them and generating heat [28]. During the oxygen injection, some iron and other impurities (aluminum, manganese, etc.) are oxidized and, combined with  $\text{CaO}$ , form the electric arc furnace slag (EAF). This slag is collected over the molten steel bath and is tapped by tilting the furnace on one side, while for the recovery of the molten steel, the furnace is tilted in the opposite direction.

There are two different types of electric arc furnace slag, depending on the type of steel produced:

- EAF-C: electric arc furnace slag from carbon steel production;
- EAF-S: electric arc furnace slag from stainless/high alloy steel production.



**Figure 5.** Simple schematic representation of the electric arc furnace.

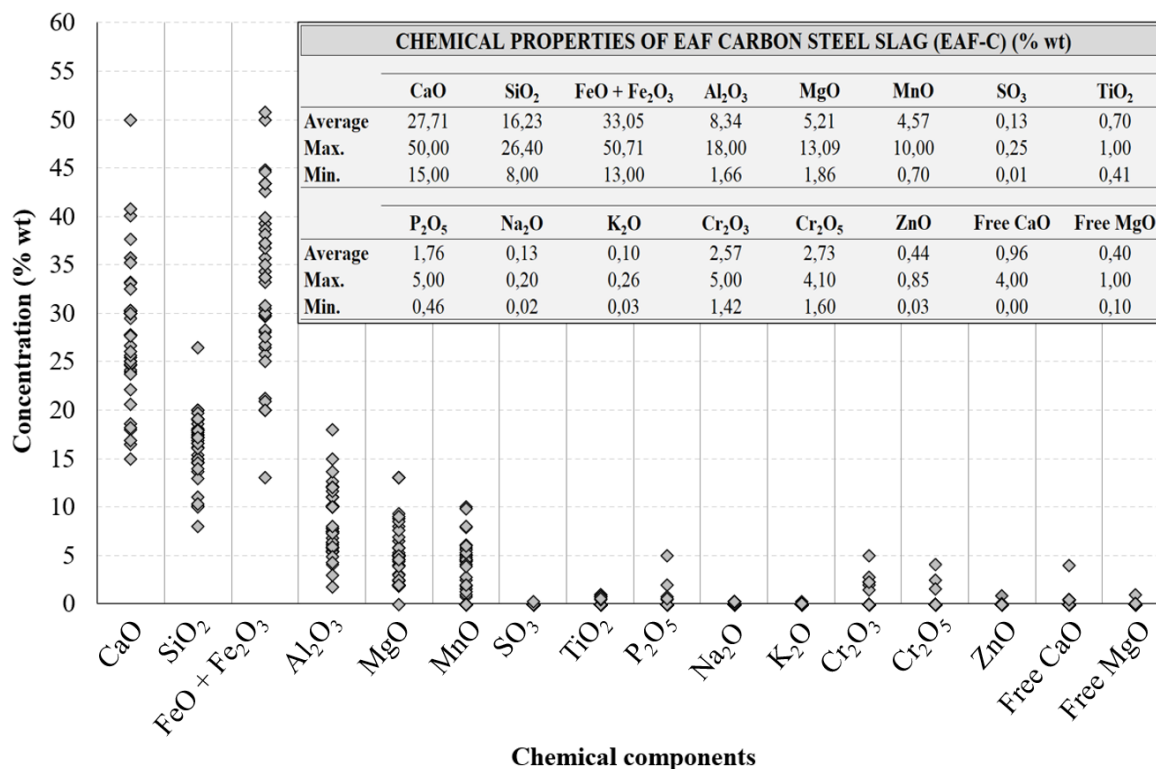
Table 6 summarizes the physical properties of the electric arc furnace slag from the literature (for a comparison with the properties of the standard aggregates used in concrete production, see Table 5).

**Table 6.** Physical properties of the electric arc furnace (EAF) slag from the literature.

Physical Properties	Units	EAF	
		Values	References
Dimension (fine)	mm	0.063–4.75	[5,10,11,32,43–53]
Dimension (coarse)	mm	4.75–32.00	[5,11,43–47,49,50,53–55]
Pores dimension (average)	mm	0.21; 6.76	[56]
Density	kg/m <sup>3</sup>	2840–3854	[9,11,32,39,49,50,53,55–59]
Specific weight	kg/m <sup>3</sup>	3010–3970	[5,43–46,51,54,60,61]
Specific surface	cm <sup>2</sup> /g	4990–5050	[9,32]
Fineness modulus	%	2.83–7.78	[51,57,61]
Volumetric expansion	%	0.14; 0.25	[43,57]
Water absorption	%	0.18–10.5	[5,11,39,43–46,49–51,54–57,59–61]
Porosity	%	7.8; 14.4	[56]
Los Angeles test	%	14–24	[5,39,43,44,46,56]
Crushing value	%	13–17	[49,57]
Flakiness index	-	1–6	[5,45,58,61]
Micro Deval abrasion	%	6.5–9.5	[5,49]
Abrasion AAV (EN 1097-8)	%	3	[57]
Thaw/freeze cycle strength	%	0–2.1	[5,39,49,57]
Volumetric stability	%	1.3–2.9	[49]
Smoothing strength (PSV)	%	58–64	[39,57]
Shape index	-	1.5–10	[5,39,61]
Polish strength	%	0.44; 0.47	[5]
Thermal shock	%	1; 2	[5]
Aggregate-bitumen affinity	%	10; 15	[5]
Compressive strength	MPa	320; 350	[39]
Shape	-	Pointed	[55,61]
Initial color		Black	
Color after aging		Dark gray	



Figure 6 shows the chemical composition of the electric arc carbon steel furnace slag (EAF-C) from the literature and how the concentrations of the different chemical components are distributed.



**Figure 6.** Chemical composition of the electric arc furnace slag from carbon steel production (EAF-C) from the literature (average, maximum and minimum values, and distribution of the concentration (in % of weight) of each chemical component). [5,9,11,37,39,43–46,48–50,52,54–56,58–64].

EAF-S slag has a chemical composition closely related to the particular production processes to obtain special or alloy steels. Some examples, from the literature, are shown below:

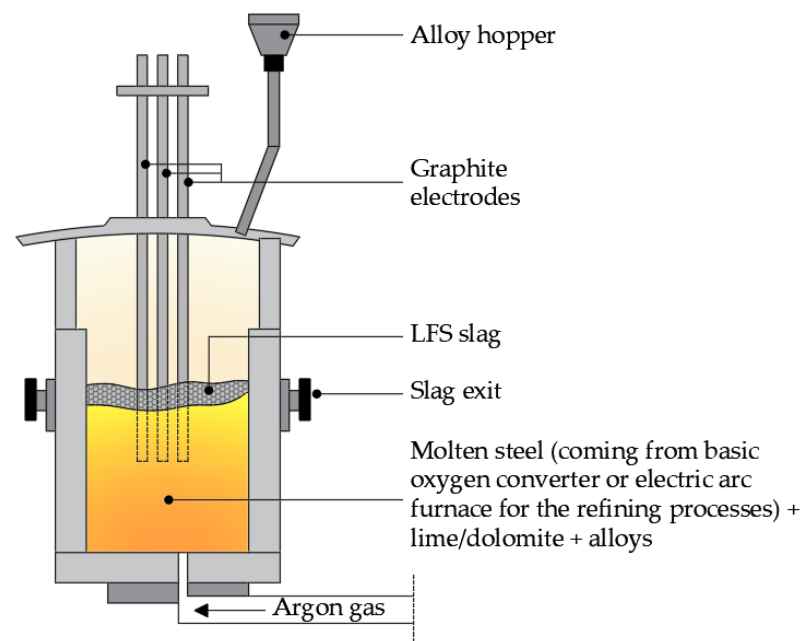
- CaO (43.22%), SiO<sub>2</sub> (27.82%), Fe<sub>2</sub>O<sub>3</sub> (7.54%), Al<sub>2</sub>O<sub>3</sub> (2.74%), MgO (7.35%), MnO (0.68%), SO<sub>3</sub> (1.73%), TiO<sub>2</sub> (0.59%), P<sub>2</sub>O<sub>5</sub> (0.45%), Cr<sub>2</sub>O<sub>5</sub> (0.95%), free CaO (0.58%) [32];
- CaO (15–25%), SiO<sub>2</sub> (5–25%), FeO<sub>x</sub> (30–50%), Al<sub>2</sub>O<sub>3</sub> (1–3%), MgO (1–3%), Cr<sub>2</sub>O<sub>3</sub> (5–30%) [62] (slag from alloy steel production (indicated with the letter “B” in the reference article));
- CaO (20–50%), SiO<sub>2</sub> (10–40%), FeO<sub>x</sub> (5–30%), Al<sub>2</sub>O<sub>3</sub> (5–15%), MgO (5–15%), Cr<sub>2</sub>O<sub>3</sub> (0.5–5%) [62] (slag from special steel production (indicated with the letter “C” in the reference article));
- CaO (56.90%), SiO<sub>2</sub> (23.00%), Fe<sub>2</sub>O<sub>3</sub> (1.41%), Al<sub>2</sub>O<sub>3</sub> (5.27%), MgO (6.23%), MnO (1.68%), TiO<sub>2</sub> (1.50%), P<sub>2</sub>O<sub>5</sub> (0.10%), Cr<sub>2</sub>O<sub>3</sub> (2.96%) [10].

From XRD and XRF analyses, EAF slags are characterized by the following mineralogical phases (depending on their basicity/alkalinity (CaO/SiO<sub>2</sub>): 0.9–2.7 (low hydraulic reactivity), >2.7 (high hydraulic reactivity) [32]): wustite (solid solution of FeO), brownmillerite (Ca<sub>2</sub>(Al,Fe)<sub>2</sub>O<sub>5</sub>), mayenite (C<sub>12</sub>A<sub>14</sub>O<sub>33</sub>), belite (C<sub>2</sub>S), alite (C<sub>3</sub>S), RO phase (i.e., a solid solution of CaO-FeO-MnO-MgO), ferrite (C<sub>4</sub>AF), gehlenite (Ca<sub>2</sub>Al(AlSi)O<sub>7</sub>), olivina (Mg,Fe)<sub>2</sub>SiO<sub>4</sub>, merwinite (Ca<sub>3</sub>Mg(SiO<sub>4</sub>)<sub>2</sub>), and calcium silicate (β-Ca<sub>2</sub>SiO<sub>4</sub>) [32,39,43,45,46,48,49,55,61].

#### 2.4. Ladle Furnace Slag (LFS)

Steel produced in a basic oxygen furnace or in an electric arc furnace usually goes to refining processes in the ladle furnace (secondary processes). This furnace (Figure 7) looks like a smaller version of the electric arc furnace, with three graphite electrodes used to heat the steel [28]. The refining processes in the ladle furnace are:

- Final desulphurization: consists of eliminating sulphur by adding specific substances (Mn, CaO, etc.) or desulfurizing agents (Mg, CaSi, CaC<sub>2</sub>, etc.) through a lance. The presence of minimal traces of sulphur leads to lower quality steels; through this process, the sulphur concentration in the steel can be lowered to 0.0002%;
- Degassing of oxygen, nitrogen, hydrogen, and carbon compounds: can be achieved, for example, by providing the ladle with a sealing cover connected to the vacuum system. In this way, the steel in the ladle furnace is exposed to the action of the vacuum; however, this action is quickly attenuated below the steel surface. For this reason, the steel must be constantly stirred in order to bring the metal that is deep into the surface and vice versa. This stirring is achieved by argon injection from the bottom of the ladle furnace, or by an electromagnetic action;
- Chemical composition adjustment: can be achieved by adding the desired alloys to the molten steel in order to produce different types of steel [28];
- Temperature adjustment;
- Improvement of purity of the steel through the separation of non-metallic inclusions;
- Final decarburization [28].



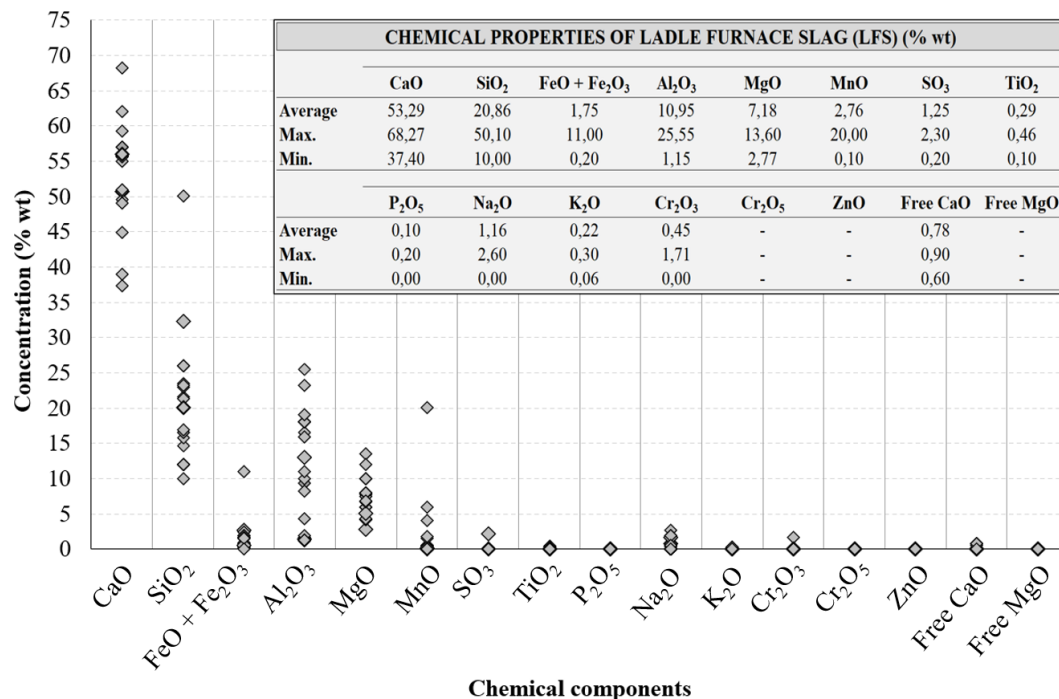
**Figure 7.** Simple schematic representation of the ladle furnace (adapted from [28]).

The slag generated by these refining processes, called ladle furnace slag (LFS), has different physical properties and chemical composition if compared to GBS/ABS, BOF, or EAF slags. Table 7 summarizes the physical properties of the ladle furnace slag from the literature.

**Table 7.** Physical properties of the ladle furnace slag (LFS) from the literature.

Physical Properties	Units	LFS	
		Values	References
Dimension	mm	0.063–0.600	[10,65,66]
Density	kg/m <sup>3</sup>	2555–3030	[12,57,65,67,68]
Specific surface	cm <sup>2</sup> /g	1200–8490	[57,66,67]
Fineness R <sub>45</sub>	%	22	[57,65]
Blaine Fineness	cm <sup>2</sup> /g	3000	[68,69]
Volumetric expansion	%	22; 37	[12]
Volumetric expansion	mm	0.49	[57]
Pozzolanic index (28 days)	%	92	[57]

Figure 8 shows the chemical composition of the ladle furnace slag from the literature and how the concentrations of the different chemical components are distributed.



**Figure 8.** Chemical composition of the ladle furnace slag from the literature (average, maximum and minimum values, and distribution of the concentration (in % of weight) of each chemical component). [10,12,39,57,65–70].

From XRD and XRF analyses, LFS slags are mainly characterized by the following mineralogical phases (their basicity/alkalinity (CaO/SiO<sub>2</sub>) is high, almost 2 [29]): crystallinity, belite (C<sub>2</sub>S), akermanite (Ca<sub>2</sub>MgSi<sub>2</sub>O<sub>7</sub>), RO phase (i.e., a solid solution of CaO-FeO-MnO-MgO), merwinite (Ca<sub>3</sub>Mg(SiO<sub>4</sub>)<sub>2</sub>), wollastonite (β-CaO·SiO<sub>2</sub>), anortite (CaO·Al<sub>2</sub>O<sub>3</sub>·2SiO<sub>2</sub>), bredigite (Ca<sub>7</sub>Mg(SiO<sub>4</sub>)<sub>4</sub>), and αAl<sub>2</sub>O<sub>3</sub> [29,39,66,69]. A complete mineralogical analysis of seven different types of LFS is available in the literature [69].

### 3. Reuse of Slags in Concrete

Although iron and steelmaking slags can be reused in different fields, one of the most common reuses regards the production of concrete [16]. Depending on their physical, chemical, and mechanical characteristics and the treatments they undergo prior to their reuse, slags may be reused in substitution of binder, fine, or coarse aggregates.

### 3.1. Blast Furnace Slag: Reuse in Concrete

Due to their physical and chemical properties (Section 2.1), blast furnace slags are commonly used in partial substitution of the cement in concrete production. Several studies showed that the addition of this type of slag can lead to an improvement in the properties of the concrete mixture and, at the same time, allows a considerable saving of cement (from 20 to 70%). This leads to a reduction in both costs and environmental impact related to the production of cement (e.g., CO<sub>2</sub> emissions).

Concerning the workability of the concrete with blast furnace slag as partial replacement of the cement, an improvement was observed [6,7,71,72]. Initial and final setting times were higher than that of standard concrete [9,24,26] and the development of the strength was slower [9,19,71] at early age. The compressive strength increased with the time and became equal or higher than that of standard concrete [10,19,20,22,24,25,71–75]. This increase in compressive strength was related to the high content of SiO<sub>2</sub> in GBS slag, which contributed to increasing the pozzolanic properties [10]. The maximum increase in the compressive strength was obtained with a GBS-binder replacement percentage between 20 and 30% [75]; replacement rates above 50% were not recommended as the compressive strength decreased below that of standard concrete [71]. The development of tensile strength was similar to that of compressive strength, with slower increase at early age and higher development over time [9,20,72,74]. An optimal GBS-cement replacement percentage for the development of the tensile strength was around 30% [72]. The flexural strength in concrete with GBS slag as partial substitution of cement was higher [19,22,25,66,74], but the Young modulus was slightly lower than that of standard concrete (approximately 7 and 16% lower for slag-cement substitution percentages of 30 and 50%, respectively) [71]. As regards the durability properties, no improvement in terms of water absorption was noted in case of partial substitution of the cement with fly ash (15%) and GBS slag (15%) [72]. In case of sand replaced with ABS slag, the water absorption of concrete specimens made with 72% of ABS slag and 28% of sand (w/b ratio equal to 0.88) was similar to the control mix. When the ABS slag totally replaced the sand, the water absorption increased and became higher than that of the control mix [20]. Air content of concrete with GBS slag was similar to that of standard concrete [9,75] and lower volumetric expansion was observed in concrete specimens made with GBS slag in partial substitution of the cement [22]. The resistance to chloride penetration was higher in concrete with GBS slag as partial replacement of cement [26] and fine aggregates [23]. The resistance to water and chloride penetration could be improved by adding chemical activators [24]. In addition, further testing must be carried out on the resistance to chloride penetration and to sulphate attack, for longer times [26]. The carbonization depth was smaller in concrete with GBS slag as partial replacement of cement [24] and fine aggregates [23]. In [71], the authors noted that the pores volume tended to decrease as the percentage of GBS-cement replacement increased (especially at 28 and 56 days, when hydration processes have reduced the pores in the matrix); this is advantageous in case of chemical attacks or exposition to adverse environmental conditions. The leaching tests carried out in the literature confirmed that this slag did not cause damage to the environment. In particular, the leachate of all chemical components (even chromium) analyzed decreased when GBS slag was used as a partial replacement of the cement in concrete mixtures [19,22]. Extensive leaching tests were also carried out on 11 blast furnace slag composite samples, not added to the concrete [76]. The results showed that all the slag samples met the standards to be considered “non-hazardous”. Despite the many advantages related to the reuse of blast furnace slag in concrete production as a partial replacement of the cement, there are also some problems to consider. The first problem is related to the greater autogenous and drying shrinkage of GBS slag concrete if compared to the standard one: in [9], the autogenous shrinkage began to stabilize after 20 days in case of standard concretes and in 30 days in case of GBS slag concretes, with higher values. These results might be associated with the amount of latent hydration materials in GBS slag concretes, due to the high cementitious properties of the slag. The second problem

is related to the higher setting time of GBS slag concretes, which may affect construction schedules where quick setting is required.

When the blast furnace slags were used as replacement of coarse aggregates (granite), a decrease in workability and in compressive strength was observed. According to the authors, the reduction in workability might be due to the more angular shape and to the lower weight of the slag compared to the granite, then requiring more water to make the concrete workable [77]. The problem of a possible reduction in workability can be easily solved by adding a superplasticizer additive. The decrease in compressive strength could be due to different factors: poor paste–aggregate bond caused by the presence of reaction products on the surface of the coarse slag, high void volume on the surface and inside the coarse slag, the flakiness and roughness of the coarse slag that could affect the loading capacity, and the interlocking bond between the aggregates. In particular, the authors made some mixes using granite and blast furnace slag as a partial substitution of the granite as coarse aggregate. All the specimens with slag showed lower compressive strength compared to the standard one, both at 7 and 28 days (of about 10.5% and 4%, respectively) [77].

### 3.2. Basic Oxygen Furnace Slag: Reuse in Concrete

BOF slags represent one of the most abundant and scarcely reused by-products in the world, even if, as already shown in Table 3, their crystalline structure and good mechanical properties (impact and crushing values, skid resistance, etc.) make them an ideal aggregate for road construction. Nevertheless, their high volumetric expansion and poor hydraulic activity still hinder their use in civil engineering applications. Reuse options include their use as partial replacement of coarse aggregates in asphalt mixtures [78,79], as partial replacement of cement in concrete upon rapid quenching outside the furnace [80], or as a  $\text{Ca}(\text{OH})_2$  source for activating blast furnace slag (BFS) in order to obtain a hydraulic road binder [81]. Some researchers tried to reuse this type of slag as a partial replacement of the binder or aggregates in the production of concrete, obtaining conflicting results.

#### 3.2.1. BOF Slag as Partial Replacement of Cement

The high content of calcium silicate phases (mainly dicalcium silicate (belite or  $\text{C}_2\text{S}$ ) and tricalcium silicate (alite or  $\text{C}_3\text{S}$ )) caused lower activity if compared to that of cement clinker; this was probably due to the crystal size particles and dense structure formed at a higher temperature in the basic oxygen furnace [29,37]. Under a slow cooling process (see Table 3), there was a polymeric transformation of  $\beta\text{-C}_2\text{S}$  in a non-hydraulic component,  $\gamma\text{-C}_2\text{S}$ , and this contributed to the low reactivity of BOF slag [29]. Concerning the hydraulic properties, the hydration process was similar to that of cement but the BOF slag hydration rate was much lower [82]. In addition, the RO phase was almost inert and the interface between the particles of this phase and the C-S-H gel (deriving from the hydration of BOF slag) proved to be a weak region of the system [82]. The slag and cement influenced each other by changing the hydration environment but the steel slag did not react with cement hydration products [2]. The dormant period of the BOF slag-cement binder was greater than that of traditional cement and increased as the amount of slag increased. In [35], the authors tested BOF slag concretes with a constant w/b ratio and concretes with the same compressive strength at 28 days, but with different replacement percentages of cement. Table 8 summarizes the main results of this wide research.

**Table 8.** Main results from Wang et al. [35].

Properties	Conditions	Results	Authors Comments
Compressive strength	Constant w/b ratio	Reduction with an increase in cement-slag replacement	The negative effect of adding BOF slag on the compressive strength was lower for lower w/b ratios
	High w/b ratio, 30% of BOF-cement replacement	Less if compared to the standard concrete (this gap reduced for lower w/b ratios)	
Initial and final compressive strength	Constant compressive strength (28 days)	Lower initial but higher final compressive strength if compared to the standard concrete	
Drying shrinkage	High w/b ratio	Faster if compared to the standard concrete, but after 90 days, the values were quite similar	The effect of adding slag on drying shrinkage was lower for lower w/b ratios
Ions chloride permeability	Constant w/b ratio, 28 days	Higher as the percentage of replacement increased	The negative effect of the slag on chloride ions permeability was lower when the w/b ratio decreased
	High w/b ratio, over 28 days	Higher if compared to the standard concrete, in mixes with a high replacement percentage	
	Low w/b ratio, over 28 days	Similar if compared to the standard concrete, in mixes with a high replacement percentage	
Carbonation resistance	Constant w/b ratio, low replacement percentage	Small influence on the carbonation resistance	The negative effect of the slag on the carbonation resistance was lower for lower w/b ratios and for longer aging period
	Constant w/b ratio, high replacement percentage	Lower carbonation resistance	

In [32], the authors used BOF slag previously exposed to the weather and to laboratory conditions for the volumetric stability. As a result of the intense grinding, the slag showed an improvement in the water reduction effect. The BOF slag mortar's compressive strength was higher than that of EAF-S mortar, for all ages and all degrees of cement replacement and the pH value of the cement containing 50% of BOF was below that of pure cement, but still above the value which leads to the breaking of the protective film on the surface of the reinforcement steel bar (important when this material is used in environments with high aggressiveness). In [83], the authors used BOF slag with high MgO content: although the compressive strength at 2, 7, and 28 days was lower for all the slag-concrete mixes compared to the standard one (from 9 to 57%), the physical and mechanical properties of the resulting concrete were acceptable for the Turkish Standards Institute (TSE). Some authors carried out research on the possibility of an acceleration of the hydration rate of the concrete with BOF slag as partial replacement of cement by increasing the fineness of the particles, the temperature, or the solution alkalinity. In [3], the authors proposed a new free-CaO extinguishing procedure, as an alternative to that provided by the EN 13282-2 [84], which allowed a reduction in the volumetric expansion and a better compressive strength.

### 3.2.2. BOF Slag as Partial Replacement of Aggregates

The main problem related to the reuse of the BOF slag as a partial replacement of natural coarse and fine aggregates in the concrete production is the high content of free-CaO and MgO (see Figure 4). Without any treatments, these two components cause a volume expansion of 98% and 148%, respectively (due to the formation of  $\text{Ca}(\text{OH})_2$  and  $\text{Mg}(\text{OH})_2$ ) [40]. Another problem is related to the presence of the RO phase (20–30% of the slag weight), which causes defects in concrete structure due to its irregular distribution [40]. Some authors developed treatments that allow a reduction in the percentage of free-CaO and MgO, in order to guarantee greater volumetric stability. In [8], the slag was stored for more than two years and was used as a partial replacement for sand in concrete: when the

w/b ratio was 0.39 and the replacement percentage was 60%, the compressive strength of concrete was very close to that of the traditional concrete, at 7 days. In [31], the authors used two different slag treatment methods to reduce the free-CaO content: steam aging ranging from 8 h to 12 h and an autoclave process lasting for 3 h under 2.0 MPa at 215 °C. The autoclave treatment method significantly improved the volume stability of BOF slag as fine aggregate. The mortar made with autoclave-treated BOF slag did not show any decrease in strength and the expansion rate did not sharply increase during the curing period. The 8 h steam treatment reduced the free-CaO content from 3.56% to 1.07% but the 12 h steam treatment was not as effective because the difference in free-CaO content (between 8 h and 12 h) treatments was only 0.13%. For the untreated and steam treated BOF slag, the compressive strength did not increase with the prolongation of curing age and the flexural strength decreased, accompanied by the sharp increase of linear expansion rate. In [40], the authors replaced the natural aggregates (NA) with a ground carbonated BOF slag (called CSA aggregate) and made a comparison with the untreated BOF slag (called SSA aggregate). The technological process used to obtain the CSA slag is called “accelerated carbonation”. The workability of concrete with CSA aggregate was not significantly affected, despite the water absorption of CSA aggregate being higher than those of NA and SSA aggregates. After accelerated carbonation, the “harmful” pores (size 50–200 nm) of the CSA aggregate decreased by 24.4%, while the “harmless” pores (size < 20 nm) increased by 67.9% (pore nomenclature from [85]). Although the mechanical properties of the CSA aggregates were lower than those of NA or SSA aggregates, the compressive strength of CSA slag concrete was 20% and 60% higher than those of NA and SSA aggregate concretes, at 28 days, due to the angular shape of the slag which would improve their interaction with the cement matrix. The interfacial transition zone (ITZ) between the cement matrix and CSA aggregates also improved. According to the authors, the direct use of untreated BOF slag (SSA) as an aggregate in concrete would cause evident damage within 48 h, due to the volumetric instability. The carbonation treatment could significantly reduce the free-CaO content of the slag from 7% to 1% by weight in 3 h. The CSA slag concrete did not show sign of damage after 240 h of testing by steam vulcanization. Consequently, BOF slag treated by carbonation could be used as aggregates with good volumetric stability. In the literature, there are another two different BOF slag treatment processes to reduce the free-CaO and MgO content [34]. The first one is the “scrubbing attrition process”, which consists of mixing, with a stirrer, the slag in a liquid/solid solution. In this way, the free-CaO can be removed from the surface of the BOF slag thanks to the mutual collision between the slag particles and with the stirrer walls. After being removed from the stirrer, BOF slags are subjected to the “chelating process”: this treatment consists of adding a chelating reagent (oxalic acid) which remains on the surface of the slag. If the water penetrates the slag, part of this reagent is dragged with it and reacts with the internal free-CaO, thus preventing the volumetric expansion of the slag. Due to these treatments, the linear expansion of the concrete samples made with treated BOF slag as aggregates decreased from >0.95% to 0.03%, with an increase in oxalic acid concentration. According to the authors, with the scrubbing attrition process, more than 30% of free-CaO content can be removed from the surface of the BOF slag. In the case of higher content of free-CaO, the combination of scrubbing attrition process and chelating process can remove a great amount of free-CaO and reduce the autoclave expansion of cement mortars to 0.16% [34]. The compressive and flexural strengths reached satisfying values after 180 days (of about 32 MPa and 5.5 MPa, respectively, for slag with low free-CaO content treated only with the chelating process; of about 45 MPa and 7 MPa, respectively, for slag with high free-CaO content subjected to both treatments) [34]. Extensive leaching tests were also carried out on 17 BOF composite samples, not added to the concrete [76]. The results showed that all the slag samples met the standards to be considered “non-hazardous”.

### 3.3. Electric Arc Furnace Slag: Reuse in Concrete

#### 3.3.1. EAF Slag as Partial Replacement of Cement

The reuse of EAF slag as cement replacement material has been widely studied in the literature. The use of EAF-C slag as partial replacement of cement in concrete production led to less workability and less air content as compared to the control mix (−25%); this might be due to the difference between the dimensions of the binder once EAF-C slags are added [9]. The initial and final setting times were higher: authors added a small amount of gypsum which slightly reduced the setting time of the fresh concrete, but did not show significant differences at early ages [9]. It was noted that the setting time of EAF-C slag concrete was very similar to that of GBS slag concrete. This was a positive result for EAF-C slag as it is GBS slag that is usually used as a replacement for standard cement. As already shown for GBS slag in Section 3.1, even for EAF-C slag concrete the autogenous shrinkage, stabilized at 20 days, was higher (+40%) as compared to that of the standard concrete [9]. Even if the development of resistance was slower at early ages, there was not a significant reduction in compressive and tensile strength at 28 days for the EAF-C slag concrete if compared to the control mix. On the other hand, the use of EAF-S slag from stainless steel production, as partial replacement (25%) of cement in concrete and cement mortar production, led to higher workability and setting time if compared to control mix [10]. EAF-S slag also provided low water consumption. The negative point was a reduction in compressive strength (of about 30, 25, and 25% after 7, 28, and 90 days, respectively [10]). No direct link between workability and compressive strength was found [10,32]. On the other hand, in [86], authors obtained good results for compressive strength, especially for mixes with 10% EAF-C slag-cement replacement (about 27, 27, 7, 8, and 13% higher after 3, 7, 28, 60, and 90 days, respectively, compared to the mix with natural aggregates). Regarding flexural strength, increases of approximately 11, 8, and 6% were obtained after 7, 28, and 90 days, respectively, for mixes with 10% EAF-C slag-cement replacement. However, its development was slower than that of the control mix [52]. The water permeability was minimal and morphological tests showed that the concrete containing slag appeared to be denser than the standard concrete. The results of the leaching tests showed that the partial replacement of the cement with EAF-C slag did not represent any threat to the environment [86]. Other tests revealed a decrease in the electric conductivity over time, low pozzolanic properties due to a low content of  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  in EAF-C slag, and a continuing loss of weight with the increase of the temperature and minerals with predominant amorphous structure, coexisting with some crystalline peaks [52]. In [32], a pH analysis showed that, although the pH value of EAF-S slag concrete was below that of pure cement, it was still above the value that leads to the breaking of the protective film on the surface of the steel bar reinforcement (therefore, it is necessary to take this into account when using this type of reinforced concrete in environments with high aggressiveness (e.g., marine)).

#### 3.3.2. EAF Slag as Partial Replacement of Aggregates

The EAF slag can be reused as replacement of fine or coarse aggregates in concrete production; this has both advantages and disadvantages. The density of the EAF slag concrete is higher than that of standard concrete due to the higher density of the slag if compared to natural aggregates (25–30%, considering average values). This entails a greater own weight of the elements, a greater seismic vulnerability, and higher transportation costs, effectively limiting the possibility of reusing this type of slag in concrete [45]. The EAF slag concrete density increased as the percentage of slag-aggregate substitution increased and the cooling process was very important for the density [11]. In [56], the authors used two types of EAF slag: EAF1 which undergone a normal cooling process and EAF2 which undergone a slower cooling process, with better evacuation of the gasses contained in it. EAF2 showed lower porosity and water absorption but higher density which resulted in a higher density of the EAF2 slag concrete mix. The second problem in the reuse of the EAF slag as aggregate in concrete is related to the presence of free CaO and MgO. These



chemical components, contained in the slag, react once the slag is added in the concrete mixture, causing volumetric expansion (at early age for free CaO and over time for free MgO, when the concrete has already hardened). Some methods are present in the literature in order to limit the problem of volumetric expansion: expose the slags to the external environment and spray them regularly with water for 90 days before their use [46,54], air drying of the slag in the laboratory for two months [87], natural aging or with the use of steam [57], expose the slag in a climatic chamber to high temperatures [53], or expose the slag in a damp environment for four months [88]. The third problem of the EAF slag concrete is related to the high tendency to the formation of cracks, due to the higher elastic modulus [57,59] and the higher drying shrinkage [4,11]. The drying shrinkage (at 90 days) was more significant for higher aggregate-slag replacement percentages (for a substitution percentage equal to 25%, the drying shrinkage increased by about 30% compared to that of the reference concrete). This might be due to a greater water absorption caused by the presence of the EAF slag [11]. To reduce this phenomenon, an alternative would be to soak the slag in the water before adding them to the mix. In [59], the drying shrinkage (at 60 days) of the EAF slag concrete was similar to that of the standard one (this was due to the reduction of the aggregate/cement ratio which acted in the opposite way compared to a water/cement ratio variation). Table 9 summarizes the behavior of the concrete made with EAF slag as partial replacement of fine or coarse natural aggregates compared to the concrete made with natural aggregates.

**Table 9.** Behavior of the concrete made with EAF slag as partial replacement of fine or coarse aggregates compared to the concrete made with natural aggregates.

Workability	References
<ul style="list-style-type: none"> <li>• Could be controlled by adding superplasticizer additives.</li> </ul>	[4,54]
<ul style="list-style-type: none"> <li>• Decreased with the increasing in aggregate-slag replacement percentage, perhaps due to the higher water absorption of the EAF slag.</li> </ul>	[11,46,55,89]
<ul style="list-style-type: none"> <li>• Could be controlled by mixing EAF slag with sand or fine aggregates.</li> </ul>	[57]
Compressive Strength	
<ul style="list-style-type: none"> <li>• Increased with the increasing of the aggregate-slag replacement percentage (e.g., about 20% higher for a 25% replacement percentage).</li> </ul>	[4,11]
<ul style="list-style-type: none"> <li>• Increased by about 30% for a high slag-aggregate substitution percentage (<math>\cong 85\%</math>).</li> </ul>	[44]
<ul style="list-style-type: none"> <li>• Increased from 42 to 100% over the predictions made during the mix design phase.</li> </ul>	[45]
<ul style="list-style-type: none"> <li>• Increased by 30% and 17.5% when the EAF slag was used as replacement of the roundish and fragmented aggregate, respectively.</li> </ul>	[54]
<ul style="list-style-type: none"> <li>• Increased by about 40 and 35% at 7 and 28 days, respectively, for a 100% slag-aggregate substitution percentage (high strength concrete).</li> </ul>	[55]
<ul style="list-style-type: none"> <li>• Increased by 35% after 28 days. After 56 days, it decreased by 5–10%. This indicated a rapid development of the compressive strength in EAF slag concrete.</li> </ul>	[56]
<ul style="list-style-type: none"> <li>• Increased by 30% and 40% in mixtures with w/b ratio of 0.54 and 0.45, respectively.</li> </ul>	[59]
<ul style="list-style-type: none"> <li>• Increased with the aging of the EAF slag concrete.</li> </ul>	[87]
<ul style="list-style-type: none"> <li>• Increased by about 10% for a slag-aggregate substitution percentage up to 60%.</li> </ul>	[89]
<ul style="list-style-type: none"> <li>• Increased by about 8, 11, and 11% after 7, 28, and 90 days, respectively, for M20 concrete mixes with a 50% slag-aggregate substitution percentage.</li> </ul>	[90]
<ul style="list-style-type: none"> <li>• Increased by about 1, 6.5, and 7% after 7, 28, and 90 days, respectively, for M30 concrete mixes with a 50% slag-aggregate substitution percentage.</li> </ul>	[90]
<ul style="list-style-type: none"> <li>• Increased by 20%.</li> </ul>	[91]

Table 9. Cont.

<b>Collapse behavior</b>	
<ul style="list-style-type: none"> <li>After the compression test, the collapse occurred with cracks that only affected the matrix and not the slag aggregates, while in standard concrete, the cracks affected both the matrix and the natural aggregates (this indicated a better quality of the EAF slag as compared to the natural aggregates, in terms of strength).</li> </ul>	[55]
<b>Tensile strength</b>	
<ul style="list-style-type: none"> <li>No increment.</li> </ul>	[45,56,88]
<ul style="list-style-type: none"> <li>Increased with the increasing of the aggregate-slag replacement percentage (e.g., about 17% higher for a 25% replacement percentage).</li> </ul>	[11]
<ul style="list-style-type: none"> <li>The increase could be given by a rougher contact surface and a greater friction of the EAF slag aggregate.</li> </ul>	[46]
<ul style="list-style-type: none"> <li>Increased by about 20% for a slag-aggregate substitution percentage of 100%.</li> </ul>	[55]
<ul style="list-style-type: none"> <li>Increased by about 25% for a slag-aggregate substitution percentage up to 60%.</li> </ul>	[89]
<ul style="list-style-type: none"> <li>Increased by about 10, 5, and 4% after 7, 28, and 90 days, respectively, for M20 concrete mixes with a 50% slag-aggregate substitution percentage.</li> </ul>	[90]
<ul style="list-style-type: none"> <li>Increased by about 2.5, 1.3, and 1.6% after 7, 28, and 90 days, respectively, for M30 concrete mixes with a 50% slag-aggregate substitution percentage.</li> </ul>	[90]
<b>Flexural strength</b>	
<ul style="list-style-type: none"> <li>No increment.</li> </ul>	[59,88]
<ul style="list-style-type: none"> <li>Increased with the increasing of the aggregate-slag replacement percentage (e.g., about 20% higher for a 25% replacement percentage).</li> </ul>	[11]
<ul style="list-style-type: none"> <li>Increased by about 20% for a slag-aggregate substitution percentage up to 60%.</li> </ul>	[89]
<ul style="list-style-type: none"> <li>Increased by about 6, 7, and 8% after 7, 28, and 90 days, respectively, for M20 concrete mixes with a 50% slag-aggregate substitution percentage.</li> </ul>	[90]
<ul style="list-style-type: none"> <li>Increased by about 3, 4.5, and 5% after 7, 28, and 90 days, respectively, for M30 concrete mixes with a 50% slag-aggregate substitution percentage.</li> </ul>	[90]
<b>Abrasion strength</b>	
<ul style="list-style-type: none"> <li>Increased.</li> </ul>	[57]
<b>Fragmentation strength</b>	
<ul style="list-style-type: none"> <li>Improved (lower weight loss compared to the standard concrete).</li> </ul>	[56]
<b>Air Content</b>	
<ul style="list-style-type: none"> <li>Increased as the aggregate-slag substitution percentage increased (with replacement percentages higher than 15%, the air content was about 2%). This was due to a greater addition of additive to achieve the desired workability.</li> </ul>	[11]
<ul style="list-style-type: none"> <li>Similar to that of the standard concrete.</li> </ul>	[45]
<b>Freeze/thaw behavior</b>	
<ul style="list-style-type: none"> <li>Better behavior after freeze/thaw cycles, in terms of strength and degradation.</li> </ul>	[43,53,57]
<ul style="list-style-type: none"> <li>After freeze/thaw cycles repeated for 25 days, the EAF slag concrete showed a decrease in the compressive strength (about −7%) compared to the standard concrete (which instead showed an increase).</li> </ul>	[44]
<ul style="list-style-type: none"> <li>Similar behavior after freeze/thaw cycles, in terms of strength and degradation.</li> </ul>	[50]

Table 9. Cont.

<b>Wet/dry behavior</b>	
<ul style="list-style-type: none"> <li>The exchange of water with the external environment was simulated with wet/dry cycles. The water tended to mobilize the products of the corroded iron nodules present in the EAF slag and deposit them on the surface of the specimens with the consequent formation of stains (to be taken into account in case of elements with aesthetic function or exposed to water).</li> </ul>	[50]
<b>Sorptivity behavior</b>	
<ul style="list-style-type: none"> <li>Better sorptivity test behavior, at all ages.</li> </ul>	[90]
<b>Ions chloride permeability</b>	
<ul style="list-style-type: none"> <li>Greater (or similar) compared to that of the standard concrete.</li> </ul>	[53]
<ul style="list-style-type: none"> <li>The corrosion of the steel reinforcement bars was higher (however, it must be considered that the EAF slag, such as, in general, all the slags deriving from the steel production, contain a slight fraction of iron in their composition in the form of small nodules and they have a negative influence on the resistivity and on the measurements of the corrosion potential of the EAF slag concrete).</li> </ul>	[45,53]
<b>Sulphate attack</b>	
<ul style="list-style-type: none"> <li>After one year of exposure, EAF slag mortar specimens showed less expansion compared to the standard one. Over time, these mortars showed an increase in compressive strength, thus confirming the absence of internal damage and zero reactivity of the fine fraction of the EAF slag aggregate.</li> </ul>	[53]
<b>Alkali-silica reaction</b>	
<ul style="list-style-type: none"> <li>Regarding the alkali-silica reaction, the expansion of the EAF slag concrete did not exceed the limit values (UNE 146508:1999 EX [92]) and the slag can be considered “non-reactive”.</li> </ul>	[53]
<b>Penetration of water under pressure</b>	
<ul style="list-style-type: none"> <li>Greater depth of penetration, maybe due to the high porosity of the EAF slag.</li> </ul>	[50]
<ul style="list-style-type: none"> <li>Lower depth of penetration.</li> </ul>	[56,90]
<b>Carbonation depth</b>	
<ul style="list-style-type: none"> <li>One to six times greater than standard concrete (high risk of steel bars corrosion in case of reinforced concrete).</li> </ul>	[50]
<b>Leaching behavior of EAF Slag Aggregates</b>	
<ul style="list-style-type: none"> <li>Good results and the concentration of potentially harmful elements in the eluate did not exceed the limits established by the different standards.</li> </ul>	[43,44,46,51,55]
<ul style="list-style-type: none"> <li>Extensive leaching tests carried out on 45 EAF slag composite samples, not added to the concrete. All the slag samples met the standards to be considered “non-hazardous”.</li> </ul>	[76]
<b>Leaching behavior of EAF concrete specimens</b>	
<ul style="list-style-type: none"> <li>Good results and the concentration of potentially harmful elements in the eluate did not exceed the limits established by the different standards.</li> </ul>	[50,57,59]
<b>General considerations on the leaching behavior</b>	
<ul style="list-style-type: none"> <li>Despite compliance with the reference standards, EAF slag with smaller particle sizes produced a higher release of dangerous substances in the leached water than that of EAF slag with larger particle sizes.</li> </ul>	[43]

In addition to their use in the standard concrete, few studies on the reuse of the EAF slag as a partial substitution of the natural aggregates in special concretes are available in the literature: pervious concrete [93], high-strength concrete [94], self-compacting concrete [95], and fiber reinforced concrete (using both steel and synthetic fibers) [58].

### 3.3.3. EAF Slag for the Production of Full-Scale Elements

The study of the possible reuse of slag in concrete has the main purpose of making full-scale elements commonly used in construction, taking advantage of all the advantages that slag can offer, and being careful of the negative aspects related to their reuse. Several studies on real elements are available in the literature and the results are quite encouraging. In [96], the authors made a full-scale beam-column node with EAF slag as partial or total replacement of coarse aggregates and the results showed how the EAF slag could increase the mechanical properties of the concrete: greater ultimate load, less displacement, greater stiffness (due to the higher elastic modulus of the EAF slag), less crack development (better meshing of the EAF aggregates), slightly greater dissipation (due to the achievement of a higher ultimate load and a lower crack pattern), and greater shear stresses, especially in the first load cycle, for the EAF slag element compared to the standard concrete element. In [60], the authors made full-scale RC beams with EAF slag as replacement of both fine and coarse aggregates. These beams showed better mechanical performances as compared to the natural aggregate concrete (due to a better consolidation given by the higher density of the EAF slag) and the existing formulae gave good predictions about the real bond between steel bars and EAF slag (however, when the contribution of the transverse reinforcement was ignored to simplify the design, the equation provided by the American Concrete Institute (ACI) code underestimated the experimental results of about 1.8 times). In [97,98], the authors tested the flexural behavior of full-scale RC beams with EAF slag as replacement of aggregates. The results showed high flexural strength, less deformation before the peak load (due to the higher elastic modulus of the EAF slag), and better ductility (1.13–3.21 times higher [97]). The ACI 318 [99] criteria provided very good previsions of experimental results for both the studies. The bending theory reflected the experimental results in terms of moment-curvature relationship and flexural behavior of the elements. In the initial phase of the applied moment, the EAF slag beams developed only 1–3 cracks, while the traditional RC beams developed as many as 6 cracks and the number of cracks in each element, after yielding, did not vary significantly [98]. Another study on full-scale RC beams with EAF slag as partial replacement of the aggregates showed higher shear and flexural strengths than traditional RC beams, as well as a higher first cracking moment; the crack openings and the crack patterns were similar between beams with and without EAF slag [61]. In [100], the authors made full-scale RC columns with EAF slag as replacement of both fine and coarse aggregates. These elements were subjected to combined bending and axial loads and EAF slag improved the ductility of the concrete (when the axial force was set to 20 and 30%, the displacement ductility indexes were 1 to 5 and 2 to 6 times higher, respectively, than those of standard concrete elements). The development of the crack pattern was studied in depth and the ultimate bending moment was calculated according to ACI 318 [99], obtaining very good results: the current standard previsions can be used to predict, in a conservative way, the flexural strength of EAF slag concrete full-scale columns. In [101], the authors made full-scale RC beams with EAF as partial replacement of natural aggregates. From flexural tests, the failure modulus was higher than that of the standard concrete (cracks in EAF samples did not extend more than those in the standard concrete) and the yielding and ultimate moments were very similar compared to those of standard concrete elements.

### 3.4. Ladle Furnace Slag: Reuse in Concrete

Due to the refining processes in the ladle furnace, this type of slag shows different physical, chemical, and mineralogical properties if compared to the others. Some research carried out so far has focused on the possibility of reusing the LFS slag as a cement replacement material.

During the cooling process, LFS slags tend to self-pulverize due to the conversion of  $\beta$ -C<sub>2</sub>S into  $\gamma$ -C<sub>2</sub>S; this phase is not hydraulically active so LFS slags must be specially treated to increase their activity or be activated by a special alkaline activator (NaOH or Na-silicate) in order to reuse them as a cement replacement in concrete production [29,102].

The hydration reaction and the hardening process largely depend on the mineralogical composition of the slag. A wide study on seven different types of LFS slags is available in the literature [69]. Their hydraulic properties are much lower than those of standard Portland cement and particular attention should be paid to the cooling method. After the disposal, these slags tend to self-pulverize and should come in contact with water, developing hydration reactions before their reuse; this would lead to hydraulically inactive materials with a lower strength development [69]. Concerning the workability, discordant results were obtained. In [65], the authors found good workability properties, while in [10], an extremely dry consistency of the mix was found. In [12], the authors studied the two common types of LFS slags (LFS with high alumina content ( $\text{Al}_2\text{O}_3$ ) and LFS with high silica content ( $\text{SiO}_2$ )): after the cooling process, these slags were constituted of single polyhedral crystals or irregular structure. There were cavities and pores which were the main causes of the higher water absorption of the LFS slag if compared to the standard cement. The consistency of the mix was dry and a greater addition of additive was needed to obtain the same workability as the control mix. In [70], the setting time was higher than the minimum imposed by the standard reference. This was due to the high content of  $\text{MgO}$ , which delayed the hydration of the cement and increased the setting time. Discordant results were obtained with the density: the LFS mix density was similar to the standard one, due to the similar density between the considered LFS slag ( $3030 \text{ kg/m}^3$ ) and the standard cement ( $3100 \text{ kg/m}^3$ ) [12]. In [68] instead, the LFS mortar mixes densities were higher than those of the standard mixes, due to the “filling function” of the slag, as well as the decrease in trapped air. Concerning the compressive strength, a great number of studies were carried out and the main results are summarized in Table 10.

**Table 10.** Influence of LFS slag on concrete compressive strength.

Compressive Strength	References
<ul style="list-style-type: none"> <li>• Lower <math>\text{SiO}_2</math> content led to a lower compressive strength.</li> </ul>	[10]
<ul style="list-style-type: none"> <li>• Decreased with an increase in the cement-LFS slag replacement percentage;</li> <li>• Concrete specimens made with high <math>\text{SiO}_2</math> content LFS slag showed loss of compressive strength of 8, 16, 26, and 46% compared to the standard mix, for slag-cement substitution percentages of 10, 20, 30, and 40%, respectively;</li> <li>• Concrete specimens made with high <math>\text{Al}_2\text{O}_3</math> content LFS slag showed loss of compressive strength of 10, 25, 32, and 37% compared to the standard mix, for slag-cement substitution percentages of 10, 20, 30, and 40%, respectively;</li> </ul>	[12]
<ul style="list-style-type: none"> <li>• High <math>\text{Al}_2\text{O}_3</math> LFS slag showed a lower compressive strength if compared to that of high <math>\text{SiO}_2</math> LFS slag; however, both were less than that of the standard mix;</li> <li>• Maximum replacement percentage suggested: 30%;</li> <li>• The long-term mechanical behavior (180–365 days) with a replacement percentage higher than 20% must be studied in depth.</li> </ul>	
<ul style="list-style-type: none"> <li>• High losses in compressive strength (up to 72% with a cement-slag replacement percentage of 50%);</li> <li>• Lower <math>\text{SiO}_2</math> content led to a lower compressive strength;</li> <li>• LFS slag can be used for non-structural applications.</li> </ul>	[19]

Table 10. Cont.

Compressive Strength	References
<ul style="list-style-type: none"> <li>Higher compressive strength in mixes with LFS slag with high percentage of dicalcium silicate in the <math>\beta</math>-C<sub>2</sub>S form (this mineral is also present in the clinker and, thanks to its hydration, the C-S-H phase is formed, the basis for the cement strength);</li> <li>High <math>\gamma</math>-C<sub>2</sub>S content led to low hydraulic activity and low strength development;</li> <li>An increase in the basicity index (CaO/SiO<sub>2</sub> or "C/S") led to an increase in hydraulic activity and in strength development (good strength properties for mixes with C/S ratio higher than 2.6).</li> </ul>	[69]
<ul style="list-style-type: none"> <li>Good compressive strength, similar to that of Portland cement;</li> <li>C<sub>3</sub>S contributed to the development of the compressive strength in the first 4 weeks.</li> </ul>	[70]

In [19], mixtures with LFS slag showed a loss in flexural strength which was half the loss in compressive strength. The abrasion resistance in LFS mixes was better than that of the standard cement mixes [57,94]. Concerning the durability of mixes made with LFS in partial substitution of cement, discordant results were obtained: good freeze/thaw resistance in [65] while in [103], the inclusion of LFS slag led to expansion problems and, consequently, a decrease in durability. The capillarity was the main cause of the water absorption in LFS slag if compared to the standard cement [12]. The water penetration under pressure test showed similar results (slightly higher) for LFS mixes if compared to the others [10]. The drying shrinkage of all specimens was very similar (values between  $-0.8$  mm/m and  $-1$  mm/m); however, mixes with high SiO<sub>2</sub> content LFS slag showed less shrinkage than the control mix. Mixes with high Al<sub>2</sub>O<sub>3</sub> content LFS slag showed the highest shrinkage [12]. Satisfying results were obtained from the leaching test, which confirmed that the LFS slag in partial substitution of cement did not cause damage to the environment [19,57]. The presence of free-CaO and MgO in LFS slag could cause volumetric expansion. In [12], volumetric expansions of the mixes with replacement percentages of 10, 20, and 30% were similar while mixes with a replacement percentage of 40% showed higher expansions (especially the mortar mix with high Al<sub>2</sub>O<sub>3</sub> content LFS slag). In the literature, there are several suggested processes to control or reduce this phenomenon: rapid cooling, exposing the slag to the open air for a predetermined period, or mixing with inert materials [67,83]. In [67], for example, authors reused LFS of low free-CaO and MgO contents, subjected to weathering in outdoor conditions for 1 year, for low-strength applications. In general, the studies that used this treatment for LFS slag showed that is possible to reuse them as a partial replacement of the binder in civil engineering applications (preferably where high mechanical strength is not required). However, other studies suggested reusing these slags in unrestrained construction applications (e.g., soil stabilization), where the expansion phenomena are less problematic [67].

#### 4. Future Perspectives on the Use of Slags in Concrete

Due to the different characteristics of slags, the possibilities of their reuse in the concrete production sector are very wide. As highlighted in the previous paragraphs, there are many studies in the literature that agree that iron and steelmaking slags can be used as materials capable of improving the physical and mechanical properties of the concrete mixtures in which they are incorporated. However, there are some aspects that deserve to be deeply studied.

Regarding the blast furnace slag (GBS, ABS), their reuse in cement production or in addition as a binding material in concrete is now consolidated (in Europe, the reuse rate of blast furnace slag is around 94–100%, where 72–80% are used for the production of cement or for additions in concrete [13]). Despite the in-depth knowledge of the behavior of this type of slag, it would be necessary to carry out further tests regarding some aspects related

to the durability of the concrete made with them (in particular, the resistance to chloride penetration and to sulphate attack, especially considering the long-term behavior).

Due to their characteristics, BOF slags are commonly used as an aggregate in unbound applications (e.g., road construction). Their reuse as a partial replacement of the natural aggregate for the concrete production would be possible but it is complicated because of the volumetric expansion of the granules. To solve this problem, some researchers developed different methods to reduce the free-CaO and MgO content in the slag (as described in Section 3.2.2). However, due to their good cementitious properties, the reuse of BOF slag as a partial replacement of the cement turned out to be the best solution for bound applications. Finally, it should be underlined that unbound applications are the most appropriate for this type of slag, further studies on the reuse in concrete are not so needed.

The EAF slag can be reused both in partial replacement of cement and aggregates for the concrete production. This second option is preferable because the first one showed some problems (increase in setting times, less initial strength development, and slightly greater autogenous shrinkage compared to the standard concrete). However, their reuse as partial replacement of the cement is possible if combined, for example, with small percentages of gypsum or steel sludge. The reuse of EAF slag as a partial replacement of natural aggregates is instead widespread and consolidated, but some aspects regarding the durability need to be studied in depth (among others, the behavior after freeze/thaw cycles, the resistance to the penetration of water under pressure, and the behavior in aggressive environments (e.g., marine)). There are some studies that demonstrate the good behavior of this type of slag used to replace standard aggregates for the production of full-scale elements, such as beams, columns, or beam-column nodes. The research should certainly be deepened. In particular:

- Continuing to study structural elements. It would be very useful to analyze the entire behavior of a structure: shear, bending, bond (through pull-out tests), and long-term behavior;
- Expanding the range of full-scale elements manufactured by the slag (new jersey, pipes, or non-structural elements).

As already mentioned in Section 3.4, the reuse of the LFS for concrete production is difficult because of their low hydraulic properties and volumetric instability. However, a few studies showed that is possible to reuse them as a partial replacement of cement in concrete for civil engineering applications that required low mechanical strength, by using special alkaline activators. For reuse as a binding material, a few aspects related to workability and durability (especially the freeze/thaw cycle behavior) should be studied more in depth before studying real applications.

The leaching tests carried out in the literature, both on granular slag samples and on slag-concrete specimens, gave positive results in terms of release of substances potentially harmful to the environment. It may be useful to carry out further tests on the release of any contaminants from monolithic concrete specimens, both cracked and uncracked.

Finally, an important aspect to be considered in order to reuse all these types of slag to replace cement or aggregates in concrete is how they vary the internal environment in terms of pH. Detailed analyses are necessary to investigate any pH variations that could cause deterioration problems to the reinforcement steel bars.

## 5. Conclusions

This paper summarized research carried out on the characteristics of the main types of iron and steelmaking slags and their possible reuse for concrete production. A deep analysis of the existing literature was carried out, highlighting the state of the art, the main perspectives, and possible future developments on the topic.

Blast furnace slags (BFS) have characteristics similar to the standard cement and their reuse as a partial replacement of the binder in concrete is now consolidated (as shown by

the reuse percentages). However, a few aspects related to the durability of this BFS concrete need to be studied more in detail (e.g., the resistance to chloride and the sulphate attack).

Currently, the main reuse field of basic oxygen furnace slag (BOF) is in unbound applications, such as road construction. Their reuse in concrete, as a partial replacement of both the binder and the natural aggregate, is still possible. For the latter option, particular attention should be paid to the treatment that the slag must inevitably undergo before being reused to reduce the volumetric instability mainly due to the high content of free-CaO and MgO. However, due to the important use in unbound applications, further studies regarding the reuse in concrete are not so needed.

The reuse of electric arc furnace slag (EAF) as a partial replacement of the binder or natural aggregate allows to obtain concrete with similar or even better mechanical characteristics than the standard one. Their reuse as an aggregate is certainly preferable, although few aspects related to the durability still need to be analyzed more in detail (e.g., freeze/thaw cycles, penetration of water under pressure, and behavior in aggressive environments). Encouraging results were also obtained regarding the use of these types of slags as a partial replacement of the natural aggregate for the production of full-scale concrete elements commonly used in construction. Research should continue in this direction, analyzing both short and long-term behavior and expanding the range of real elements that can be made with this type of slag.

Due to the volumetric instability, the tendency to self-pulverize during the cooling process, and the low hydraulic properties, the reuse of ladle furnace slag (LFS) as a partial replacement of the cement for the concrete production is quite difficult. Some studies showed that it is possible to reuse them in this way for civil engineering applications that required low mechanical strength, by using special alkaline activators. However, some aspects related to workability and durability should be further analyzed.

**Author Contributions:** Conceptualization, A.P., A.C., L.C., S.S., A.L. and G.P.; methodology, A.P., A.C., L.C., S.S., A.L. and G.P.; investigation, A.P., A.C., L.C., S.S.; data curation, A.P.; writing—original draft preparation, A.P.; writing—review and editing, A.P., A.C., L.C., S.S., A.L. and G.P.; supervision, A.C., S.S. and G.P. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Conflicts of Interest:** The authors declare no conflict of interest.

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