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Electric Arc Furnace slag (EAF): use in concrete for structural applications

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ABSTRACT

The iron and steel industry represents one of the largest production realities in the world, with global steel production steadily growing over the last two decades.

Despite the different techniques available, production nowadays mainly takes place according to two cycles: the "*integral cycle*" or the "*electric cycle*", to which subsequent refining in a ladle furnace is added.

In addition to the primary material (steel), all these processes also generate a large amount of secondary materials, the so-called "*iron- and steelmaking slags*". Depending on the production processes, the raw materials, the furnace management, the type of steel, the post-slagging cooling processes and the subsequent treatments, they are divided into different types, each with its own chemical-physical, mineralogical and performance characteristics.

The reuse of iron- and steelmaking slags to replace natural raw materials brings considerable advantages from an economic, social and environmental point of view. In fact, their reuse contributes to reducing the quantities destined for disposal in landfills, the exploitation of natural resources and the resulting impacts, in terms of environment, biodiversity and landscape protection.

However, in order to ensure their proper treatment for future reuse, iron- and steelmaking slags are also subjected to certain regulatory standards. In fact, depending on the classification, the treatment processes, registration and conformity assessments will be quite different and their knowledge and interpretation are therefore essential for the proper management of this type of materials.

This research aims to provide a further contribution to the knowledge of iron- and steelmaking slags, with a comprehensive focus on production, properties, classification, management and final reuses.

First of all, an intensive literature research was carried out on different types of iron- and steelmaking slags, in order to investigate and analyse their physical, chemical, mineralogical and performance properties, as well as aspects related to their possible environmental impact. Large space has been dedicated to their possible reuses, with a focus on reuse in the construction sector and in particular for concrete production.

A general and updated overview of the national regulations will then be shown, analysing the different classification possibilities and the procedures deriving from them, starting from production and going through all the phases until a compliant and marketable material is obtained.

Given the heterogeneity of iron- and steelmaking slags, it was then decided to investigate the state of the art on their production and management at a national and local level, focusing on the Lombardy Region (Italy) and the Province of Brescia

(Italy). This also made it possible to identify the most suitable type of slag for the development of an experimental campaign, the final part of this research.

The aforementioned experimental campaign concerns the reuse of slag from the production of carbon steel in electric arc furnaces (the so-called "*EAFS-C*") as an addition in concrete for structural applications. Specifically, different concrete mixtures with the addition of slag as partial replacement of fine and coarse aggregate (in three different percentages, 10, 25 and 50%) were first designed. These mixtures were then analysed by carrying out tests for material characterisation (rheological and strength properties), with the addition of tests to assess aspects related to the durability of concrete.

SOMMARIO

L'industria siderurgica rappresenta una delle maggiori realtà produttive nel panorama mondiale, con una produzione globale di acciaio in continua crescita negli ultimi vent'anni.

Nonostante le diverse tecniche disponibili, al giorno d'oggi la produzione avviene principalmente mediante due cicli: il "*ciclo integrale*" o il "*ciclo elettrico*", ai quali si aggiungono le successive affinazioni in forno siviera.

Oltre al materiale primario (acciaio), da tutti questi processi si origina anche un ingente quantitativo di materiale secondario, le cosiddette "*scorie di acciaieria*". In ragione del processo produttivo, delle materie prime, delle modalità di gestione del forno, del tipo di acciaio, dei processi di raffreddamento post-scorifica e dei successivi trattamenti, esse si suddividono in diverse tipologie, ciascuna con le proprie caratteristiche chimico-fisiche, mineralogiche e prestazionali.

Il riutilizzo delle scorie di acciaieria in sostituzione delle materie prime naturali in diverse applicazioni apporta notevoli vantaggi sia dal punto di vista economico e sociale che da quello ambientale. Un loro reimpiego contribuisce infatti alla diminuzione dei quantitativi da destinare a smaltimento in discarica nonché alla riduzione dello sfruttamento delle risorse naturali e degli impatti da esso derivanti, sia in termini ambientali che di tutela della biodiversità e del paesaggio.

Per poter però garantire un loro corretto trattamento in previsione di un futuro reimpiego, anche le scorie di acciaieria sono soggette al rispetto di determinati standard normativi. Infatti, a seconda della classificazione, i processi di trattamento, registrazione e le verifiche di conformità risulteranno molto diversi ed una loro conoscenza ed interpretazione saranno quindi fondamentali per la corretta gestione di questo tipo di materiale.

Il presente lavoro di ricerca intende dare un ulteriore contributo alle conoscenze sulle scorie di acciaieria, con un focus completo su produzione, proprietà, classificazione, gestione e riutilizzi finali.

È stata dapprima condotta un'intensa attività di ricerca bibliografica riguardante diverse tipologie di scorie di acciaieria, al fine di approfondire ed analizzare le loro proprietà fisiche, chimiche, mineralogiche, prestazionali ed i relativi aspetti correlati ad un loro eventuale impatto ambientale. Ampio spazio è stato dedicato ai loro possibili riutilizzi, con un focus sul reimpiego nel settore delle costruzioni ed in particolare per la produzione di calcestruzzo.

Verrà poi mostrato un quadro generale ed aggiornato sulla normativa nazionale, analizzando le diverse possibilità di classificazione e gli iter da esse derivanti, partendo dalla produzione ed approfondendo tutte le fasi fino all'ottenimento di un materiale conforme e commercializzabile.

Vista l'eterogeneità delle scorie di acciaieria, è stato poi deciso di indagare lo stato dell'arte sulla loro produzione e gestione a livello nazionale e locale, con focus su

Regione Lombardia (Italia) e Provincia di Brescia (Italia). Ciò ha inoltre permesso di individuare la tipologia di scoria più consona per lo sviluppo di una campagna sperimentale, parte finale della presente ricerca.

La suddetta campagna sperimentale verte sul riutilizzo della scoria derivante dalla produzione di acciaio al carbonio in forno elettrico ad arco (la cosiddetta "*EAFS-C*") come aggiunta nel calcestruzzo per applicazioni strutturali. In particolare, sono state dapprima progettate diverse miscele di calcestruzzo con l'aggiunta di scorie in parziale sostituzione dell'aggregato fine e grossolano naturale, in tre diverse percentuali (10, 25 e 50%). Queste miscele sono poi state analizzate mediante l'esecuzione di test per la caratterizzazione del materiale (proprietà reologiche e di resistenza), con l'aggiunta anche di test per la valutazione di alcuni aspetti legati alla durabilità del calcestruzzo.

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Electric Arc Furnace slag (EAF): use in concrete for structural applications

1. INTRODUCTION

1.1 Statement of problems and aim of the research

Steel production worldwide has increased by about 130% in the last two decades, reaching 1.95 billion tonnes in 2021. Nowadays, steel mills use well-known and standardised processes for the production of pig iron and steel, which differ from each other in terms of the raw materials used, furnace sizes, process timing and management, and final output products. In fact, in addition to the primary material (pig iron or steel), residues, including steelmaking slags, originate from these production processes. Depending on the process considered, they differ in their physical, chemical, mineralogical and mechanical properties and, after appropriate treatment, can be reused in several applications.

In light of the high quantities of slags produced not only globally, but also at national and especially local level, the problem of their management has become of fundamental importance to limit their disposal in landfills (which still unfortunately accounts for around 35–40% of the total amount of slags produced). Interest in the recovery of this type of materials has grown considerably in recent years, also thanks to the creation of synergies between public and private institutions and the direct involvement of the operators in the supply chain in decision-making processes, so as to ensure their proper management and valorisation.

However, the topic of steelmaking slags recovery is very wide-ranging and full of challenges. Firstly, not all types of slags lend themselves to the same reuse; a comprehensive analysis of these materials in all their aspects is therefore necessary to identify the sectors in which they can be reused. Collaborations between producers, treatment plants and research institutions are therefore crucial to increase the knowledge on the topic and to try to increase the amount of material reused in already known applications or to study and develop new areas of reuse.

Secondly, the evolution of the regulatory framework at national level has always allowed for interpretations that are often too subjective, generating uncertainty about the classification, treatment and management of steelmaking slags. Important developments have recently been implemented not only at national level, but also at local level (e.g. the Lombardy Region Council Resolution n. XI/5224 of 13 September 2021, which provides guidelines for the proper reuse of electric arc furnace slag in the Lombardy region), demonstrating the relevance of the topic and the interest that institutions are also showing in it.

In order to be able to reuse these materials in the best possible way, it is then necessary to understand what types of slags are produced on the territory, how they are managed and the sectors in which they are reused. An in-depth analysis of the quantities produced as well as of the classification, treatment, management and reuse methods at local level (carried out not only on the databases made available by public institutions but also by directly involving consortia and operators in the sector), makes it possible to represent a more or less detailed picture of the current situation, starting from the producer and arriving at the final reusers. This makes it possible to identify the types of slags produced and to highlight the benefits and possible critical aspects associated with their reuse, so as to be able to increase the quantities for recovery and reduce those destined for landfills.

Correct reuse of steelmaking slags as a substitute for natural raw materials brings considerable benefits from the environmental, economic and social points of view, making it possible, for example, to reduce the quantities destined for landfill and to limit the exploitation of natural resources, thus reducing the impacts resulting from it (in terms of the environment, atmospheric emissions, protection of biodiversity and the landscape).

In light of this, this PhD Thesis focused on the reuse of slags for the production of structural concrete and is intended as a further contribution to the world of steelmaking slags. An intensive literature review was carried out in order to analyse the different properties of commonly produced slags, also identifying possible applications, with a focus on their reuse for concrete production (highlighting benefits and possible critical aspects).

A detailed legislative framework on the possibilities of classification and management of these materials was then carried out, in order to understand the processes they must undergo and all the regulations they must comply with, so that they can be correctly registered, certified and reused.

The results of the analysis and subsequent processing of data on the production, classification, management, treatment, recovery and disposal of locally produced slags will then be presented, which, together with the results of the literature review, made it possible to identify the type of slag then used for concrete production in the experimental campaign described below.

Finally, as just mentioned, an experimental campaign was carried out at the "*Pietro Pisa*" Materials Testing Laboratory of the University of Brescia on the reuse of electric arc furnace slag from carbon steel production ("*EAFS-C*"), as a partial replacement of fine and coarse natural aggregate in 4 different percentages (0, 10, 25 and 50%), for the production of concrete. The results shown below are in line with those found in the literature and once again confirm the possibility of obtaining structural concretes with good or even better performance than standard reference concrete, in terms of rheology, strength and durability.

1.2 Organisation of the Thesis

The present PhD thesis is divided into six chapters:

Chapter 1 provides a general introduction to the topic of iron and steelmaking slags recovery, the aim of the research and the organisation of the Thesis.

Chapter 2 provides a literature review focusing on the different types of iron and steelmaking slags. The history of modern steelmaking is briefly outlined and all the production processes of pig iron and steel are described in detail. In addition, the types and properties of slags resulting from these processes are illustrated and described, as well as the treatment operations to which they are subjected and the possible recovery applications, with a focus on their reuse for concrete production.

Chapter 3 provides a review of the current state of the art legislation governing the management of iron and steelmaking slags at Italian and European level and describes the different possibilities of slag classification. Based on this, the possible regulatory procedures (treatments, classifications, analysis, registrations, compliance with sector technical standards and CE marking) are then analysed in detail to obtain a marketable product suitable for future reuse.

Chapter 4 provides an overview of iron and steelmaking slags production in Italy, with a focus on the Lombardy region and the province of Brescia. In particular, by means of Material Flow Analysis, the different methods used to analyse and process data from different sources are explained, in order to obtain a detailed and updated representation of local slag production, management, treatment, reuse and disposal.

Chapter 5 presents the results of the experimental campaign carried out on four concrete mixes, in which the natural fine and coarse aggregate was replaced by three different percentages of steelmaking slag (from steel production in electric arc furnace). These results are described and commented on, and the mixes compared to each other to investigate how the addition of slag can affect the behaviour of the concretes in terms of rheological, strength and durability properties.

Chapter 6 summarizes the main conclusions of this PhD thesis.

2. LITERATURE SURVEY

2.1 Introduction

Throughout history, there have been various processes for the production and refining of pig iron and steel, aimed at obtaining an even better product using raw materials of different origins and at the same time limiting the production of so-called "*waste*" materials or finding solutions for their alternative applications.

The use of coal (and metallurgical coke derived from it), for the production of pig iron was the key to the start of the industrial revolution. This technique was probably first used in 1620 in some English forges (*Pensnett Chase* and *Coalbrookdale*). In 1740, Benjamin Huntsman rediscovered the technique of cogwheel steel. In 1750, Abraham Darby II improved the technique of pig iron production with the use of metallurgical coke in the *Horsehay* and *Ketley* ironworks. In 1768, William Hall pioneered the puddling technique for refining pig iron, which was later patented and used in 1784 by Henry Cort in the so-called "*reverberatory furnaces*" [1,2]. The development of the steam engine between the end of the 18th and the beginning of the 19th century enabled the construction of larger rolling mills and hammers. In 1828, the "*hot wind system*" was patented (James Beaumont Neilson), reducing energy and production costs. This system was later implemented and improved by Edward Alfred Cowper in 1857, with the so-called "*Cowper recuperators*", which are still in use today.

The production of steel directly from molten pig iron by blowing air under pressure was first developed by the American William Kelly in 1854 but was not as successful as it should have been in the US market. In 1855, the Englishman Henry Bessmer implemented and patented a similar process, resulting in the "*Bessmer air converter*" (Figure 2-1), which replaced the puddling technique. Bessmer's new technique exploited the reaction of air with pig iron impurities (carbon, manganese and silicon), causing their oxidation and a sudden rise in temperature in the furnace. This process of converting pig iron into steel was thus very cheap and fast, taking less than half an hour for a casting. [1,2].

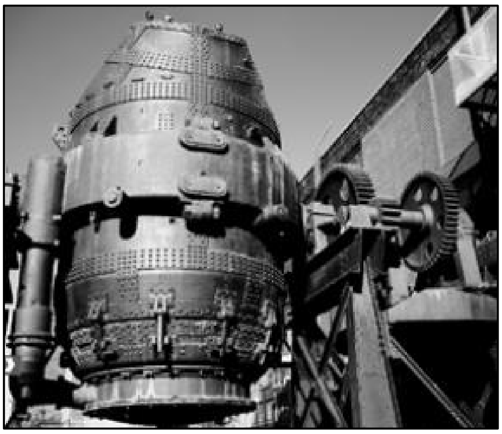


Figure 2-1: Bessmer air converter [2].

An early example of the reuse of "*waste*" material from pig iron production, otherwise destined for disposal, occurred in 1879, when Sidney Gilchrist Thomas perfected the Bessmer process for treating sulphurous cast irons; the slag from this process could be used as fertiliser [1].

Between 1850 and 1857, the German Carl Wilhelm Siemens developed his "*regenerative furnace*", which could generate temperature high enough to melt steel using hot exhaust gases from previous melting. In 1865, the Frenchman Pierre-Emile Martin applied the Siemens's technology and so the "*Martin-Siemens Furnace*" appeared for the first time on an industrial scale. It was an open-hearth process that allowed a more precise temperature control and a better quality of steel, despite requiring slightly longer production times [1,2].

After the World War II, oxygen began to be used instead of air to convert pig iron into steel. This process was already studied by Henry Bessmer in 1858 but was never fully developed due to the high cost and limited availability of pure oxygen. In 1947, the Swiss Robert Durrer took up this concept of converting pig iron into steel by oxygen blowing and shared it with two Austrian companies (based in the cities of Linz and Donawitz). Between 1952 and 1953, the two companies installed the first 30-tonne converters at their sites, which were named "*LD converters*" from the initials of the two cities. This technique of producing steel from the decarburization of the pig iron using pure oxygen (blown from a water-cooled lance lowered from above into the furnace), was then called "*LD process*" or "*Durrer process*". This process, with some adjustments and updates, is now called **BOS** ("***B****asic* ***O****xygen* ***S****teelmaking*") and is the one commonly used for the refining of pig iron and the consequent production of steel, by using a furnace called **BOF** ("***B****asic* ***O****xygen* ***F****urnace*", Figure 2-2). It is worth noting that modern BOF can convert up to 350 tonnes of pig iron into steel in less than 40 minutes [2]. In the 1960s, variants to the process were introduced, using oxygen blowing from below instead of from above, such as the OBM process (or QBOP or "*Quick Basic Oxygen Process*") [1].

Figure 2-2: Basic Oxygen Furnace (BOF) [1].

However, steel is not only produced by decarburizing pig iron, but also in processes that use electricity to melt raw materials of different origins. The first three-phase "*electric indirect arc furnace*" was patented in 1898 by the Italian Ernesto Stassano in Darfo (Italy) and ensured the production of high-quality steel from raw materials consisting of scrap (80%) and pig iron (20%). The technology was soon perfected and implemented in the rest of Europe as well. In fact, in 1899, the Frenchman Paul Luis Héroult realised the first "*electric non-conducting sole furnace*", which used graphite electrodes and three-phase current to melt the charge and produce special steels from scrap remelting. In 1905, the Swiss Paul Girod perfected the "*electric conducting sole furnace*" and combined it with a hydroelectric system, thus initiating electrometallurgy [1].

After the World War I, extensive production of special steels by refining in the "*electric arc furnace*" or "*induction furnace*" began. After the World War II, the increase of the scrap iron and the development of new techniques for its reuse in the steel production cycle allowed the birth of industries equipped with the so-called **EAF** ("***E****lectric* ***A****rc* ***F****urnace*"), Figure 2-3, which guaranteed high and efficient production. Over the years, the continuous study and refinement of production techniques made it possible to move from average furnace sizes of 25–30 tonnes per casting and production times of about 3–3.5 hours per cycle to furnaces of 70–100 (even 300 in some cases) tonnes and production times less than 1 hour per cycle [1].

Figure 2-3: Electric Arc Furnace (EAF) [2].

Steel produced by means of BOF converters and EAF furnaces is already of excellent quality, but continuous technological progress has made it possible to obtain even better steels with all the properties required by the customed, through the so-called "*out-of-furnace treatments*", carried out in a furnace called **LF** ("***L**adle* ***F**urnace*", Figure 2-4) [1].

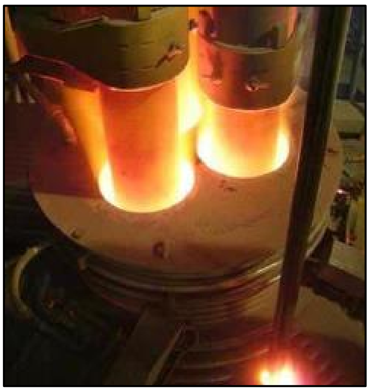


Figure 2-4: Ladle Furnace (LF) [1].

Nowadays, the production and refining of steel (and the consequent production of secondary materials, the so-called "*steelmaking slags*" or simply "***slags***") take place by means of two main different processes: the "***integral cycle***" and the "***electric cycle***". Depending on the geographical area considered, there may be a wider use of one process than the other. Consider Italy as an example, which, compared to other European countries, anticipated the transition from integral to electric cycle between the end of the 20th and the beginning of the 21st century. At that time, the production sites adopting the integral cycle were all publicly owned and therefore

more concerned with employment and size than profitability. On the other hand, private capital preferred the management of production sites adopting the electric cycle, as this was a simpler and more flexible option. In addition to management, other factors that historically have ensured the rise of EAF technology have been the scarcity of raw materials on Italian territory for the supply of blast furnaces and the need to invest in the construction of new and massive infrastructures to guarantee their retrieval and transportation to the production sites [3].
Detailed descriptions of integral cycle and electric cycle can be found in the following paragraphs.

2.2 *Steel production processes: Integral Cycle*

The Figure 2-5 shows the two main phases of the integral cycle. Firstly, operations are performed in a furnace called "*Blast Furnace*" (**BF**), starting with selected raw materials and resulting in the production of pig iron (and secondary materials). The pig iron will then be refined in a "*Basic Oxygen Furnace*" (**BOF**) in the second stage of the process, resulting in its transformation into steel. The steel produced can then be further refined through secondary operations and/or additions in a "*Ladle Furnace*" (**LF**) to be then destined for plastic processing (casting, rolling, etc.) [1,4].

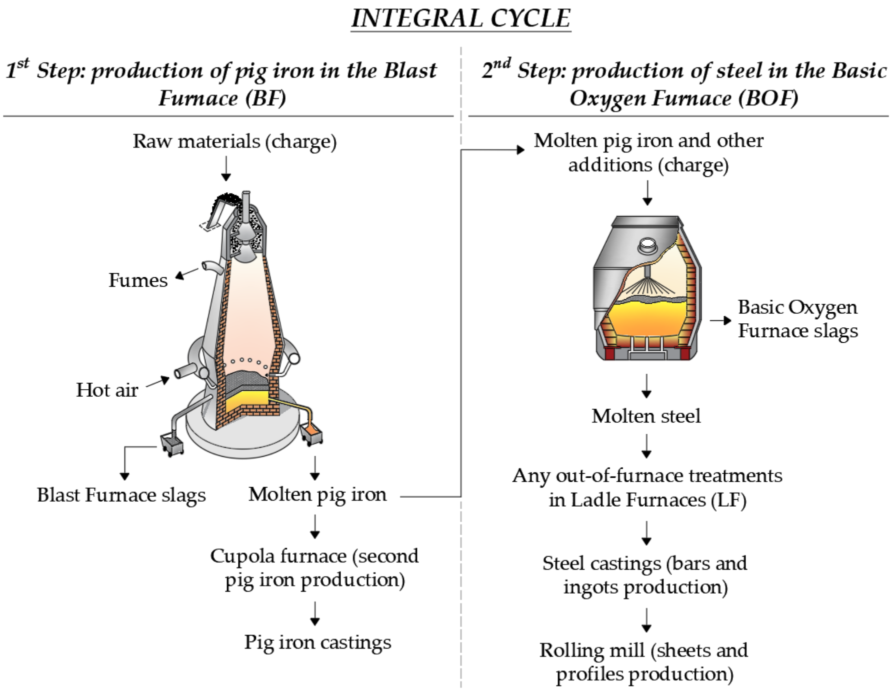


Figure 2-5: Summary of the two main phases of the integral cycle (adapted from [4]).

2.2.1 Blast Furnace ("BF")

2.2.1.1 Pig iron and Blast Furnace Slag ("BFS") production process

The modern steel plant equipped with a blast furnace (briefly illustrated in Figure 2-6, adapted from [1]) is usually located close to a harbour, for easier handling of raw material traffic and outgoing products and must also include a steel mill with a BOF furnace for the conversion of pig iron into steel (second step of the integral cycle). Around the blast furnace, there are areas destined for the storage and preparation of raw materials, as well as components and systems required for the correct working of the blast furnace itself (conveyor belts for the charge up to the upper opening of the blast furnace, gas capture and purification system and Cowper recuperators for the pre-heating of the air that will then feed the blast furnace, using the hot gases collected and coming from blast furnace itself) [5].

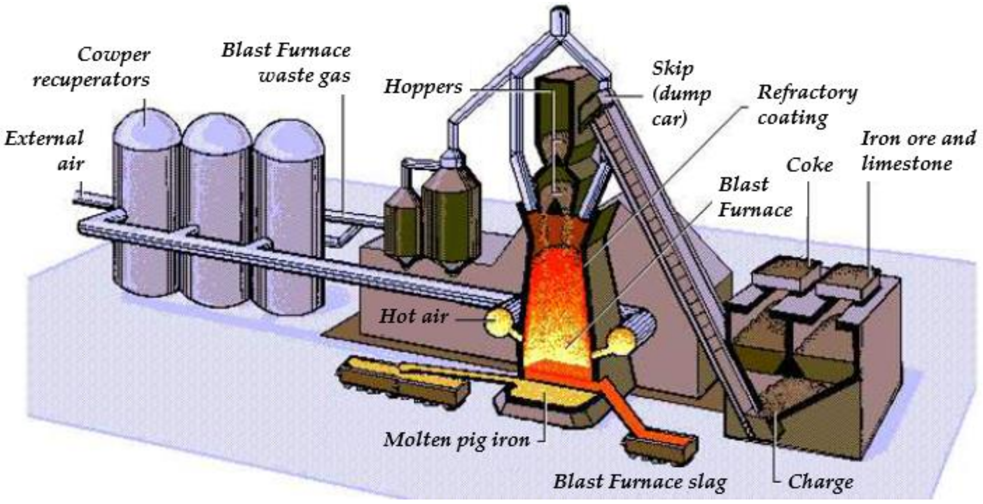


Figure 2-6: Simple representation of the main elements of a steel plant equipped with a blast furnace (adapted from [1]).

Pig iron is an iron-carbon alloy with a relatively high carbon content (2.06% < C < 6.67%). In addition to carbon, it contains other elements that characterize its composition and properties (mainly silicon, manganese, phosphorous and sulphur) [5]. In fact, its chemical composition and properties will depend mainly on the characteristics of the raw materials feeding the blast furnace, the process temperatures and the amount of secondary materials (slags) formed. The blast furnace charge consists mainly of **iron ore**. Among the most important of these are haematite (or "*ferric oxide*", weakly magnetic, crystalline and lamellar in shape), magnetite (or "*ferrous-ferric oxide*", with strong magnetic properties, a brown colour and octahedral crystal structure), goethite, hydrogoethite and limonite, which form a group of hydroxides with highly variable composition, siderite (iron-poor but very pure mineral) and ilmenite (titaniferous mineral) [5].

However, these so-called "*ferrous*" minerals are not completely pure. In fact, in addition to the ferrous component, silicates (coexisting with ferrous minerals, carbonates and hydroxides) and oxides, mainly silica (SiO_2), alumina (Al_2O_3), lime (CaO) and magnesia (MgO), which are not reduced during the mining processes and will go to form the so-called ***B****last* ***F****urnace* ***S****lags* ("***BFS***", described in detail in the following sub-section), may also be present in the deposits in variable quantities. Given the relatively heterogeneous nature of the minerals constituting the charge, it is evident that the chemical formulations in the theory must be used with care, since they refer to so-called "*pure*" compounds. In fact, in all minerals from mining, there is a lower than theoretical iron content is found due to "*dilution by crystalline isomorphism*" with other mineralogical species or non-ferrous elements [5]. To deal with this problem, minerals usually undergo "treatment and enrichment processes", which can be caried out either at mining sites (fines enrichments and pelletisation processes) or at steel plants (fines agglomeration and chemical homogenisation processes) [5].

Another fundamental constituent of the blast furnace charge is **coke**, whose carbon contributes to providing the necessary heat for the reduction and melting processes, as well as the formation of pig iron and blast furnace slag. It also acts as a permeable support (allowing gas, slag and molten steel to pass through while supporting the charge), as a reductant (generating carbon monoxide for the reduction process) and contributes to carburizing the iron to the final content found in the pig iron [5].

In Italy, there are no suitable mineral resources to deal with the high demand for raw materials in the steel industry, consequently, all the iron ore and coke used are imported, with the latter being the most expensive of all the blast furnace feed materials. Over the years, efforts have been made to reduce the blast furnace reliance on coke as much as possible, as the coke-making process is expensive and highly polluting. The easiest way to reduce the amount of coke is to inject pulverised coal in the blast furnace (at the level of the tubes), but it saves up to about 40% of the coke, with a savings rate of 100% being practically impossible to achieve [5].

In addition to iron ore and coke, which are necessary for the production of pig iron, other materials are also charged in the blast furnace, with the main function of correcting the quantity and the chemical composition of the blast furnace slag. These materials are **limestone**, **dolomite** and **quartzite** and are commonly identified as "*fluxes*" or "*correctives*" [5].

Figure 2-7 (adapted from [5,6,7]) shows a schematic representation of a blast furnace divided into sections and illustrates the main reactions that take place inside it for the production of pig iron and slag.

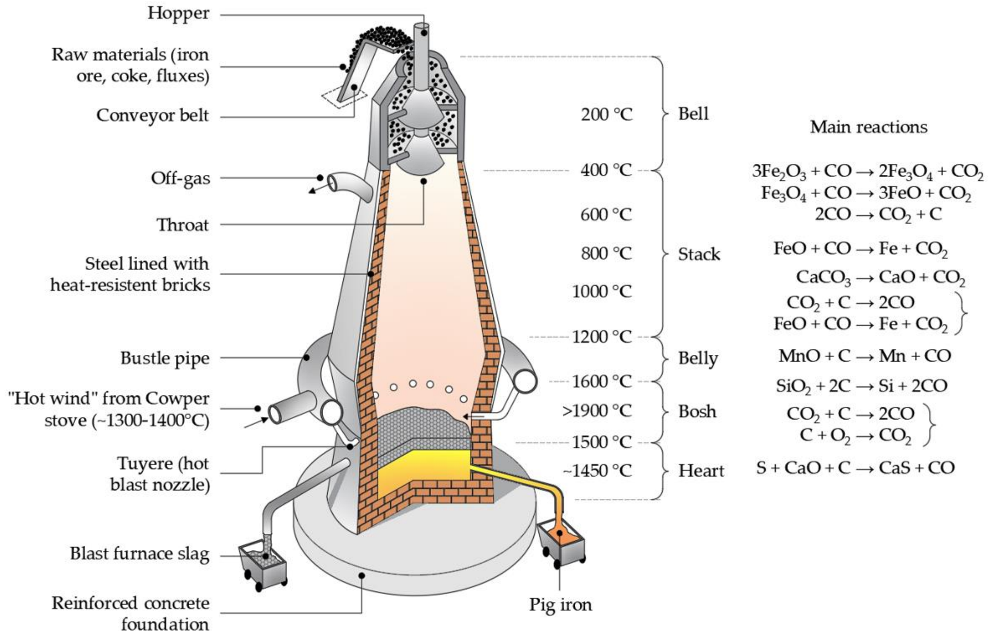


Figure 2-7: Schematic representation of a blast furnace (adapted from [5,6,7]).

In particular, the blast furnace can be divided into five different regions (from top to bottom: "***mobile bells***", "***stack***" (in turn divided into upper and lower region), "***belly***", "***bosh***" and "***heart***"), each used for different processes and characterised by increasing temperatures [5]. The main reactions occurring in the blast furnace and leading to the formation of pig iron and slag are briefly explained below.

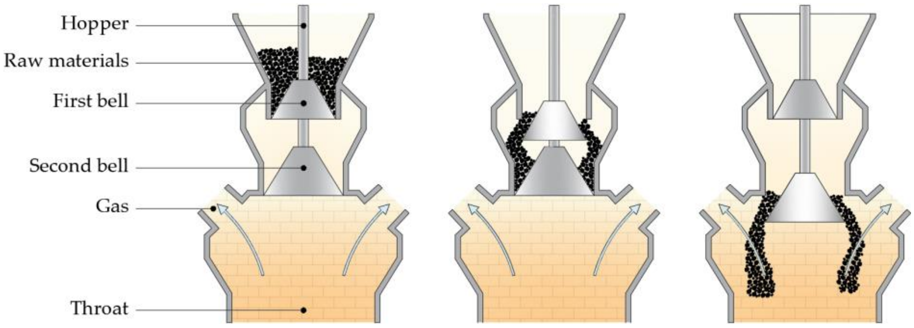
At the "*combustion region*", located in the lower part of the "*bosh*", the air preheated by the Cowper recuperators enters the blast furnace at temperature of approximately 1300–1400°C, thus contributing to the achievement of the maximum temperatures in the furnace (1800–2000°C). The oxygen (O_2) contained in the preheated air, in contact with the carbon (C) present in the coke, leads to the formation of carbon dioxide (CO_2), according to the reaction [5]:

$$C + O_2 \rightarrow CO_2 \tag{2-1}$$

Once this combustion reaction has taken place, the coke ash moves into solution and contributes to the formation of the slag. Moving upwards, the carbon dioxide (CO_2), in presence of any excess carbon (C), gives rise to carbon monoxide (CO), according to the reaction:

$$CO_2 + C \rightarrow 2CO \tag{2-2}$$

Meanwhile, in the "*mobile bells*" region, characterised by temperatures of up to 400°C, the loading of raw materials from above (transported by conveyor belts) and the capture of gases ascending the blast furnace take place simultaneously. The double bell closure system (Figure 2-8) ensures a process without gas losses to the atmosphere. Firstly, the charge is fed from above (Figure 2-8(a)). Subsequently, the first bell is lowered and the charge moves into the second chamber (Figure 2-8(b)). Finally, the first bell returns to its initial position and the second bell is lowered to allow the charge to enter the blast furnace (Figure 2-8(c). A small part of the gases will then be trapped between the first and the second bell and will be released into the atmosphere when the first bell is lowered for the next charge [5].



(a) (b) (c)

Figure 2-8: Schematic representation of the double bell closure system (adapted from [5]). .

The raw materials then enter the blast furnace and comes into contact with ascending gases in the upper region of the "*stack*". The latter are injected at the level of the "*tuyere*" (hot blast nozzle, Figure 2-7) and initially consist of carbon monoxide (CO) and nitrogen (N_2) and then enriched with carbon dioxide (CO_2) and a small amount of hydrogen (H_2), resulting from the combustion reactions of the coke with the incoming "*hot wind*" from the Cowper recuperators, as described above. The formation of hydrogen (H_2) is essentially due to the decomposition of the combined water if the raw materials in the lower region of the "*stack*", according to the reaction [5]:

$$H_2O + C \rightarrow H_2 + CO \tag{2-3}$$

The contact between raw materials and ascending gases in the upper region of the "*stack*" causes an initial loss of water and moisture in the charge. Once 400°C has been reached, the reduction reactions of the iron oxides (Fe_2O_3, Fe_3O_4, FeO) operated by the carbon monoxide (CO) contained in the ascending gases begin, with the consequent production of carbon dioxide (CO_2) and possible carbon deposit (C), according to the following reactions [5,7]:

$$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2 \tag{2-4}$$

$$Fe_3O_4 + CO \rightarrow 3FeO + CO_2 \tag{2-5}$$

$$FeO + CO \rightarrow Fe + CO_2 \tag{2-6}$$

The reduced part (Fe) melts and deposits in the "*heart*" of the blast furnace, contributing to the formation of pig iron.

Once the reduction reactions have taken place, the charge passes into the lower region of the "*stack*", characterised by temperatures ranging between 800 and 1000°C. At 800°C, the decomposition of the carbonates ($CaCO_3$) in the charge begins, according to the reaction [5]:

$$CaCO_3 \rightarrow CaO + CO_2 \tag{2-7}$$

At 900–1000°C, the carbon dioxide (CO_2) produced by these reactions contributes to the "gasification" of carbon (C), resulting in the formation of carbon monoxide (CO), according to the reaction [5]:

$$CO_2 + C \rightarrow 2CO \tag{2-8}$$

Once these reactions have taken place, there will be material in the lower region of the "*stack*" consisting of a mixture of coke, iron sponge, parts of unreduced ore, gangue (i.e. the impurities contained in the iron ores) and quicklime (CaO).

The formation of the first liquid pig iron and slag occurs when the materials reach the "*bosh*". Specifically, the following processes take place in the "*bosh*" [5]:

- Remelting of materials, with the exception of coke);
- Combination of the quicklime (CaO) with parts of the gangue and oxides (mainly FeO and MnO) that have not been reduced yet and subsequent formation of the first "***liquid slag***";
- Completion of the reduction of iron oxides;
- Continuation of the reduction of the phosphorus and manganese oxides (P_2O_5 and MnO, respectively) and possible beginning of the reduction of silica (SiO_2), according to the reactions:

  $$P_2O_5 + 5C \rightarrow P_2 + 5CO \tag{2-9}$$

  $$MnO + C \rightarrow Mn + CO \tag{2-10}$$

  $$SiO_2 + 2C \rightarrow Si + 2CO \tag{2-11}$$

- Carburization of reduced iron (Fe), which passes to a liquid state and brings other reduced elements into solution, thus forming the first "***liquid pig iron***". Carburization takes place according to the reactions:

  $$3Fe + 2CO \rightarrow Fe_3C + CO_2 \tag{2-12}$$

  $$3Fe + C \rightarrow Fe_3C \text{ (carburization by direct coke reaction)} \tag{2-13}$$

Once the first liquid pig iron and slag are formed, they drip downwards filling the blast furnace "*heart*". The liquid slag has a lower density than the liquid pig iron ($\rho_{pig\ iron} \sim 70\ kN/m^3$; $\rho_{slag} \sim 27\ kN/m^3$) and settles on top of the latter, making contact. The pig iron, which is formed continuously in the blast furnace, must pass through the slag layer to decant and collect at the bottom of the "*heart*". Thanks to the high temperatures and the kinetics of the exchanges that take place between pig iron and slag, there is an almost complete removal of residual oxygen, the start of the pig iron desulphurisation reactions (carried out by manganese and lime) and the absorption of unwanted impurities into the pig iron. These processes contribute to the final chemical composition of the pig iron [5].

In practice, a modern blast furnace is 30–40 m high, has a "belly" diameter of about 15m and an internal volume of about 5000 m^3. The charge consists of 1.5–1.7 tonnes of raw materials, 270–300 kg of coke, 150–200 kg of coke coal powder injected at the "tuyere" and about 900 m^3 of hot air [5,8]. The pig iron is usually tapped at a temperature of about 1450°C, intermittently every 30–60 minutes, and generally has a chemical composition of Fe and other minor elements (4.5% C, 0.6% Si and Mn, 0.1% S and P [5]). It can be cast in ingot moulds or shells to form "*ingots*" for subsequent remelting in other plants or loaded into "*torpedo ladles cars*" for subsequent refining for steel production [1].

For each tonne of pig iron, approximately **250–300 kg of blast furnace slag** is produced [6]. It is tapped in small quantities in order to be chemically analysed and, if it fulfils the requirements, it is tapped at regular intervals, cooled, treated and destined for different reuses (further discussed in the following paragraph).

2.2.1.2 Blast Furnace Slag ("BFS"): types, properties and possible reuses

Once all the reactions described in the previous paragraph have taken place, the liquid blast furnace slag is deposited on the pig iron bath due to its lower density. Small quantities of liquid slag are taken for analysis. If the characteristics of the slag meet the company's production standards, it is tapped and subjected to cooling and subsequent treatments to make it suitable for future reuse in various applications. These processes result in slag with very different properties. Table 2-1, Table 2-2, Table 2-3 and Table 2-4 show the four different types of slag obtainable from the production of pig iron in the blast furnace. The cooling processes, common treatments and main fields of reuse are briefly described [6,9,10,11,12].

Table 2-1: Granulated Blast Furnace Slag (“GBFS”) [6,9,10].

Granulated Blast Furnace Slag (“GBFS”)	
Cooling process	Quick cooling with high pressure, high volume and cold water sprays in a specialised plant (“*granulator*”)
Material aspect	Amorphous, vitrified and coarse material with hydraulic cementitious properties
Common treatments	Grinding to powder (< 100 μm) to produce ***G**round **G**ranulated Blast **F**urnace **S**lag* (“***GGBFS***”) or addition of ground Portland cement clinker
Common reuses	• *As aggregate for* bituminous and hydraulically bound mixtures (asphalt, concrete, road binder, etc.), unbound mixtures, production of GGBFS, ground stabilisation, embankment and fills, sand blasting • *For the manufacture of* cement, concrete (as GGBFS), fertilizer, glass (blended with other components), stone wool

Figure 2-9: Granulated Blast Furnace Slag (“GBFS”) [9].

Table 2-2: Ground Granulated Blast Furnace Slag (“GBFS”) [6,9,10].

Ground Granulated Blast Furnace Slag (“GGBFS”)	
Cooling process	Quick cooling with high pressure, high volume and cold water sprays in a specialised plant (“*granulator*”)
Material aspect	Amorphous, vitrified and coarse material with hydraulic cementitious properties
Common treatments	This slag is the GBFS when crushed or milled to cement fineness. It becomes a cementitious binder in the presence of an activator
Common reuses	Slag blended with cement for concrete production, direct supplementary cementitious material added in concrete

Figure 2-10: Ground Granulated Blast Furnace Slag (“GGBFS”) [9].

Table 2-3: Air-cooled Blast Furnace Slag ("ABFS") or Rock Slag [6,9,10].

Air-cooled Blast Furnace Slag ("ABFS") or Rock Slag	
Cooling process	Slow cooling with air in slag pits located near the furnace
Material aspect	Crystalline rock-like material with comparable properties and similar reuse applications as the conventional quarry products
Common treatments	Crushing, sieving and grading to produce aggregates or grinding to powdered material (< 300 μm)
Common reuses	• *As aggregate for* bituminous and hydraulically bound mixtures (asphalt, concrete, road binder, etc.), unbound mixtures, ground stabilisation, embankment and fills, railway ballast, wastewater treatment, gabions • *For the manufacture of* fertilizer, glass (blended with other components), stone wool

Figure 2-11: Air-cooled Blast Furnace Slag ("ABFS") or Rock Slag [9].

Table 2-4: Pelletised Blast Furnace Slag ("PBFS") [6,12].

Pelletised Blast Furnace Slag ("PBFS")(*)	
Cooling process	Production of pellets instead of solid mass by cooling and solidification with water and quenching in air in a rotating drum
Material aspect	By controlling the process: • Pellets with crystalline structure (advantageous for use as aggregates) • Pellets with glassy structure (advantageous in cement applications) Faster quenching results in more vitrification and less crystallisation
Common treatments	• Grinding to powder (< 10 mm) and addition of ground Portland cement clinker • Crushing, sieving and grading (> 10 mm)
Common reuses	Portland slag cements and Blast Furnace Slag cements, lightweight aggregates, concrete

(*) *From 2000 to 2010, the range of PBFS production in Europe was between 1 and 2% of the total Blast Furnace Slags produced. Since 2010, PBFS is no longer produced in Europe.*

Table 2-5: Expanded or Foamed Blast Furnace Slag [11,12].

Expanded or Foamed Blast Furnace Slag	
Cooling process	Accelerated cooling and solidification process by adding controlled amounts of water, air or steam
Material aspect	Light weight slag of expanded and cellular nature (distinguished from ABFS by its relatively high porosity and low bulk density)
Common reuses	Lightweight aggregate for Portland cement concrete

(*) *The production of Expanded or Foamed Blast Furnace Slag has almost completely been replaced by the pelletised procedure for pelletised slag production.*

Table 2-6, Table 2-7 and Table 2-8 summarise the main **physical properties** of Blast Furnace Slag, in particular those of "*GBS*", "*GGBS*" and "*ABFS*".

Table 2-6: Granulated Blast Furnace Slag ("GBFS") physical properties.

Granulated Blast Furnace Slag ("GBFS") physical properties			
Property	**Units**	**Values**	**References**
Density	[kg/m^3]	2800–3100	[8,13,14]
Apparent density	[kg/m^3]	2000–2850	[8]
Bulk density	[kg/m^3]	0.700–1450	[8,15]
Porosity	[%]	2.10–31.00	[8,13,16]
Glass content	[%]	60.40–100	[8,14,15,17]

Table 2-7: Ground Granulated Blast Furnace Slag ("GGBFS") physical properties.

Ground Granulated Blast Furnace Slag ("GGBFS") physical properties			
Property	**Units**	**Values**	**References**
Dimension	[mm]	< 0.063	[18,19]
Density	[kg/m^3]	2780–2950	[18,20,21,22,23,24,25]
Specific surface	[cm^2/g]	3900–5700	[18,20,21,22,23,26,27]
Fineness modulus	[-]	3.35	[28]
Blaine fineness	[cm^2/g]	3800–4690	[24,29]
Loss on ignition (LOI)(*)	[%]	0.42–1.20	[23,24,27,29,30,31]

(*) *Property that typically accompanies the chemical composition of the slag, shown in this table for a better comprehension*

Table 2-8: Air-cooled Blast Furnace Slag ("ABFS") or Rock Slag physical properties.

Air-cooled Blast Furnace Slag ("ABFS") or Rock Slag physical properties			
Property	**Units**	**Values**	**References**
Dimension	[mm]	0.00–31.50	[32,33,34,35,36,37]
Bulk density	[kg/m^3]	1220–1720	[15,32,33,35,36]
Specific density	[kg/m^3]	2000–3130	[12,15,32,33,34,35,37]
Fineness modulus	[-]	2.80–7.00	[32,33,35,37]
Water absorption	[%]	0.35–8.90	[12,15,32,33,34,35,36,37]
Loss on ignition (LOI)(*)	[%]	1.01–3.00	[15,31,34,37]
Glass content	[%]	40.61–46.14	[15]

(*) *Property that typically accompanies the chemical composition of the slag, shown in this table for a better comprehension*

Over the years, methodologies for the production of Pelletised Blast Furnace Slag ("*PBFS*") and "*Expanded or Foamed Blast Furnace Slag*" have been gradually abandoned due to the continuous upgrading and improvement of production processes. As a result, there is limited material available in the literature that can fully describe their properties. However, some physical properties of these two types of slag are given below (Table 2-9 and Table 2-10).

Table 2-9: Pelletised Blast Furnace Slag ("PBFS") physical properties.

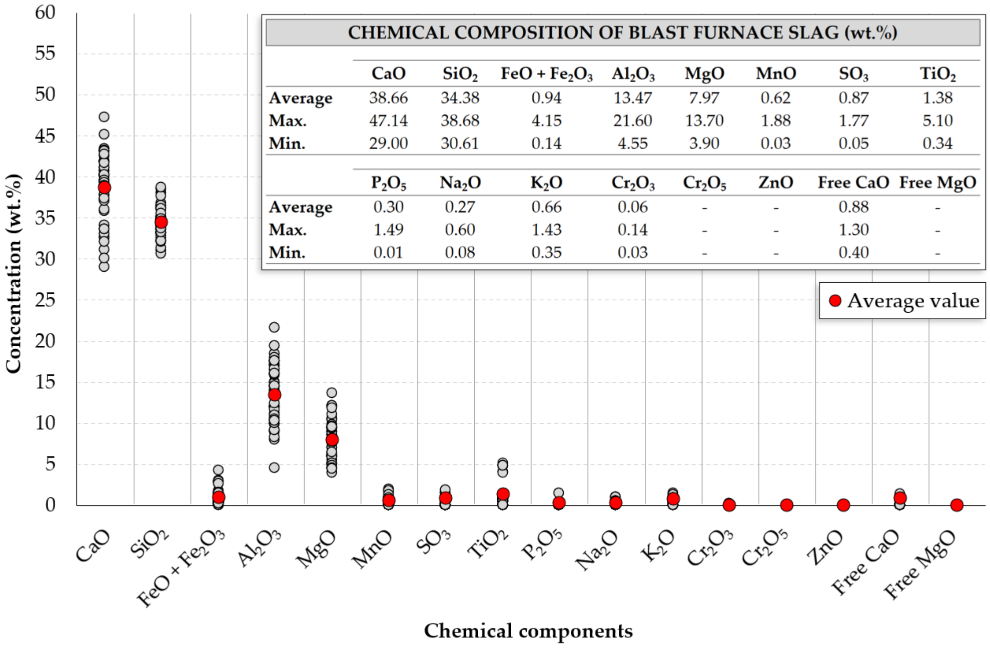
Pelletised Blast Furnace Slag ("PBFS") physical properties			
Property	**Units**	**Values**	**References**
Dimension	[mm]	0.10–20.00	[12,17,38]
Compacted unit weight	[kg/m^3]	840	[12,38]
Shape	[-]	Round / spheric	[12,17,38]
Surface	[-]	Smooth / sealed	[12,38]

Table 2-10: Expanded or Foamed Blast Furnace Slag physical properties.

Expanded or Foamed Blast Furnace Slag physical properties			
Property	**Units**	**Values**	**References**
Compacted unit weight	[kg/m^3]	720–1040	[12,38]
Shape	[-]	Angular / roughly cubical	[12]

The Figure 2-12 shows the typical **chemical composition** of Blast Furnace Slag, in particular "*GBFS*", "*GGBFS*", "*ABFS*" and "*PBFS*". No studies concerning possible differences in the chemical composition of *Expanded or Foamed Blast Furnace Slag* were found in the literature. For better understanding, the graph is accompanied by a table in which the minimum, maximum and average values are indicated for each component (the average value is also marked by a red dot on the graph). From each paper consulted, the chemical compositions of the slag used were obtained, represented by the grey dots in the graph [13–15,17,18,20–24,26,27,29–32,34,36,37,39,40,41].

From a comparison, it can be seen that calcium oxide (CaO), silica (SiO_2) and alumina (Al_2O_3) are the main components of the blast furnace slag, about 85% by weight (wt.%) summing up the average values. There are also important concentrations of magnesium oxide (MgO). Other elements are present in very low concentrations, due to both the already low concentration in the raw materials and the reactions that take place in the blast furnace (see Subsection 2.2.1.1). Some of these are the ferrous and ferric oxides (FeO and Fe_2O_3), manganese oxide (MnO), sulphuric anhydride (SO_3), titanium dioxide (TiO_2), phosphoric anhydride (P_2O_5), sodium oxide (Na_2O) and potassium oxide (K_2O), dichromium trioxide (Cr_2O_3) and some traced of free calcium oxide (free CaO).



CHEMICAL COMPOSITION OF BLAST FURNACE SLAG (wt.%)

	CaO	SiO_2	FeO + Fe_2O_3	Al_2O_3	MgO	MnO	SO_3	TiO_2
Average	38.66	34.38	0.94	13.47	7.97	0.62	0.87	1.38
Max.	47.14	38.68	4.15	21.60	13.70	1.88	1.77	5.10
Min.	29.00	30.61	0.14	4.55	3.90	0.03	0.05	0.34

	P_2O_5	Na_2O	K_2O	Cr_2O_3	Cr_2O_5	ZnO	Free CaO	Free MgO
Average	0.30	0.27	0.66	0.06	-	-	0.88	-
Max.	1.49	0.60	1.43	0.14	-	-	1.30	-
Min.	0.01	0.08	0.35	0.03	-	-	0.40	-

Figure 2-12: Chemical composition of Blast Furnace Slag [13–15,17,18,20–24,26,27,29–32,34,36,37,39–41].

With regard to **mineralogical properties**, the main constituents of Blast Furnace Slag are shown in Table 2-11.

Table 2-11: Mineral constituents of Blast Furnace Slag.

Constituent	Formula	References
Gehlenite	$Ca_2Al_2SiO_7$	[14,15,17,39]
Akermanite	$Ca_2MgSi_2O_7$	[15,17,31,39]
Melilite(*)	$(Ca,Na)_2(Al,Mg,Fe++)(Si,Al)_2O_7$	[15,17,31]
Merwinite	$Ca_3Mg(SiO_4)_2$	
Belite (dicalcium silicate)	C_2S (or Ca_2SiO_4)	[15]
Spinel	$MgAl_2O_4$	
Isolated crystals of Oldhamite	$Ca_{0.9}Mg_{0.05}Fe^{2+}_{0.05}S$	[17]
Minor constituents:		[15]
• Monticellite	$CaMgSiO_4$	
• Rankinite	$Ca_3Si_2O_7$	
• Wollastonite	$CaSiO_3$	
• Forsterite	$Mg_2(SiO_4)$	
For “*GBFS*”, presence of amorphous and glassy phases, with crystalline structures mostly isolated and in percentages varying from 8 to 30%		[15,17,39]

(*) *Complete solid solution consisting of gehlenite and akermanite.*

The mineralogical composition of slag can change if it is treated for research purposes or to make it suitable for future reuses. For example, in [31], the Authors used mechanical activation processes on “*GGBFS*” and “*ABFS*” and changes in crystallinity were monitored by XRD analysis. The non-mechanically treated “*ABFS*” contained akermanite, melilite and merwinite in crystalline form. The application of a ball milling process led to a partial destruction in akermanite and melilite. Analysis of alkali-activated pastes based on “*GGBFS*” and “*ABFS*” (the latter mechanically activated) revealed a formation of the aluminate-substituted calcium silicate hydrate (“*CASH*”) and this structure was also detected in both sodium silicate-activated slags. Much attention must therefore be given to the treatment processes and how these can change the internal structure of the material, making it more or less suitable for a particular application.

2.2.1.3 Blast Furnace Slag (“BFS”): reuse for concrete production

As described in the previous section, depending on the raw materials, the operation of the plant, the cooling process and the planned treatments, different types of slag can be obtained from the blast furnace, each with its own physical, mineralogical and performance characteristics, to be destined for very different fields of reuse.

Among the many applications (Table 2-1, Table 2-2, Table 2-3, Table 2-4 and Table 2-5), this section will examine the one in which blast furnace slag is used as a partial or total replacement of binder, fine and/or coarse aggregate in concrete production.

There are many positive factors due to the use of iron and steel slags in the construction sector, particularly as alternative materials in the production of cement and as substitutes for cement and natural aggregates for the production of concrete. By looking at the data available in the literature, a strong increase in cement production and consumption worldwide can be seen in recent years (approximately 4.28 billion tonnes produced [42] and 4.14 billion tonnes consumed [43] in 2020). Depending on the source considered, the estimate of atmospheric carbon dioxide (CO_2) emissions per tonne of cement produced may vary (e.g. the IEA estimates 0.50–0.60 tCO_2/t cement [42] while the GNR estimates 0.60 – 0.70 tCO_2/t cement [44]). Without going into too much detail, a purely indicative value of total CO_2 emissions from cement production worldwide can be obtained by multiplying the total cement production by an average emission value per tonne of cement produced (remember that contributions from electricity, transport, etc. must also be considered). The result is approximately 2.5 billion tonnes of CO_2 emitted annually (purely indicative estimation), which represents around 8% of the world's total CO_2 production (also confirmed by [45]). The use of iron and steel slags as a partial or total replacement of cement in concrete production would lead to a reduction in cement production, thus reducing CO_2 emissions [6].

The scarcity of raw materials extracted from quarries and the continuous increase in demand of natural aggregates for concrete production are causing a crisis in the mining sector. Considering that aggregates constitute about 70–75% of the weight of the concrete mix, the reuse of iron and steel slags would ensure a reduction in the demand of natural raw materials, also in light of the large quantities of concrete produced worldwide (estimated in about 32 billion tonnes) [6,45].

Greater reuse of iron and steel slags would also bring important benefits from an environmental point of view. In fact, there would be less quantities of slags destined for landfill disposal, with a consequent reduction in the space occupied by the latter and less risk of possible release of contaminants in the case of open-air storage [6].

In Table 2-12, the rheological, performance and durability properties of the **N**ormal **S**trength **C**oncrete ("***NSC***") with the addition of blast furnace slag will be analysed, in order to understand how the addition of slag can affect the behaviour of the concrete mix itself when compared with a reference concrete (i.e. without slag).

*Table 2-12: Behaviour of the **N**ormal **S**trength **C**oncrete ("**NSC**") made with Blast Furnace Slag ("BFS") as a partial or total replacement of binder, fine and/or coarse aggregate compared to the reference concrete (without the addition of slag).*

Slag	**Used as**	**Property:** ***Workability***	**Ref.**
GBFS	Binder / Fine aggregate	• Comparable	[13]
GGBFS	Binder	• Comparable	[18]
GGBFS	Binder	• Comparable or slightly higher	[20]
GGBFS	Binder	• Higher	[22]
GGBFS	Binder	• Higher	[25]
GGBFS	Binder	• Comparable (maintained)	[30]
ABFS	Fine aggregate	• Comparable	[32]
ABFS	Fine / Coarse aggregate	• Comparable, thanks to the addition of a superplasticizer	[35]
GGBFS	Binder	• Significant increase and less loss over time	[46]
GGBFS	Binder	• Higher slump at higher GGBFS contents	[47]
GGBFS	Binder	• Comparable	[48]
GBFS	Coarse aggregate	• Lower (natural aggregates fully replaced)	[49]

Slag	**Used as**	**Property:** ***Air content***	**Ref.**
GBFS	Binder / Fine aggregate	• Comparable	[13]
GGBFS	Binder	• Comparable	[20]
GGBFS	Binder	• Comparable	[48]

Slag	**Used as**	**Property:** ***Density***	**Ref.**
GGBFS	Binder	• Very similar	[19]
GGBFS	Binder	• Lower	[22]
ABFS	Fine aggregate	• Comparable	[32]
GGBFS	Binder	• Comparable	[48]
GBFS	Coarse aggregate	• Lower (natural aggregates fully replaced)	[49]

Slag	**Used as**	**Property:** ***Initial and final setting times***	**Ref.**
GGBFS	Binder	• Both higher	[20]

Table 2-12: Cont.

Slag	**Used as**	**Property:** ***Development of the strength***	**Ref.**
GBFS	Fine aggregate	• Slower for early age, faster after	[11]
GBFS	Binder / Fine aggregate	• Slower	[13]
GGBFS	Binder	• Slower	[19]
GGBFS	Binder	• Slower • The addition of gypsum accelerated the strength development	[20]
GGBFS	Binder	• Faster since early age	[22]
ABFS	Fine aggregate	• Slower (stabilization after 90 days)	[32]
GGBFS	Binder	• Slower	[47]
GGBFS	Binder	• Slightly slower	[48]

Slag	**Used as**	**Property:** ***Compressive strength***	**Ref.**
GBFS	Fine aggregate	• Slightly lower at early age, similar at 28 days, higher at 56 days • The best mix is the one with 50% slag–natural aggregates substitution	[11]
GBFS	Binder / Fine aggregate	• Lower at 7 days, similar at 28 days, higher at 56 days	[13]
GGBFS	Binder	• Higher due to the high SiO_2 content of the slag (increased pozzolanic properties of the mixes) • Slag with low SiO_2 content is responsible for high compressive strength losses	[18]
GGBFS	Binder	• Lower in the first days, equal at 7 day, higher after • Low SiO_2 content is the cause of lower strengths	[19]
GGBFS	Binder	• Lower at early age, higher after	[20]
GGBFS	Binder	• Lower • Decreased with the increasing of GGBFS replacement percentage	[25]
GGBFS	Binder	• Lower compared to the control mix, but higher with the addition of 7% of lime, compared to other GGBFS + lime mixes	[30]
ABFS	Fine aggregate	• Comparable for the mix with 100% of ABFS • Lower for the mix with 72% of ABFS	[32]
GGBFS	Binder	• Lower at early age, higher after • 50% is the maximum replacement percentage without strength reductions	[47]

Table 2-12: Cont.

Slag	**Used as**	**Property:** ***Compressive strength*** **(cont.)**	**Ref.**
GGBFS	Binder	• Lower • Decreased with the increasing of GGBFS replacement percentage	[48]
GBFS	Coarse aggregate	• Slightly lower (natural aggregates fully replaced)	[49]

Slag	**Used as**	**Property:** ***Flexural strength***	**Ref.**
GGBFS	Binder	• Lower at 28 days, higher after 90 days	[19]
GGBFS	Binder	• Lower compared to the control mix, but higher with the addition of 7% of lime, compared to other GGBFS + lime mixes	[30]
ABFS	Fine aggregate	• Higher for the mix with 100% of ABFS • Comparable for the mix with 72% of ABFS	[32]

Slag	**Used as**	**Property:** ***Split tensile strength***	**Ref.**
GGBFS	Binder	• Lower at early age and similar at 28 days	[20]
GGBFS	Binder	• Lower • Decreased with the increasing of GGBFS replacement percentage	[25]
GGBFS	Binder	• Lower compared to the control mix, but higher with the addition of 7% of lime, compared to other GGBFS + lime mixes	[30]
ABFS	Fine aggregate	• Higher, perhaps due to a better bond between matrix and slag	[32]

Slag	**Used as**	**Property:** ***Elastic modulus***	**Ref.**
GGBFS	Binder	• Lower	[22]
GGBFS	Binder	• Lower • Decreased with the increasing of GGBFS replacement percentage	[47]

Slag	**Used as**	**Property:** ***Pores volume***	**Ref.**
ABFS	Fine / Coarse aggregate	• Lower	[35]
GGBFS	Binder	• Decreased with the increasing of GGBFS replacement percentage	[47]

Table 2-12: Cont.

Slag	**Used as**	**Property:** ***Porosity***	**Ref.**
GBFS	Fine aggregate	• Higher • Optimal GBFS replacement percentage: 20%	[16]
GGBFS	Binder	• Lower	[19]
ABFS	Fine / Coarse aggregate	• Lower • Improvement of ITZ (“*Interfacial Transition Zone*”) between aggregate and matrix	[35]

Slag	**Used as**	**Property:** ***Water absorption***	**Ref.**
GGBFS	Binder	• Higher	[25]
ABFS	Fine aggregate	• Similar	[32]
ABFS	Fine / Coarse aggregate	• Lower	[35]

Slag	**Used as**	**Property:** ***Autogenous and drying shrinkage***	**Ref.**
GGBFS	Binder	• Increased autogenous shrinkage • Comparable or lower drying shrinkage	[20]
ABFS	Fine aggregate	• Higher for the mix with 100% of ABFS • Comparable for the mix with 72% of ABFS	[32]

Slag	**Used as**	**Property:** ***Chloride penetration***	**Ref.**
GBFS	Binder / Fine aggregate	• Lower • Decreased as compressive strength increased	[13]

Slag	**Used as**	**Property:** ***Carbonation depth***	**Ref.**
GBFS	Binder / Fine aggregate	• Lower for higher percentage substitution	[13]

Slag	**Used as**	**Property:** ***Penetration of water under pressure***	**Ref.**
GGBFS	Binder	• Lower	[18]

Slag	**Used as**	**Property:** ***Behaviour after freeze-thaw cycles***	**Ref.**
GBFS	Fine aggregate	• Lower loss of compressive strength for 10–30% substitution percentages (higher durability) • Higher strength loss at higher replacement rates (similar values up to 50% replacement rate)	[16]

Table 2-12: Cont.

Slag	Used as	Property: *High temperature resistance*	Ref.
GBFS	Fine aggregate	• Comparable	[16]

Slag	Used as	Property: *Leaching behaviour*	Ref.
GGBFS	Binder	• The addition of GGBFS does not cause damage to the environment	[19]
GBFS / ABFS	Slag, not added to concrete	• 11 Blast Furnace Slag samples analysed: all the samples met the standards to be considered "non-hazardous"	[50]

In addition to the reuse as binder or aggregate for the production Normal Strength Concrete (Table 2-12), the following tables show other possibilities for the reuse of different types of blast furnace slags in the construction sector. In particular, some results concerning the reuse in **H**igh-**P**erformance **C**oncrete ("***HPC***"), **S**elf-**C**ompacting **C**oncrete ("*SCC*"), **H**igh-**S**trength **S**elf-**C**ompacting **C**oncrete ("***HSSCC***"), **F**ibre-**R**einforced **C**oncrete ("***FRC***"), **U**ltra-**H**igh-**P**erformance **F**ibre-**R**einforced **C**oncrete ("***UHPFRC***"), mortars and slag composite cement production will be briefly highlighted.

*Table 2-13: Behaviour of **H**igh-**P**erformance **C**oncrete ("**HPC**") made with Blast Furnace Slag ("BFS") as a partial or total replacement of binder, fine and/or coarse aggregate compared to the reference concrete (without the addition of slag).*

Slag	Used as	Results	Ref.
GGBFS	Binder	• 20, 35 and 50% GGBFS substitution percentages • Higher workability at higher GGBFS content • Lower compressive and tensile strengths at higher GGBFS content • Lower elastic modulus at higher GGBFS content • Higher autogenous shrinkage at higher GGBFS content	[27]
ABFS	Coarse aggregate	• 50 and 100% ABFS substitution percentages • Lower workability at higher ABFS content • Comparable density • Slower strength development at early age • Lower compressive strength at higher ABFS content • Lower tensile strength • Lower elastic modulus at higher ABFS content	[33]

*Table 2-14: Behaviour of **S**elf-**C**ompacting **C**oncrete (“**SCC**”) made with Blast Furnace Slag (“BFS”) as a partial or total replacement of binder, fine and/or coarse aggregate compared to the reference concrete (without the addition of slag).*

Slag	Used as	Results	Ref.
GGBFS	Binder	• GGBFS and metakaolin used as binder • 15, 20, 25 and 30% GGBFS substitution percentages • 10% metakaolin substitution percentage • Increased fresh properties of the concrete • Lower strength development at early age • Higher compressive, tensile and flexural strengths (except for the mix with 15% of GGBFS and 10% of metakaolin) • Recommended binder replacement percentages: 10% metakaolin and 25% GGBFS	[23]
ABFS	Fine / Coarse aggregate	• 50 and 100% ABFS substitution percentages • The addition of 100% of slag led to an increase in the required water and thus to a more porous matrix • Slightly lower density at higher ABFS content • Lower compressive strength at higher ABFS content • Higher flexural strength • Slightly lower tensile strength at higher ABFS content • The slag met the leaching test limits to be classified as inert waste	[34]

*Table 2-15: Behaviour of **H**igh-**S**trength **S**elf-**C**ompacting **C**oncrete (“**HSSCC**”) made with Blast Furnace Slag (“BFS”) as a partial or total replacement of binder, fine and/or coarse aggregate compared to the reference concrete (without the addition of slag).*

Slag	Used as	Results	Ref.
GBFS	Fine aggregate	• 20, 30 and 40% GBFS substitution percentages • Higher workability • Comparable development of strength • Higher compressive, tensile and flexural strengths at higher GBFS content	[51]

*Table 2-16: Behaviour of **F**ibre-**R**einforced **C**oncrete ("**FRC**") made with Blast Furnace Slag ("BFS") as a partial or total replacement of binder, fine and/or coarse aggregate compared to the reference concrete (without the addition of slag).*

Slag	**Used as**	**Results**	**Ref.**
GGBFS	Binder	• 20, 40 and 60% GGBFS substitution percentages • Steel fibers inclusion at 1.5% V_f • Results after accelerated corrosion tests • Addition of corrosion inhibitors in some mixes • Comparable workability, thanks to the addition of superplasticizer • Higher compressive and flexural strengths for mix with corrosion inhibitors	[28]

*Table 2-17: Behaviour of **U**ltra-**H**igh-**P**erformance **F**iber-**R**einforced **C**oncrete ("**UHPFRC**") made with Blast Furnace Slag ("BFS") as a partial or total replacement of binder, fine and/or coarse aggregate compared to the reference concrete (without the addition of slag).*

Slag	**Used as**	**Results**	**Ref.**
ABFS	Coarse aggregate	• 30, 50 and 100% substitution percentages • Lower workability at higher ABFS content • Lower density at higher ABFS content • Compressive and tensile strengths slightly lower • Elastic modulus slightly lower	[36]

*Table 2-18: Behaviour of **mortar** made with Blast Furnace Slag ("BFS") as a partial or total replacement of binder, compared to the reference mortar (without the addition of slag).*

Slag	**Used as**	**Results**	**Ref.**
GGBFS	Binder	• Ordinary Portland Cement ("*OPC*") was replaced by a mix of GGBFS and steel slags in percentages of 20, 40, 60 and 80% • Lower specific weight • Retarded setting times • Higher expansion (due to the higher specific surface of the mix GGBFS and steel slags) • Better behavior to chloride and sulphate attacks • Better resistance to sodium sulphate than that to magnesium sulphate • Higher high temperature durability (due to the fineness of the slags)	[29]

Table 2-19: Behaviour of ***slag composite cement*** *made with Blast Furnace Slag ("BFS") as a partial or total replacement of the clinker, compared to the Ordinary Portland Cement.*

Slag	Used as	Results	Ref.
GBFS	Clinker addition / substitution	• Mechanically activated GBFS was used to replace clinker for cement production in percentages from 50 to 95% • Faster strength development • Uncompromised strengths of up to 85% clinker–slag substitution • Higher strengths at early age (1 and 28 days) • Attention to slag fineness • Mechanical activation led to: increased hydration of C_3S in the clinker, increased hydration of the slag due to its higher reactivity, early formation and consumption of CH and more compact structure at higher slag content	[14]
BFS	Clinker addition / substitution	• Addition of BFS in percentages from 24 to 30%, mixed with constant clinker, gypsum and steel slag contents • Addition of compounds activators • Higher strength development due to the addition of the compound activator • Higher early age compressive strength in mixes with the compound activators • Higher content and interaction among hydration products in mixes with the compound activators, resulting in pore filling and greater structure density	[41]

Good results in terms of workability, fluidity, exudation, leaching of any hazardous substances and mechanical response (compressive and flexural strengths) were also obtained with regard to the addition of different percentages of *GGBFS* for the production of **cement-based grouts** [21]. Furthermore, the applicability of grouting materials with the addition of *GGBFS* and carbon fibres was also investigated, confirming the suitability of *GGBFS* for this type of application [52].

Finally, discordant results were obtained with regard to the use of *ABFS* as fine and coarse aggregate for the production of **road pavement concrete** [37]. Although the performance met the expected standards, the Authors reported decreases in workability, compressive, tensile and flexural strengths, accompanied by an increase in air content and chloride penetration as the slag content in the mix increased.

2.2.1.4 Discussion

The reuse of the different types of Blas Furnace Slags ("*BFS*") analysed above is now well established worldwide. In Europe, for example, the rate of reuse of these materials is between 94 and 100%, with 72–80% of this range consisting of their reuse in cement production or for the manufacture of concrete [6].

The reuse of Ground Granulated Blast Furnace Slag ("*GGBFS*") as a binder for concrete production leads to a mix with rheological properties (workability, air content and fresh concrete density) comparable to those of the reference concrete. The development of strength is lower at early age, but then reaches values comparable to those of the reference mix (this could affect construction times, when the site schedule requires a concrete with relatively rapid setting). As a result, the compressive, tensile and flexural strengths are lower at early age and then reach or exceed those of the reference concrete over time (mainly from 28 days). This increase in mechanical strength is mostly due to the high silicon dioxide (SiO_2) content of the slag, which enhances its pozzolanic properties. However, several Authors have recorded a decrease in strength with higher slag contents, thus suggesting binder-slag substitution values not exceeding 50%. The elastic modulus is lower as the percentage of binder-slag substitution increases. An increase in the substitution percentage ensures a lower pore volume in the matrix, especially over time (28–56 days), due to the development of hydration products that fill the pores of the matrix. The addition of "*GGBFS*" as a binder causes an increase in the autogenous shrinkage of the mix, which starts to stabilise at longer time than that of the reference concrete. Comparable results were recorded for drying shrinkage. Concerning the durability aspects, good results were obtained with regard to the penetration of water under pressure, chlorides penetration and carbonation depth. However, few results are available in the literature and more tests should be carried out to better study and understand the long-term behavior and potential of this material. Finally, the results of leaching tests carried out on "*GGBFS*" "*as is*" or in addition to the binder in the concrete met the different standards to be considered "*non-hazardous*".

Due to their characteristics, Air-cooled Blast Furnace Slag ("*ABFS*") is used for the production of concrete as partial or total replacement of natural fine and coarse aggregates. The rheological properties are comparable to those of reference concrete. The addition of admixture can help to keep workability under control. As with "*GGBFS*" used as a binder, concretes with "*ABFS*" used as aggregates also show slower strength development at early age. Compressive and flexural strengths are comparable to those of the reference concrete, while higher values of tensile strength have been recorded by some Authors. This increase is probably due to a better bond between the matrix and the slag. The decrease in pore volume and matrix porosity could be due to a better development and organisation of the

Interfacial Transition Zone ("*ITZ*") between the matrix and the slag. In contrast, discordant results have been obtained by several Authors with regard to water absorption. As with "*GGBFS*", few results are available in the literature concerning long-term tests aimed at investigating the durability of this conglomerate. Finally, no problems have been recorded regarding the possible release of hazardous substances from "*ABFS*" "*as is*" or as aggregates in concrete.

The continuous development of the research has made it possible to investigate the possibility of including Blast Furnace Slags also in the production of concretes different from the "standard" one, such as self-compacting concrete, high-strength concrete and fibre-reinforced concrete, obtaining discordant results in terms of rheological and mechanical properties, but nevertheless encouraging for further research in this direction.

2.2.2 Basic Oxygen Furnace ("BOF")

2.2.2.1 Steel and Basic Oxygen Furnace Slag ("BOFS") production process

As described in Subsection 2.2.1.1, the pig iron produced in the blast furnace can be cast into ingots for cupola furnace treatments (so-called "*second melting pig iron*") for the production of pig iron castings or it can be destined for the second step of the integral cycle, i.e. refining in a converter, for the production of steel. The processes occurring at this step are called "*conversion or refining processes*" and consists of treating the pig iron with an oxidising agent in order to reduce the carbon (C) content and correct the presence of other elements and impurities. These processes for converting pig iron into steel are very complex, rapid and do not require the supply of energy from outside; in fact, all the necessary heat comes from the exothermic reactions that take place inside the furnace [1,5].

Over the years, the continuous development of production technology has made it possible to correct certain problems related to the quality of steel produced, resulting from the presence of harmful elements such as sulphur, phosphorous and nitrogen. As already mentioned in Section 2.1, such developments occurred in Austria in 1952 with the introduction of the Linz-Donawitz ("*LD*") process. Further updates of this led to the present-day technology of producing steel by means of a *Basic Oxygen Converter* or ***B**asic **O**xygen **F**urnace* (**BOF**) [5].

The Basic Oxygen Furnace (Figure 2-13) is a kind of vessel internally coated with refractory material consisting of a double layer of masonry, the first for safety ("*permanent lining*") and the second of wear, which must be periodically rebuilt after a certain number of castings. Externally, the furnace is supported by two lateral pins that allow it to rotate by means of an electromechanical system, so as to facilitate charging, control, tapping and slag evacuation operations. A water-cooled lance for the insufflation of oxygen at supersonic speed is lowered inside, positioning itself close to the molten bath (approximately 1.5–3m). The process of converting pig iron into steel usually takes 15–20 minutes, which becomes 30–50 minutes considering the charging, the tapping and the eventual repair of the refractories. The furnace size varies from 60 to 350t, depending on production capacity and company organisation [1,5,53].

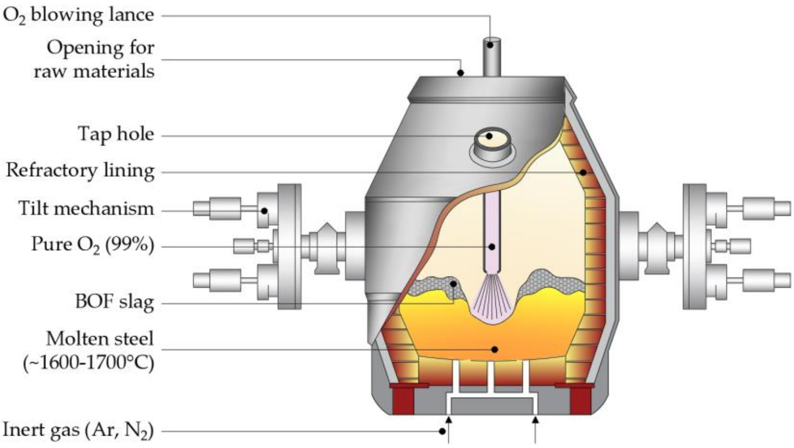


Figure 2-13: Simple schematic representation of a Basic Oxygen Furnace (adapted from [6]).

With regard to the metal part of the raw materials, **liquid pig iron** constitutes approximately 80–90% of the charge (the so called "*hot charge*") and is previously analysed and checked for silicon (Si), manganese (Mn) and phosphorous (P) contents (e.g. the phosphorous content is limited to 0.15%). **Steel scrap** and **solid pig iron** complete the metallic part of the charge and represent the so-called "*cold charge*". The presence of steel scrap and solid pig iron helps to ensure the cooling of the converter by maintaining temperatures around 1600–1700°C, necessary for chemical reactions to take place [54]. On the other hand, the non-metallic part of the charge consists of materials required for the refining of the pig iron (for steel production) and the production of slag. These materials are **lime**, **dolomite**, **fluorspar**, **iron ores and oxides,** and **limestone** [5,6,55]. Once the charge is placed in the converter (filling it to about 20% of its volume due to the strong swelling reactions and projections of metal and slag during the production process), a lance is lowered into it. In modern steel mills, there are different configurations of lances for blowing oxygen at supersonic speed, which are equipped with multiple nozzles. In Figure 2-14, an example of a lance with one, three and four nozzles is shown, but typically they are between four and seven (the number of nozzles affects the stirring of the molten steel bath) [53]. Cooling of the lance is ensured by a water (or low-temperature oxygen) recirculation system inside the lance itself [5].

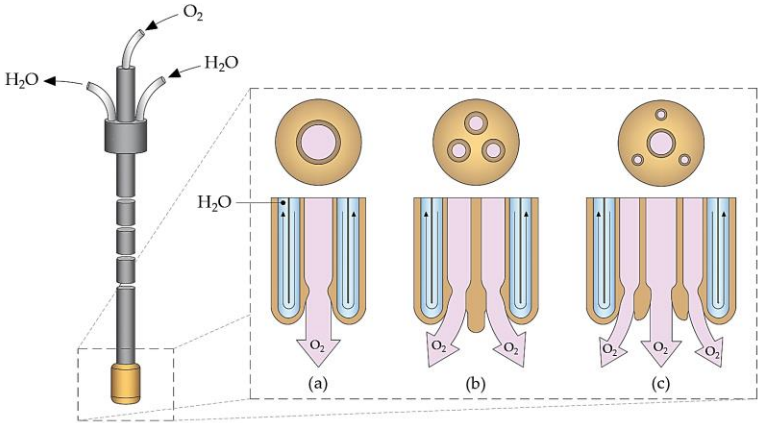


Figure 2-14: Example of three different possible designs of the blowing oxygen lance: single nozzle (a); three nozzles (b); four nozzles (c). The water recirculation system to ensure lance cooling is also highlighted (adapted from [5]).

Over the years, the technology that has undergone the most studies and updates is the oxygen blowing methodology. Figure 2-15 shows three different possibilities of blowing oxygen and inert gases, e.g. argon (Ar) or nitrogen (N_2), the latter with the sole purpose of ensuring agitation of the bath by bubbling. These possibilities are: blowing oxygen from above (Figure 2-15(a)), blowing oxygen from above and bubbling gas from below (Figure 2-15(b)), bubbling oxygen and gas from below (Figure 2-15(c)). Figure 2-15 also shows two oxygen blowing methods called "*soft blowing*" (Figure 2-15(a.1)) and "*strong blowing*" (Figure 2-15(a.2)) [5].

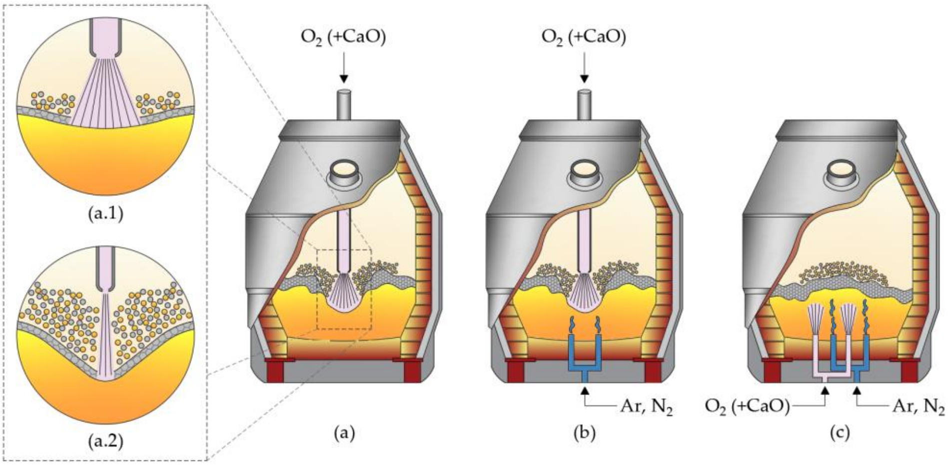


Figure 2-15: Different possibilities for blowing oxygen and gas: oxygen from above (a); oxygen from above and gas from below (b); both oxygen and gas from below (c). "Soft blowing" (a.1) and "strong blowing" (a.2) methods are also shown (adapted from [5]).

Depending on the different types of blowing, different converter families are identified, each classified by its own abbreviation, as shown in Table 2-20. The type of blowing is identified by letters referring to the Figure 2-15.

Table 2-20: Converter families identified by their abbreviations according to the oxygen and gas blowing methodology (blowing is identified by the letters in Figure 2-15) [5].

Blowing	**Abbreviation**	**Notes**
(a)	LD, BOF	-
(a)	OLP, LD-AC	Lime (CaO) injection from lance
(b)	LBE, LD-CB, TBM, BAP	Bubbling Ar, N_2
(b)	LD-KGC, NK-CB	Bubbling various gases and powder
(c)	OBM, LWS, Q-BOP, KMS/KS	-
(b) + (c)	K-OBM, K-BOP, LD-OB	O2 from above and below

As mentioned earlier, the process of refining pig iron is very complex and dependent on the reaction environments and mass transfer conditions. There are several reaction zones, where interchanges of elements occur between gas and metal bath, metal bath and slag and slag and gas. The kinetics of the process are characterised by multiple parameters and, for the individual reaction zone, can be expressed as a function of the interface area between the phases, the temperature and the physico-chemical nature of the interactions [56].

Various researchers worldwide are still trying to solve some of the problems associated with understanding the complex interactions that take place within the basic oxygen furnace. For example,. studies can be found in the literature on the effects of difference lance configurations (number of nozzles, nozzle angle, orientation, blowing speed, etc.) on the reactions and, consequently, on the quality of steel and slag [53] and on comparisons between methods for estimating the endpoint temperature of the converter itself [57]. From these studies, dynamic models are derived based, for example, on certain theories such as multi-zone kinetic theory, in order to try to understand and optimise the reactions occurring in the jet impact zone and between slag and molten steel bath [56].

Given the complexity of the phenomenon, Figure 2-16 summarises the main reactions occurring in the converter, subdividing them according to zones. For a better understanding of steel processes, in the writing of chemical reactions the molten metal and all elements in solution in it are represented in square bracket “*[]*”, slag and the elements in solution in it in round brackets “*()*” and gases in brace “*{}*”. Finally, for diatomic gases (e.g. oxygen or nitrogen) soluble in metal in atomic form, the notation “*[N]*” is used, while the same gas in molecular state is written “*{N_2}*” [5].

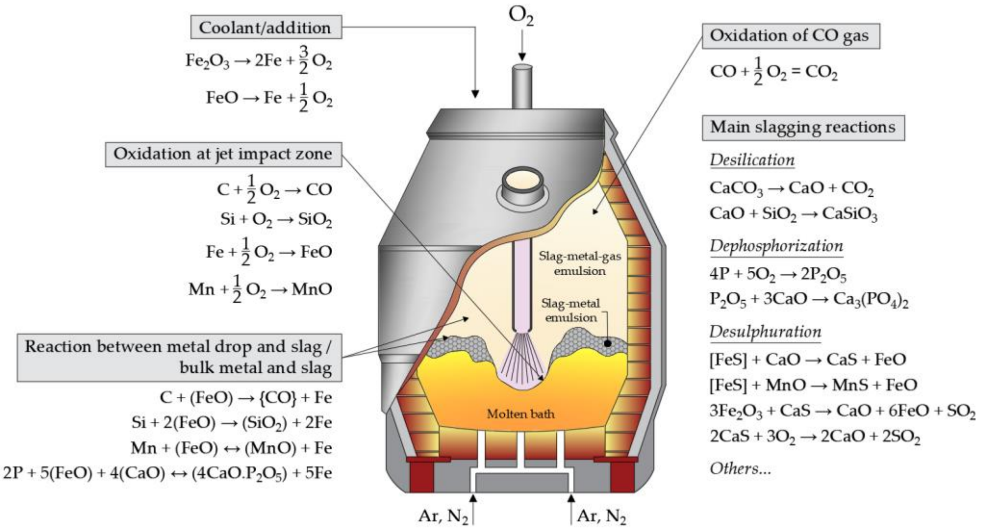


Figure 2-16: Main reactions occurring in the Basic Oxygen Furnace, subdivided according to zones (adapted from [53,56]).

During the complex process of producing steel from pig iron, there are several elements that are considered as harmful impurities for the quality of steel itself. Therefore, their content must necessarily be reduced or, in some cases, eliminated. During the 15–20 minutes of oxygen injection, the converter is charged with the non-metallic part of the charge (so-called "*fluxes*", such as lime (CaO) and dolomite ($Mg(CaCO_3)_2$)), which combines with carbon and the abovementioned impurities, resulting in the formation of the so-called ***B**asic **O**xygen **F**urnace **S**lag* ("***BOFS***") [54]. For each tonne of steel produced, approximately **100–150 kg of basic oxygen furnace slag** are produced [6]. The chemical composition of this slag is particularly affected by the large number of reactions that occur during the removal of impurities from the molten steel bath. In a very brief summary, the main constituents of BOFS are lime (CaO), iron oxides (FeO and Fe_2O_3) and silicon dioxide (SiO_2). In the pig iron conversion process, a certain percentage of iron (Fe) in the molten bath will not be "used" for steel formation and will inevitably contribute to the formation of slag. Depending on the efficiency of the single converter, the slag Fe content can vary from 10 to 40%. The slag silicon dioxide (SiO_2) content is usually lower than in the blast furnace slags, since most of the silica impurities are already trapped in the latter and will therefore not be present in the pig iron loaded into the converter. Finally, large lime (CaO) contents characterise BOFS, due to the high usage of lime and dolomite during the refining process. Other minor constituents of BOFS are oxides of other impurities (Al, Mn, Ti, etc.) [54]. A more precise and detailed analysis of BOFS chemical composition will however be shown in the following sub-section.

The lower density of BOFS results in it being deposited on the top of the molten steel bath, forming a layer. At the end of the refining process of the pig iron and the consequent formation of steel, and after all steel and slag composition analyses have passed the requirements, the converter is tilted to one side to remove the steel ("*tapping*" process). Once this step is completed, the converter is tilted in the other direction to allow the liquid slag to be spilled into ladles ("*slagging*" process) [54]. The liquid slag will then be destined for cooling and subsequent processing to ensure its future reuse (more details in the following sub-sections).

2.2.2.2 Basic Oxygen Furnace Slag ("BOFS"): types, properties and possible reuses

Once the slag has been removed from the converter, it will be subjected to cooling processes and subsequent treatments to ensure its future reuse. Depending on the type of cooling adopted by the steel mill, the slag characteristics may vary in terms of chemical composition, physical properties, mineralogy and even leaching behaviour. Table 2-21 shows and summarises the most common cooling processes, treatments and applications of BOFS [6,10,58].

Table 2-21: Most common cooling processes, treatments and applications of Basic Oxygen Furnace Slag ("BOFS") [6,10,58].

Basic Oxygen Furnace Slag ("BOFS")	
Cooling process	• Slow (or extreme slow) air-cooling in slag pits • Air quenching • Water spraying
Material aspect	• Crystalline material with grain size < 100 mm • In case of BOFS treated with O_2 and SiO_2, crystalline and volume stable material with grain size < 300 mm
Common treatments	• Weathering to achieve volumetric stability • Crushing, sieving and grading • Grinding to a powdered material (< 300 μm)
Common reuses	• *As aggregate for* bituminous and hydraulically bound mixtures (asphalt, concrete, road binder, etc.), top layers for high skid resistance, unbound mixtures, dams (road construction and noise protection), wastewater treatment, embankments and fills, railway ballast, sealing in surface layers, roofing, ground stabilisation, armour stone, gabions • *For the manufacture of* cement and other hydraulic binders, fertilizer, glass (blended with other components), stone wool

Figure 2-17: Basic Oxygen Furnace Slag (“BOFS”) [59].

Table 2-22 summarises the main **physical properties** of the Basic Oxygen Furnace Slag.

Table 2-22: Main Basic Oxygen Furnace Slag (“BOFS”) physical properties.

Basic Oxygen Furnace Slag (“BOFS”) physical properties			
Property	**Units**	**Values**	**References**
Dimension (fine)	[mm]	0–4.75	[40,54,60,61,62,63,64,65,66]
Dimension (coarse)		4.75–20.00	[54,63,64,66,67,68,69,70]
Density	[kg/m³]	3100–3600	[71,72,73,74]
Apparent density	[kg/m³]	2395	[40]
Bulk density	[kg/m³]	1726–2040	[64,68,69]
Packing density	[kg/m³]	1475	[40]
Specific gravity	[-]	2.86–3.57	[54,61,64,65,66,67,68,69,70,75,76]
Specific surface area	[cm²/g]	4000–5060	[61,75,77,78]
Fineness modulus	[%]	2.08–5.71	[40,60,69]
Water absorption	[%]	0.7–8.91	[54,62,64,66,68,70,73,76]
Water content	[%]	2.38–8.00	[64,72]
Loss on ignition (LOI)(*)	[%]	0.25–7.54	[54,64,65,68,75,78,79,80,81]
Insoluble residues	[%]	3.71–9.97	[68,75]
Los Angeles (LA)	[%]	11.3–22	[68,70,73,76,82]
Grindability index	[-]	0.7	[71]
Crushing value	[%]	13–21	[68,70,73]
Impact value	[%]	16	[68]
Glass content	[%]	7	[74]

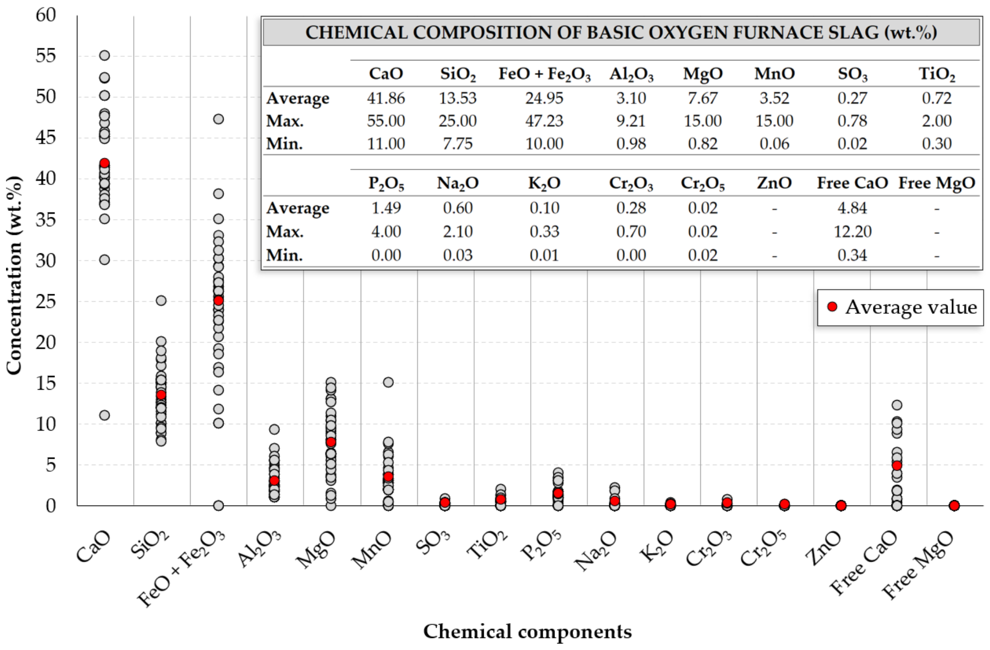
(*) *Property that typically accompanies the chemical composition of the slag, shown in this table for a better comprehension*

BOFS are characterized by a shape that changes from sub-rounded to angular [54,61,68], with abundant edges and many surface pores [54,62]. Depending on the characteristics and treatment processes, BOFS colour can change from dark brown

[61] to grey and black [62,68]. For example, high basicity slag has a grey/white colour, while low basicity slag tends more towards grey/brown [72].

Figure 2-18 shows the typical **chemical composition** of Basic Oxygen Furnace Slag (“*BOFS*”). For better understanding, the graph is accompanied by a table in which the minimum, maximum and average values are indicated for each component (the average value is also marked by a red dot on the graph). From each paper consulted, the chemical compositions of the slag used were obtained, represented by the grey dots in the graph [40,54,60–75,77–82,83,84,85,86,87].

From a comparison, it can be seen that calcium oxide (CaO), silica (SiO_2) and iron oxides (FeO and Fe_2O_3) are the main components of the basic oxygen furnace slag, summing up the average values. There are also important concentrations of magnesium oxide (MgO). Other elements present in very low concentrations are alumina (Al_2O_3), manganese oxide (MnO), sulphuric anhydride (SO_3), titanium dioxide (TiO_2), phosphoric anhydride (P_2O_5), sodium oxide (Na_2O), potassium oxide (K_2O) and dichromium trioxide (Cr_2O_3). Unlike blast furnace slag, BOFS has a high free calcium oxide (free CaO) content (up to 12%), which, together with other components, contributes to the volumetric instability of the slag itself (discussed in more detail in the following section).



CHEMICAL COMPOSITION OF BASIC OXYGEN FURNACE SLAG (wt.%)

	CaO	SiO_2	$FeO + Fe_2O_3$	Al_2O_3	MgO	MnO	SO_3	TiO_2
Average	41.86	13.53	24.95	3.10	7.67	3.52	0.27	0.72
Max.	55.00	25.00	47.23	9.21	15.00	15.00	0.78	2.00
Min.	11.00	7.75	10.00	0.98	0.82	0.06	0.02	0.30

	P_2O_5	Na_2O	K_2O	Cr_2O_3	Cr_2O_5	ZnO	Free CaO	Free MgO
Average	1.49	0.60	0.10	0.28	0.02	-	4.84	-
Max.	4.00	2.10	0.33	0.70	0.02	-	12.20	-
Min.	0.00	0.03	0.01	0.00	0.02	-	0.34	-

Figure 2-18: Chemical composition of Basic Oxygen Furnace Slag (BOFS) [40,54,60–75,77–87].

With regard to **mineralogical properties**, the main constituents of Basic Oxygen Furnace Slag are shown in Table 2-23.

Table 2-23: Mineral constituents of Basic Oxygen Furnace Slag.

Constituent	Formula	References
Belite (dicalcium silicate)	C_2S (or Ca_2SiO_4)	[60,61,63–66,70–72,74,77–81, 83,87]
Alite (tricalcium silicate)	C_3S (or Ca_3SiO_5)	[60,61,64–66,70–72,74,77,78, 80,81,87]
Srebrodolskite (dicalcium ferrite)	C_2F (or $Ca_2Fe_2O_5$)	[60,61,66,72,74,77,79,81,83,87]
Portlandite (calcium hydroxide)	$Ca(OH)_2$	[60,63,65,70,81,83]
Calcite (calcium carbonate)	$CaCO_3$	[60,63,65,66,81,83]
RO Phase	MgO-FeO-MnO solid solution	[60,61,70–72,77,78,83]
Brownmillerite	C_4AF (or $Ca_2(Al,Fe)_2O_5$)	[61,65,69,71,78,79]
Olivine(*)	$(Mg,Fe)_2SiO_4$	[61,71]
Merwinite	$Ca_3Mg(SiO_4)_2$	[61,71,87]
Wustite	FeO	[63,65,66,74,79]
Magnesioferrite	$MgFe_2O_4$	[63,66,81]
Tricalcium aluminate	C_3A (or $Ca_3Al_2O_6$)	[64]
Magnetite	Fe_3O_4	[65,81]
Fluorite	CaF_2	[69,80]
Akermanite	$Ca_2MgSi_2O_7$	[69,87]
Gehlenite	$Ca_2Al_2SiO_7$	[73]
Amorphous phase	-	[69]

(*) *Isomorphic mixture of forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4)*

As shown in Table 2-21, BOFS can be reused for multiple applications. Its crystalline structure and physical, chemical and mineralogical properties, combined with good mechanical (including abrasion, grinding, crushing and impact resistances) and leaching behaviour, make it suitable for massive reuse in road construction, an application that provides the highest recovery rate [88]. Good results were obtained, for example, with regard to the reuse of BOFS for the production of asphalt mixtures [62,70,76,85,86], for the activation of blast furnace slag (GGBFS) for hydraulic road binder production [81] and as railway ballast [82].
In view of its possible reuse in different sectors and in order to make the most of all the properties of this type of slag, some studies have focused only on its physical, chemical and mineralogical properties [73,79], investigating different issues such as its hydration properties [78] and its characteristics according to the different cooling

processes to which it may be subjected [74]. On the other hand, other researchers have focused their attention on the study and further development of criteria for the use of BOFS as granular material (for concrete and road construction), with a focus on its volumetric instability [67], which will be described in more detail in the following section, focusing on the reuse on BOFS in concrete.

2.2.2.3 *Basic Oxygen Furnace Slag ("BOFS"): reuse for concrete production*

As previously mentioned, some researchers have attempted to reuse BOFS slag as a partial or total replacement of cement and aggregates in the production of concrete, obtaining quite conflicting results. In fact, despite its good physical, chemical and mechanical properties, its high volumetric instability and low hydraulic activity are two of the main parameters that hinder its reuse in the civil sector. In particular, with regard to the phenomenon of **volumetric instability**, it is mainly caused by the presence of so-called "*unstable*" components in the chemical and mineralogical composition of BOFS. Some "*expansive*" reactions that cause volumetric expansion in BOFS are listed below [54]:

- Expansion of free lime (free-CaO)

$$CaO + H_2O \rightarrow Ca(OH)_2 \tag{2-14}$$

- Expansion of free periclase (MgO)

$$MgO + H_2O \rightarrow Mg(OH)_2 \tag{2-15}$$

- Conversion of belite (dicalcium silicate, C_2S or Ca_2SiO_4)

$$\beta - C_2S \rightarrow \alpha - C_2S \tag{2-16}$$

- Carbonation of Ca and Mg hydroxides

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{2-17}$$

$$Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O \tag{2-18}$$

- Oxidation of iron

Studies have shown that the main cause of the volumetric expansion of BOFS is its high content of free calcium oxide ("*free-CaO*") which gives rise to the formation of Portlandite ("*$Ca(OH)_2$ or calcium hydroxide*") in the presence of water. Its lower density, compared to that of calcium oxide, results in an increase of volume. The high percentage of free-CaO in BOFS is mainly caused by [54]:

- Undissolved lumps (residues) from the converter charge;
- Lime precipitated during the cooling processes or during the conversion of alite (C_3S) to belite (C_2S).

The hydration process of free-CaO is rather rapid, with volume increments of around 90–100% within a few days as it changes from oxide to hydroxide [64,66,67,89]. The hydration process would appear to affect all the calcium oxide present in the slag. However, in BOFS with higher dimensions, some calcium oxide may also be present in small pockets within the slag itself. It is therefore not a fact that all the calcium oxides in the slag will hydrate; they may not come into contact with water. In case of contact, the hydration proceeds and the calcium oxide in the pockets could cause further crack openings in the slag, resulting in its expansion and possible disintegration [89].

The second component that causes expansion is the free magnesium oxide (“*free-MgO*”), which hydrates at a much slower rate than free-CaO, thus causing volumetric instability over longer periods (half a year or years). The volume increments of magnesium oxide after transformation into hydroxide are typically between 120 and 150% [64,66]. The continuous technological development of converter steel production and a special focus on raw material inputs have led to the production of slag with ever lower free MgO contents over the years, varying mainly according to the corrective agents used in the process. Some authors have therefore classified steel slags according to their MgO content, also establishing threshold values depending on the applications. In addition, magnesium oxide that is not present in “*free form*” but, for example, in solid solution with FeO or MnO in the form of a crystal mixture, could also expand in contact with water [90].

A third cause of BOFS expansion is due to the presence of dicalcium silicate (C_2S) in its mineralogical composition. C_2S exists in four polymorphs: α, α', β and γ. The first type (“α-C_2S”) is stable at high temperatures (>630°C). Once the slag has been removed from the converter, it starts to cool down and the temperatures drop. At 630°C, α-C2S undergoes a transformation into β-C_2S. Reaching even lower temperatures (<500°C), β-C_2S starts to transform into γ-C_2S, causing a volumetric expansion of the slag [54].

Finally, the calcium and magnesium hydroxides ($Ca(OH)_2$ and $Mg(OH)_2$) can absorb CO_2 from the air, giving rise to carbonation processes, resulting in slag expansion. The oxidation of iron oxide (FeO) is also an expansive reaction, but there is limited information on the subject in the literature. Compared to the expansion caused by the hydration phenomenon, the expansion caused by the oxidation and carbonation reactions can be considered negligible. [54].

As a consequence of these phenomena, the overall expansion of BOFS aggregates is typically between 5 and 10% [54,63,66,82].

Over the years, many Authors have focused their attention on the phenomenon, or rather, the phenomena of volumetric expansion of BOFS, trying to understand their causes and ultimately aiming to reduce them. Several different methodologies can be found in the literature, each with advantages and disadvantages. Table 2-24 summarises the main methods for reducing the free-CaO and free-MgO contents in BOFS.

Table 2-24: Main methods for reducing free-CaO and free-MgO contents in BOFS.

BOFS treatment methods	Results after treatments	Refs.
• Steam ageing from 8 to 12h • Autoclave ageing for 3h under 2.0 MPa at 215°C	• Free-CaO content reduced from 3.56 to 1.07% after 8h of steam aging • No significant differences between the 8h and 12h steam aging • Less free-CaO content after autoclave aging	[60]
• Weathering for a specific period under laboratory conditions	• Reduction in free-CaO due to its hydration and presence of Portlandite ($Ca(OH)_2$)	[61,65]
• "*Scrubbing attrition process*" (*) • "*Chelating process*" (**)	• Removal of more than 30% of free-CaO from the surface of the slag with the "*scrubbing attrition process*" • Higher free-CaO reduction with the combination of the two methods	[63]
• Mechanical treatments, sprayed with water, dried in oven, accelerated carbonation	• Reduction of free-CaO content from 7% to less than 1% in 3h with carbonation process	[64]
• Weathering at outdoor conditions along with spraying water for 9 months at regular intervals	• Free-CaO content reduced from 5.33 to 0.16% • Negligible slag volume expansion • Presence of a calcite ($CaCO_3$) coating layer on the aged slag, which cannot be removed by simple slag washing)	[68]
• Natural weathering for 4 years	• Efficient oxides hydration	[69]
• Weathering in residue areas for several years	• -	[75]
• Weathering for a few months	• Incomplete weathering and 5% residual free-CaO still present • Partial hydration reaction due to coarse slag particle size (some free-CaO particles not fully accessible to water)	[81]
• Ageing for 0, 3 and 6 months	• The three different ageing periods had little effect on the changes in physical properties • The effect of ageing can be ignored for up to six months • Attention to the long term expansion due to the presence of free-MgO	[82]

Table 2-24: Cont.

BOFS treatment methods	Results after treatments	Refs.
• Natural ageing in a lysimeter of $1m^3$ placed outdoor for 2 years	• Chromium (Cr) speciation did not change with age • Vanadium (V) seemed to oxidise to the most toxic form (pentavalent) during ageing	[83]
• Stored for 3 years in an outdoor environment	• The BOFS expansion rate met the reference standard	[86]

(*) The "scrubbing attrition process" consists of mixing, with a stirrer, the slag in a liquid/solid solution. With the mutual collision between the slag particles and between the slag and the walls, the free-CaO can be removed from the surface of the slag;
(**) The "chelating process" consists in adding a chelating agent (typically oxalic acid) which remains on the surface of the slag. When the water penetrates the slag, the agent is dragged inside the slag with it and reacts with the internal free-CaO.

BOFS is therefore commonly treated prior to its reuse, with the aim of reducing the free-CaO and free-MgO contents as much as possible in order to limit expansive phenomena in both the short and long term. These treatments are even more important when BOFS is used in bound applications, as uncontrolled expansive phenomena could lead to the opening of unwanted and unexpected cracks in the element manufactured from the conglomerate considered.
In Table 2-25, the rheological, performance and durability properties of the **N**ormal **S**trength **C**oncrete ("*NSC*") with the addition of basic oxygen furnace slag ("*BOFS*") in **partial or total replacement of fine and/or coarse aggregate** will be analysed, in order to understand how its addition can affect the behaviour of the concrete mix itself when compared with a reference concrete (i.e. without slag).

*Table 2-25: Behaviour of the **N**ormal **S**trength **C**oncrete ("**NSC**") made with Basic Oxygen Furnace Slag ("BOFS") as a partial or total replacement of fine and/or coarse aggregate compared to the reference concrete (without the addition of slag).*

Slag	Used as	Property: *Workability*	Ref.
BOFS	Fine / Coarse aggregate	• Higher compared to the reference mix • Highest for the mix with carbonated granulated BOFS	[64]
BOFS	Coarse aggregate	• Slightly lower (100% BOFS substitution for paving concrete)	[66]
BOFS	Fine / Coarse aggregate	• Comparable, thanks to the addition of superplasticiser	[69]

Table 2-25: Cont.

Slag	**Used as**	**Property:** ***Air content***	**Ref.**
BOFS	Fine / Coarse aggregate	• Lower	[64]
BOFS	Coarse aggregate	• Comparable (100% BOFS substitution for paving concrete)	[66]

Slag	**Used as**	**Property:** ***Density***	**Ref.**
BOFS	Coarse aggregate	• Higher (100% BOFS substitution for paving concrete)	[66]
BOFS	Fine / Coarse aggregate	• Higher compared to the reference mix • Decreased with the increasing of compressive strength	[69]

Slag	**Used as**	**Property:** ***Development of the strength***	**Ref.**
BOFS	Fine / Coarse aggregate	• Slightly slower	[64]

Slag	**Used as**	**Property:** ***Compressive strength***	**Ref.**
BOFS	Fine / Coarse aggregate	• Higher, due to the higher angularity of the slag which enhanced the slag-matrix interaction	[64]
BOFS	Coarse aggregate	• Lower (100% BOFS substitution for paving concrete)	[66]

Slag	**Used as**	**Property:** ***Split tensile strength***	**Ref.**
BOFS	Coarse aggregate	• Lower (100% BOFS substitution for paving concrete)	[66]

Slag	**Used as**	**Property:** ***Elastic modulus***	**Ref.**
BOFS	Fine / Coarse aggregate	• Higher	[64]

Slag	**Used as**	**Property:** ***Pores volume***	**Ref.**
BOFS	Fine / Coarse aggregate	• Lower	[64]
BOFS	Fine / Coarse aggregate	• Lower compared to the reference mix • Decreased with the increasing of compressive strength	[69]

Table 2-25: Cont.

Slag	Used as	Property: *Porosity*	Ref.
BOFS	Fine / Coarse aggregate	- Lower	[69]

Slag	Used as	Property: *Water absorption*	Ref.
BOFS	Fine / Coarse aggregate	- Slow absorption speed despite the high water absorption of the carbonated slag	[64]
BOFS	Fine / Coarse aggregate	- Lower compared to the reference mix - Decreased with the increasing of compressive strength	[69]

Slag	Used as	Property: *Autogenous and drying shrinkage*	Ref.
BOFS	Coarse aggregate	- Higher drying shrinkage (100% BOFS substitution for paving concrete)	[66]

Slag	Used as	Property: *Carbonation depth*	Ref.
BOFS	Fine / Coarse aggregate	- Lower, with reduction up to 80% - Lower than the minimum concrete cover (25mm) required by the Brazilian standard	[69]

Slag	Used as	Property: *Behaviour after freeze-thaw cycles*	Ref.
BOFS	Coarse aggregate	- Acceptable (100% BOFS substitution for paving concrete)	[66]

Slag	Used as	Property: *Volumetric expansion*	Ref.
BOFS	Fine / Coarse aggregate	- Higher volumetric stability for concrete with carbonated slag	[64]

Slag	Used as	Property: *Interfacial Transition Zone (ITZ)*	Ref.
BOFS	Fine / Coarse aggregate	- Enhanced	[64]
BOFS	Fine / Coarse aggregate	- More uniform, less thick and less porous	[69]

Slag	Used as	Property: *Leaching behaviour*	Ref.
BOFS	Slag, not added to concrete	- 17 BOFS samples analysed: all the samples met the standards to be considered “non-hazardous”	[50]

In addition to the reuse as aggregate, some researchers have tried to study the behaviour of **BOFS used as a binder replacement for the production of concrete**. With regard to this application, the high content of belite (dicalcium silicate or "*C_2S*") and alite (tricalcium silicate or "*C_3S*") causes lower hydraulic activity compared to standard cement clinker [71,91].
As previously described for expansion phenomena, once temperatures below 500°C re reached (especially during slow cooling), the component β-C_2S undergoes a transformation into γ-C_2S, a phase with low hydraulic properties. This contributes to the low reactivity of BOFS when used as a binder for concrete production [91].
Another component present in BOFS is the RO Phase (MgO-FeO-MnO solid solution) which is almost inert and thus generates a very weak interface between the slag particle and the cement matrix [78].
A number of studies on the reuse of BOFS as a binder for the production of concrete can be found in the literature. In particular, very interesting are the results of a research (summarised in Table 2-26) in which the Authors tested concretes with the addition of BOFS considering two particular conditions [77]:

- Different BOFS–binder substitution percentages and constant water/binder ratio (w/b);
- Different BOFS–binder substitution percentages and same compressive strength at 28 days.

Table 2-26: Main results from the reuse of Basic Oxygen Furnace Slag ("BOFS") as partial replacement of ***binder*** *for the production of concrete, under different conditions, compared to the reference concrete (without the addition of slag) [77].*

Properties	**Conditions**	**Results**
Compressive strength	Constant w/b ratio	Lower as BOFS content increases
	• High w/b ratio • 30% BOFS-binder replacement	Lower
Initial and final compressive strength	Constant compressive strength at 28 days	• Lower initial • Higher final
Drying shrinkage	High w/b ratio	• Higher at early age • Quite similar after 90 days
Ions chloride permeability	• Constant w/b ratio • 28 days	Higher as BOFS content increases
	• High w/b ratio • Over 28 days	Higher in mixes with a high replacement percentage
	• Low w/b ratio • Over 28 days	Similar in mixes with a high replacement percentage

Table 2-26: Cont.

Properties	Conditions	Results
Carbonation resistance	• Constant w/b ratio • Low replacement percentage	Small influence on the carbonation resistance
	• Constant w/b ratio • High replacement percentage	Lower

Finally, still remaining in the construction sector, BOFS can also be **reused as a binder** replacement for the production of **mortar** (some results briefly summarized in Table 2-27), after appropriate slag treatments to reduce the content of components responsible for volumetric instability (e.g. free-CaO).

Table 2-27: Behaviour of the ***mortar*** *made with Basic Oxygen Furnace Slag ("BOFS") as a partial or total replacement of binder compared to the reference mortar (without the addition of slag).*

Slag	Used as	Results	Ref.
BOFS	Binder	• BOFS weathered under laboratory conditions for a certain period • Ordinary Portland Cement ("*OPC*") replaced by BOFS in percentages of 0, 15, 30 and 45% • Increased setting time for 15 and 30% and decreased for 45 and 60% replacement ratios • Lower compressive strength (decreased with the increase in replacement ratios) • pH slightly higher • Lower water demand (better fluidity for higher replacement ratios)	[61]
BOFS	Binder	• Slag weathered in residue areas for several years • Ordinary Portland Cement ("*OPC*") replaced by BOFS in percentages of 0, 15, 30 and 45% • Higher initial and final setting times • Lower volume expansion • Lower compressive and bending strengths	[75]

2.2.2.4 Discussion

The reuse of Basic Oxygen Furnace Slag ("*BOFS*") in mortars and concretes is made difficult by the volumetric expansion phenomena to which the slag is subjected. Many Authors have identified the causes and have researched and validated different methods to enable a reduction of the responsible components and ensure the proper reuse of BOFS in this sector. Nevertheless, the reuse of BOFS in partial or total replacement of natural aggregates for the production of concrete has led to conflicting results. The workability of the concrete improves with the use of specially treated slag but tends to decrease as the percentage of slag–natural aggregate substitution increases. However, it can be kept under control by the addition of appropriate amounts of superplasticizer. The air content of the mixtures tends to decrease while the density increases as the replacement percentage increases (due to the higher density of the slag compared to natural aggregate). The development of strength is slightly slower and discordant results have been obtained regarding compressive strength. An increase in compressive strength may be due to the high angularity of the slag, which promotes interaction with the surrounding matrix. On the other hand, high replacement rates lead to a reduction in compressive strength. Lower water absorption of the concretes was also recorded, despite rather high values of water absorption of the slag aggregates. With regard to the issue of concrete durability, tests for the evaluation of the carbonation depth showed lower values and acceptable values were obtained with regard to resistance after freeze-thaw cycles for specimens with BOFS. Finally, proper treatments of slag prior to its reuse in bound applications ensures less volumetric expansion. In real life, however, these slag stabilisation treatments are far from "*simple*" and sometimes prove to be rather "*complicated*" from a technical (concepts, equipment, space, etc.), economic and time-consuming perspective (slag complete stabilisation may take months or years). In the light of the advantages and especially the disadvantages discussed above, it can be seen that the reuse of BOFS in concrete is rather difficult from several points of view. In fact, thanks to their physical and performance properties, BOFS is mostly reused for unbound applications (e.g. road construction), for which the problems relating to volumetric instability are still present but not as relevant as they are for bound applications.

2.3 Steel production processes: Electric Cycle

In addition to the Integral Cycle discussed in the previous Sections, another methodology for steel production is the **Electric Cycle**, where production takes place in a single step in the so-called *Electric Arc Furnace* (**EAF**). As described in Section 2.1, the discovery of the possibility of producing steel using the heat that an arc irradiates at high temperatures dates back to the 19th century (Siemens, 1878). Compared to integral cycle technologies, those underlying the electric cycle had a much slower and more gradual development, caused mainly by the limited availability of energy and its very high cost. However, towards the beginning of the 20th century three different prototype types of electric furnace were developed in three different parts of Europe: "*direct arc furnace*" (Héroult, France, 1899), "*indirect arc furnace*" (Stassano, Italy, 1898), "*induction furnace*" (Kjellin, Sweden, 1900) [5].
The success of the electric furnace is mainly due to the following aspects [5]:

- Possibility of controlling the potential oxygen in the system;
- Thermal flexibility, with the possibility of dosing and controlling the heat supply according to process requirements. This also makes it possible to act on the physico-chemical properties not only of the primary material (steel, with benefits in terms of desulphurisation and the content of non-metallic inclusions), but also on those of the secondary material (slag);
- Plant flexibility, with sizes varying between 1.5 and 8m for internal diameter and between 0.5 and 400 tonnes for capacity (with average values of 80–120t);
- Non-dependence on integral cycle, due to the use of solid charge instead of liquid charge;
- Possibility of use in areas with high steel scrap production and where there is a large steel utilisation market.

2.3.1 Electric Arc Furnace ("EAF")

2.3.1.1 Steel and Electric Arc Furnace Slag ("EAFS") production process

As mentioned before, the different ways to producing heat at high temperatures using electricity have allowed the development of three main furnace types [1,5]:

- "*Electric resistance furnaces*", in which electricity is converted into heat directly within the charge, thanks to the resistance (e.g. the "*induction furnace*", which allows the remelting and heating of small quantities of material and the production of very high quality special steel);
- "*Indirect arc furnaces*", (Figure 2-19(a))which are of limited practical interest in the iron and steel industry. The charge is not passed through by electric current but is heated by radiation from an arc between the electrodes. An example of this id the "*Stassano furnace*" (first prototype in 1898), which fell into disuse in the early 1900s due to its poor suitability for the producing of large quantities of material;
- "*Direct arc furnaces*", derived from the "*Héroult furnace*" (1899). In this type of furnace the arc is formed between the electrodes and passes through the charge, thus allowing the charge to close the electrical circuit.

The most widespread electric furnaces in the steel industry worldwide are certainly **direct arc furnaces**, which exploit the power from a discharge generated by ionisation of the "*gaseous medium*" between two electrodes at different potentials. The passage of electricity is enabled by the plasma that is generated as a result of ionisation. Very high temperatures are reached in the central zone of the arc (in order of 10000–12000*C), which drop to around 3500°C in the zone outside the plasma. In general, temperatures in an electric furnace are above 2000°C [1,3,5].

Over the years, there have been various designs for electric furnaces, which are briefly summarised in Figure 2-19.

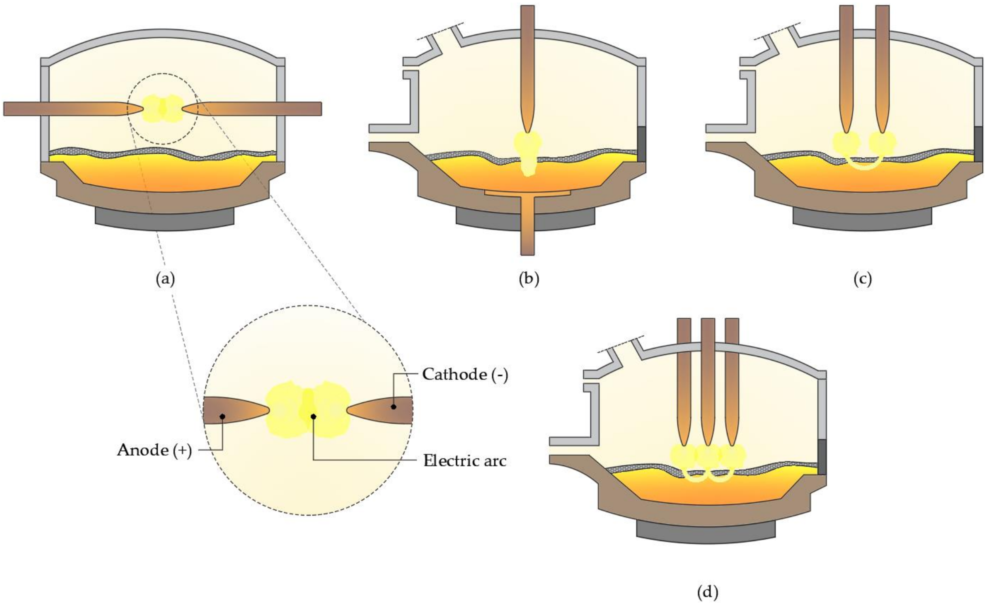


Figure 2-19: Different electric furnace operating configurations: (a) indirect electric arc furnace; (b) and (c) single-phase direct electric furnace; (d) three-phase direct electric furnace. A detail of the electric arc formed between electrodes at different potentials is also shown (adapted from [5]).

The electric arc furnace essentially consists of three main elements [1,3,5]:

- "*Sole*", the lower part of the furnace, concave in shape and with a refractory lining. It is used to contain the molten steel and the layer of slag that is deposited on top of it and is shaped so that it can be easily tilted to allow tapping and slagging operations. The furnace is tilted by means of electromechanical or hydraulic servomechanisms;
- "*Vat*" (or "*cage*" or "*crucible*"), the central part of the furnace, cylindrical in shape and composed of a metal plate lined internally with refractory material. It contains the materials to be melted and is equipped with two side doors to ensure access to the furnace for maintenance and management work;
- "*Mobile vault*", an upper element that forms the roof of the electric arc furnace. Like the vat, it is also water-cooled and has three holes (typically arranged in an equilateral triangle) for the electrodes, plus a fourth larger hole to allow the extraction of gases and fumes exiting the furnace. Since it

is mobile, the vault can be removed to uncover the vat for loading from above.

One of the main components of the electric arc furnace is certainly the electrodes that are lowered into it to ensure the melting of steel. The most common modern electric arc furnaces are the three-phase furnaces (Figure 2-19(d) and Figure 2-20), i.e. they are equipped with three electrodes arranged in an equilateral triangle, which are lowered into the furnace through special holes in the vault. The electrodes are made of graphite and carry the electricity inside the furnace. The alternating current passing through the electrodes, with a voltage of around 400–900V and intensity around 44000A, causes ionisation of the air between the electrode and the charge, generating an arc with very high temperatures (10000–12000°C). This results in the transformation of electrical energy in heat, which is transmitted to the charge, firs by radiation and then by conduction. During the melting process, the electrodes are subjected to extremely high thermal and mechanical stressed and oxidation actions occurring at high temperature. In order to guarantee resistance to all these stresses, they must meet certain requirements such as non-fusibility, resistance to erosion, resistance to sublimation, resistance to oxidation at high temperature, good electrical and thermal conductivity, low thermal expansion coefficient, resistance to thermal shock, resistance to interaction with liquid steel and slag, etc. [3,5].

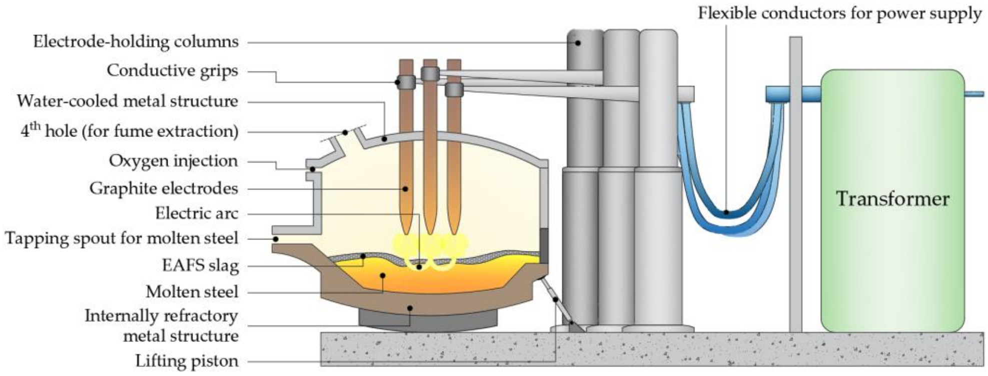


Figure 2-20: Schematic representation of the Electric Arc Furnace and the equipment necessary for supplying electrical energy to the electrodes (adapted from [5,6]).

The basic **raw material** for steel production in electric arc furnace is the **iron and steel scrap**. Both its physical (shape and size) and chemical characteristics are measured. The first have a great influence on the charge volume, melting rates, furnace charging times, internal processes and reactions taking place in the furnace itself, while the second have a greater influence on the refining processes, the quality of the steel and the presence of any impurities. Until a few years ago, scrap was the main source of supply for electric furnaces. Nowadays, however, it is rather difficult to find good quality scrap, mainly due to the widespread use of electric furnaces and the consequent increase in the cost of this raw material. Another reason for the reduction in the supply of high-quality scrap is the continuous development of steel treatment techniques, such as galvanising, painting, application of anti-oxidants, etc., which cause the presence of undesirable elements in a steel that is then destined for reuse in a furnace as scrap (e.g. Nickel (Ni), Chromium (Cr), Manganese (Mn), Silicon (Si), Tin (Sn), organic products, etc.). Scrap from uncertain and unknown origin has to be carefully analysed and selected, while scrap from stainless steel elements has to be collected separately from conventional scrap (due to the rather high presence of Nickel (Ni) and Chromium (Cr)) [3,5].

Besides scrap, another material present in the charge is the **cast iron**, which usually does not exceed 10–15% of the total charge. Nowadays, the electric arc furnace is also charged with **iron pre-cast**, in the form of sponge and/or pellet (benefits in terms of cleaning the raw material with regard to any undesirable elements).

Before entering the furnace, the scrap can undergo crushing and grinding operations and then be pre-heated (to temperatures varying between 300 and 800°C) in special "*baskets*" equipped with a burner sized to ensure pre-heating of the scrap between charges. The pre-heating process can also be carried out by the hot gases exiting the furnace and recovered through the "*fourth hole*" in the roof vault and allow s for a reduction in energy consumption and faster melting. A check on the properties of the exiting fumes is therefore absolutely necessary. The charging of the furnace from the top of the mobile vault takes place in several steps since the excessive voluminosity of the scrap does not allow the entire charge to be done at once [3,5].

Once the charge is melted, the refining phase begins, i.e. obtaining steel of desired composition and characteristics. During the refining process in the electric arc furnace, the so-called *Electric **A**rc **F**urnace **S**lag* ("***EAFS***") is formed, with controlled chemical properties and viscosity and thanks to the addition of other raw materials such as **limestone**, **lime** and **fluorspar**. At the same time, the carbon is oxidised by the addition of **iron ore** and **mill scale** in order to obtain a steel with a certain final carbon content. Another addition could be **gaseous oxygen**, which would be blown in the furnace to ensure fast decarbonisation. During the refining process, dephosphorisation may also take place [5].

When the scrap is melted ("*melt-down*") and all appropriate additions have been made, the molten metal is deposited at the bottom of the furnace and the slag on top of it. Slagging (tilting the furnace in one direction) and tapping (tilting the furnace in the other direction) operations are then performed. The complete electric arc furnace cycle (charging, melting, refining and casting) usually lasts less than an hour [1,5].

Without going into too much detail, the main reactions occurring during the different stages of steel and slag production in the electric arc furnace are listed below [92]:

- Chemical reactions of scrap components:

$$2[Fe] + 3[O] \rightarrow (Fe_2O_3) \tag{2-19}$$

$$[Fe] + [O] \rightarrow (FeO) \tag{2-20}$$

$$[C] + [O] \rightarrow CO \tag{2-21}$$

$$[Si] + 2[O] \rightarrow (SiO_2) \tag{2-22}$$

$$[Mn] + [O] \rightarrow (MnO) \tag{2-23}$$

$$2[P] + 5[O] \rightarrow (P_2O_5) \tag{2-24}$$

$$2[Cr] + 3[O] \rightarrow (Cr_2O_3) \tag{2-25}$$

- Chemical reactions proceeding on adding “*fluxes*”:

$$(CaO) + [S] \rightarrow (CaS) + [O] \tag{2-26}$$

$$(CaCO_3) \rightarrow (CaO) + CO_2 \tag{2-27}$$

$$(MgCO_3) \rightarrow (MgO) + CO_2 \tag{2-28}$$

$$2[Al] + 3[O] \rightarrow (Al_2O_3) \tag{2-29}$$

- Chemical reactions during deoxidation:

$$[Mn] + [O] \rightarrow (MnO) \tag{2-30}$$

$$2[Al] + 3[O] \rightarrow (Al_2O_3) \tag{2-31}$$

$$[Si] + 2[O] \rightarrow (SiO_2) \tag{2-32}$$

$$2[Fe] + 3[O] \rightarrow (Fe_2O_3) \tag{2-33}$$

$$[Fe] + [O] \rightarrow (FeO) \tag{2-34}$$

$$[C] + [O] \rightarrow CO \tag{2-35}$$

- Chemical reactions with alloying additions:

$$[Mn] + [O] \rightarrow (MnO) \tag{2-36}$$

$$2[Fe] + 3[O] \rightarrow (Fe_2O_3) \tag{2-37}$$

$$[Fe] + [O] \rightarrow (FeO) \qquad (2\text{-}38)$$

$$[Si] + 2[O] \rightarrow (SiO_2) \qquad (2\text{-}39)$$

$$[C] + [O] \rightarrow CO \qquad (2\text{-}40)$$

$$2[P] + 5[O] \rightarrow (P_2O_5) \qquad (2\text{-}41)$$

$$(CaO) + [S] \rightarrow (CaS) + [O] \qquad (2\text{-}42)$$

$$2[Al] + 3[O] \rightarrow (Al_2O_3) \qquad (2\text{-}43)$$

$$2[Cr] + 3[O] \rightarrow (Cr_2O_3) \qquad (2\text{-}44)$$

$$[Zn] + [O] \rightarrow [ZnO] \qquad (2\text{-}45)$$

$$2[B] + 3[O] \rightarrow (B_2O_3) \qquad (2\text{-}46)$$

As mentioned before, Electric Arc Furnace Slag ("*EAFS*") is formed during the refining processes of molten steel in the electric arc furnace. The oxygen injected directly into the molten steel bath contributes to the oxidation of the impurities in the charge, the presence of which would results in steel with low mechanical properties. These oxidised compounds combine with the additions (the "*fluxes*", such as lime, dolomite, etc.), forming a layer of slag that is deposited in top of the molten steel bath (due to its lower density). There are several functions the slag inside the furnace: absorption of impurities that would otherwise be included in the steel, protecting the electrodes and the refractories from oxidation, protecting the molten steel bath from possible reoxidation and limiting heat loss to the environment, ensuring greater efficiency and stability of the production process. Once the production processes in the furnace are complete and the chemical compositions of steel and slag have been verified to meet the desired ones, the slagging and tapping operations are carried out [93].

From one tonne of steel produced in an electric arc furnace, **approximately 100–150 kg of electric arc furnace slag** is obtained [50,93].

2.3.1.2 *Electric Arc Furnace Slag ("EAFS"): types, properties and possible reuses*

The composition and final characteristics of electric arc furnace slag depend essentially on the type of furnace, the raw materials, the operating conditions of the furnace and the properties of the steel to be produced. Electric arc furnace slag can be of two main types, depending on the type of steel produced: so-called *Electric* ***A****rc* ***F****urnace* ***S****lag from* ***C****arbon steel production* ("**EAFS-C**") and so-called *Electric* ***A****rc* ***F****urnace* ***S****lag from* ***S****tainless/high alloy steel production* ("**EAFS-S**"). The latter differs from the former because an additional step, i.e. the addition of alloys (Ferrochromium and Nickel) is required in the stainless steel furnace production process [94]. Table 2-28 shows and summarises the most common cooling processes, treatments and applications of EAFS [10,95,96].

Table 2-28: Most common cooling processes, treatments and applications of Electric Arc Furnace Slag from Carbon steel production ("EAFS-C") [10,95,96].

Electric Arc Furnace Slag from Carbon steel production ("EAFS-C") and Electric Arc Furnace Slag from Stainless/high alloy steel production ("EAFS-S")	
Cooling process	• For EAFS-C: slow air-cooling (possibly applying small amounts of water) under controlled conditions in pots or pits • For EAFS-S: slow air- or water-cooling
Material aspect	• Rock-like and crystalline materials (with maximum sizes of 300 mm)
Common treatments	• Weathering to achieve volumetric stability • Crushing, sieving, grading and magnetic separation of the metal residues
Common reuses of EAFS-C	• *As aggregate for* bituminous and hydraulically bound mixtures (asphalt, concrete, road binder, etc.), top layers for high skid resistance, unbound mixtures, dams (road construction and noise protection), wastewater treatment, embankments and fills, railway ballast, sealing in surface layers, roofing, ground stabilisation, armour stone, gabions • *For the manufacture of* cement and other hydraulic binders, glass (blended with other components), stone wool
Common reuses of EAFS-S	• *As aggregate for* bituminous and hydraulically bound mixtures (asphalt, concrete, road binder, etc.), top layers for high skid resistance, unbound mixtures, dams (road construction and noise protection), embankments and fills, sealing in surface layers, roofing, ground stabilisation, armour stone, gabions, industrial neutralisation product • *For the manufacture of* cement and other hydraulic binders, glass (blended with other components), stone wool

Figure 2-21: Electric Arc Furnace Slag from Carbon steel production ("EAFS-C") [96].

According to data on global steel production (which will be explained and discussed in more detail in Section 3), stainless steel reached 58.3 million tonnes in 2021, which is about one-tenth of the world's total electric arc furnace steel production (563 million tonnes) [97,98]. Slag from stainless steel production ("*EAFS-S*") is therefore produced in much smaller quantities than slag from carbon steel production ("*EAFS-C*"). Also considering the great variability of EAFS-S due to the addition of different types of alloys in the production process, their properties will therefore only be mentioned in the following, while the properties of EAFS-C will be mainly investigated and analysed in detail.

Table 2-29 summarises the main **physical properties** of the Electric Arc Furnace Slag from Carbon steel production ("*EAFS-C*").

Table 2-29: Main Electric Arc Furnace Slag from Carbon steel production ("EAFS-C") physical properties.

Electric Arc Furnace Slag from Carbon steel production ("EAFS-C") physical properties			
Property	**Units**	**Values**	**References**
Dimension (fine)	[mm]	0–4.75	[66,99,100,101,102,103(*),104,105,106,107,108,109,110,111,112,113,114,115,116,117,118,119,120,121,122,123,124,125,126]
Dimension (coarse)	[mm]	4.75–32.00	[66,99,100,101,102,103,104,105,107,108,111,112,113,114,115,116,117,119,120,121,122,123,124,125,126,127,128,129,130,131,132,133]
Density	[kg/m^3]	2840–3854	[20,73,100,107,108,114,115,120,124,126]
Bulk density	[kg/m^3]	1482; 1700	[103,121,127128,130]
Specific gravity	[-]	2900–3970	[66,99,101,102,103,104,109,111,112,118,119,121,123,125,127,128,130,131,132]
Specific weight	[kg/m^3]	3350; 3440	[113,117]
Specific surface area	[cm^2/g]	5000–5100	[20]
Fineness modulus	[%]	2.83–7.78	[109,121]
Volumetric expansion	[%]	0.14–2.90	[101,107,121,128]
Water absorption	[%]	0.18–10.50	[66,73,99,100,101,102,103,104,107,108,109,112,115,117,118,119,120,121,123,125,126,127,128,130,131,132]
Pore dimension	[μm]	0.01–10.00	[123,125]
Porosity	[%]	7.8–42.96	[117,123]
Loss on ignition (LOI) (†)	[%]	-3.60; +2.24; gain	[106,118,134]

Table 2-29: Cont.

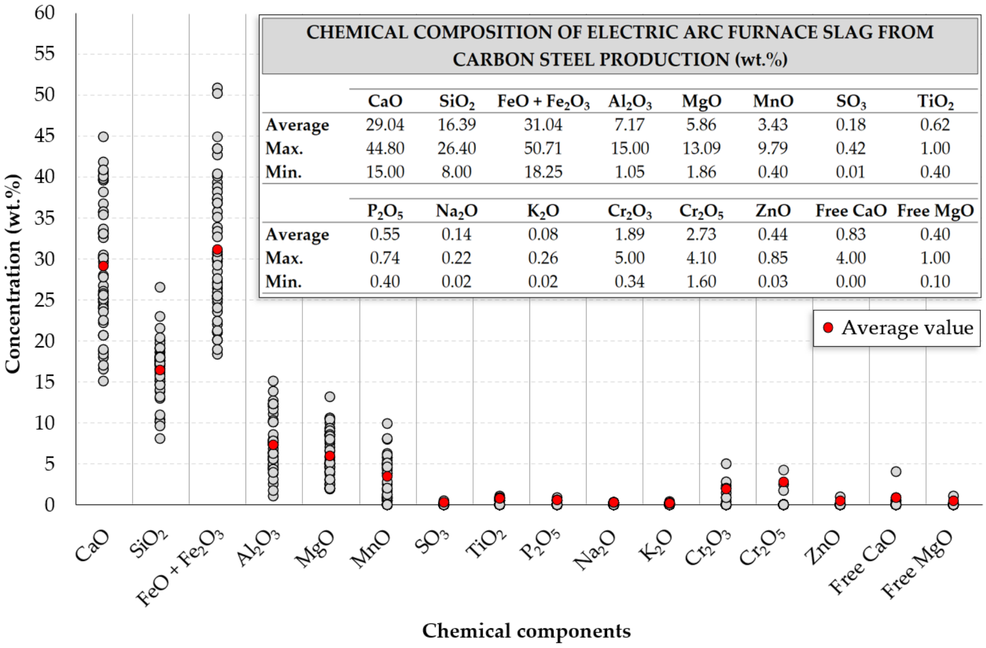
Electric Arc Furnace Slag from Carbon steel production ("EAFS-C") physical properties			
Property	**Units**	**Values**	**References**
Los Angeles (LA)	[%]	11.6–29	[73,99,101,102,104,108,112,115,119,121,123,124,125,126,128,130]
Crushing value	[%]	13–19.25	[107,130]
Impact value	[%]	24.93	[130]
Micro Deval abrasion	[%]	6.5–9.5	[99,107,126]
Mass loss after freeze/thaw cycles	[%]	0–2.1	[73,99,107,112,121,126]
Shape index	[%]	1–10	[73,99,126]
Flakiness index	[%]	1–8	[99,103,115,121,124,126]
Sand equivalent	[%]	66–92	[126]
Methylene blue value	[g/kg]	0.1–0.5	[126]
Resistance to polishing	[-]	0.44; 0.47	[99]
Thermal shock resistance	[%]	1; 2	[99]
Aggregate-bitumen affinity	[%]	10; 15	[99]
Compressive strength	[MPa]	320; 350	[73]
Shape	[-]	Cubical, sharp-pointed	[95,130,132]
Colour	[-]	Black/grey	[6,114,130]

(*) From sieving, 12.3% passing through the 5mm sieve, but slag used in concrete only as coarse aggregate.

(†) Property that typically accompanies the chemical composition of the slag, shown in this table for a better comprehension. A negative value of the LOI parameter indicates an increase in weight, a positive value indicates a loss of weight of the sample (the measurement method is very susceptible to weight losses due to atmospheric moisture content) [134]

Figure 2-22 shows the typical **chemical composition** of Electric Arc Furnace Slag from Carbon steel production ("*EAFS-C*"). For better understanding, the graph is accompanied by a table in which the minimum, maximum and average values are indicated for each component (the average value is also marked by a red dot on the graph). From each paper consulted, the chemical compositions of the slag used were obtained, represented by the grey dots in the graph [20,66,73,99–104,106–108,110,112,113,117,118,122–125,128,132,134,135,136,137,138].

From a comparison, it can be seen that calcium oxide (CaO), silica (SiO_2) and iron oxides (FeO and Fe_2O_3) are the main components of the electric arc furnace slag from carbon steel production, summing up the average values. There are also important concentrations of alumina (Al_2O_3) and magnesium oxide (MgO). Other elements present in low concentrations are manganese oxide (MnO), sulphuric anhydride (SO_3), titanium dioxide (TiO_2), phosphoric anhydride (P_2O_5), sodium oxide (Na_2O), potassium oxide (K_2O), chromium oxides (Cr_2O_3, Cr_2O_5) and zinc oxide (ZnO). Like BOFS, electric arc furnace slag also contains a certain percentage of free calcium oxide (free CaO) and periclase (MgO), although in smaller quantities. As mentioned earlier, these two compounds were studied in detail as they are mainly responsible for the volumetric instability of the slag in the short and long term. Some methods to reduce their contents have already been discussed in Table 2-24 for BOFS and will also be briefly mentioned below for EAFS-C.


CHEMICAL COMPOSITION OF ELECTRIC ARC FURNACE SLAG FROM CARBON STEEL PRODUCTION (wt.%)

	CaO	SiO_2	$FeO + Fe_2O_3$	Al_2O_3	MgO	MnO	SO_3	TiO_2
Average	29.04	16.39	31.04	7.17	5.86	3.43	0.18	0.62
Max.	44.80	26.40	50.71	15.00	13.09	9.79	0.42	1.00
Min.	15.00	8.00	18.25	1.05	1.86	0.40	0.01	0.40

	P_2O_5	Na_2O	K_2O	Cr_2O_3	Cr_2O_5	ZnO	Free CaO	Free MgO
Average	0.55	0.14	0.08	1.89	2.73	0.44	0.83	0.40
Max.	0.74	0.22	0.26	5.00	4.10	0.85	4.00	1.00
Min.	0.40	0.02	0.02	0.34	1.60	0.03	0.00	0.10

Figure 2-22: Chemical composition of Electric Arc Furnace Slag from Carbon steel production (EAFS-C) [20,66,73,99–104,106–108,110,112,113,117,118,122–125,128,132,134–138].

For the sake of completeness, here are also some examples of the chemical composition of Electric Arc Furnace Slag from Stainless/high alloy steel production ("*EAFS-S*"), highly dependent on the alloys additions:

- Stainless steel slag [18]: CaO (56.90%), SiO_2 (23.00%), Fe_2O_3 (1.41%), Al_2O_3 (5.27%), MgO (6.23%), MnO (1.68%), TiO_2 (1.50%), P_2O_5 (<0.10%), Cr_2O_3 (2.96%);

- Stainless steel slag [61]: CaO (43.22%), SiO_2 (27.82%), Fe_2O_3 (7.54%), Al_2O_3 (2.74%), MgO (7.35%), MnO (0.68%), SO_3 (1.73%), TiO_2 (0.59%), P_2O_5 (0.45%), Cr_2O_5 (0.95%), free CaO (0.58%);
- Alloy and high alloy steel slag (average results of 10 samples) [136]: CaO (15–25%), SiO_2 (5–25%), FeO_x (30–50%), Al_2O_3 (1–3%), MgO (1–3%), Cr_2O_3 (5–30%), V_2O_5 (1–2%);
- Special steel slag (average results of 46 samples) [136]: CaO (20–50%), SiO_2 (10–40%), FeO_x (5–30%), Al_2O_3 (5–15%), MgO (5–15%), Cr_2O_3 (0.5–5%), V_2O_5 (0.05–0.4%).

With regard to **mineralogical properties**, the main constituents of Electric Aer Furnace Slag are shown in Table 2-30.

Table 2-30: Mineral constituents of Electric Arc Furnace Slag.

Constituent	Formula	References
Belite (dicalcium silicate)	C_2S (or Ca_2SiO_4)	[66,103,104,106,107,114,123, 136–138]
Alite (tricalcium silicate)	C_3S (or Ca_3SiO_5)	[106,107,138]
Srebrodolskite (dicalcium ferrite)	C_2F (or $Ca_2Fe_2O_5$)	[107,123]
Calcite (calcium carbonate)	$CaCO_3$	[125,127,128,138]
Brownmillerite	C_4AF (or $Ca_2(Al,Fe)_2O_5$)	[104,106,107,136]
Olivine(*)	$(Mg,Fe)_2SiO_4$	[132,134]
Wustite	FeO	[66,103,104,106,107,114,118, 123,125,128,132,134,136,137]
Magnesioferrite	$MgFe_2O_4$	[114]
Magnesiochromite	$MgCr_2O_4$	
Magnetite	Fe_3O_4	[66,103,106,123,128,137]
Akermanite	$Ca_2MgSi_2O_7$	[123]
Gehlenite	$Ca_2Al_2SiO_7$	[114,118,123,125,128,132,134, 136]
Mayenite	$Ca_{12}Al_{14}O_{33}$	[66,104,106,107]
Bredigite	$Ca_7Mg(SiO_4)_4$	[66,103,125]
Hematite	Fe_2O_3	[104]
Calcium iron oxide	$CaFe_2O_4$	[107]
Rankinite	$Ca_3Si_2O_7$	
Fayalite	Fe_2SiO_4	[73]
Kirschsteinite	$CaFeSiO_4$	[118,123,136]

(*) *Isomorphic mixture of forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4)*

As shown in Table 2-28, Electric Arc Furnace Slag can be reused in different applications. Its similar and/or better physical and mechanical characteristics, compared to that of natural aggregates, make it ideal for reuse in the construction industry. Due to its resistance to polishing and abrasion and the excellent affinity to bitumen, EAFS slag is a valid alternative to natural aggregate in the road construction sector (e.g. for road surface treatments [95], for bituminous paving mixtures [73,107,122,134] or as fillers and sub-base layers [115]).

Although the road construction sector is the one where most of the slag is reused, a percentage is also reused for the production of cement and concrete. In [106], the Authors investigated the possibility of producing Portland cement from clinker to which a certain percentage of EAFS is added, and then analysed in detail the hydration process and some performance characteristics of pastes made with this type of cement. In [138], the Authors instead studied the mechanical properties and reaction kinetics of cement pastes composed of a mix of ordinary Portland cement and different percentages of EAFS, recording a negligible pozzolanic reactivity of the slag and obtaining compressive strength values close to those of the reference mix (made only with ordinary Portland cement), especially in the long term.

Finally, there literature contains numerous studies on the use of different percentages of EAFS for the production of concrete, partially replacing both the binder and the natural fine and/or coarse aggregate. Many of the results obtained from the aforementioned studies are analysed in detail in the following Section, which will mainly focus on electric arc furnace slag from carbon steel production (EAFS-C), neglecting slag from stainless/high alloy steel production for the reasons already stated in Section 2.3.1.2.

2.3.1.3 Electric Arc Furnace Slag from Carbon steel production ("EAFS-C"): reuse for concrete production

The good physical and mechanical properties of EAFS make it a suitable material for reuse as a binder or as fine and/or coarse aggregate for the production of concrete, providing numerous benefits but also giving rise to some **critical issues**. In particular:

- ***Density***. EAFS has a higher density (3500–3600 kg/m^3) than natural aggregate (2500–2700 kg/m^3) commonly used in concrete production. This results in a higher concrete density compared to that of standard concrete, with a consequent increase in the self-weight of structural elements, higher seismic vulnerability of the latter and higher transport costs (for the same loadable weight, the volume transported will be lower), effectively limiting the possibility of reusing this type of slag for this specific application [103]. As the substitution percentage of natural aggregate-slag increases, the concrete density will obviously increase. The cooling process of the slag after slagging is one of the main factors characterising not only its density, but also other properties such as porosity, pore size and distribution and water absorption. In [123], for example, the Authors produced concretes with two different EAFS: one that underwent a normal cooling process (called EAF1) and the other characterised by a slower cooling process, which ensured a better evacuation of the gases contained in it and led to obtaining a slag (called EAF2) with lower porosity and water absorption but with higher density compared to EAF1. Consequently, the density of the concrete produced with EAF2 was higher than that produced with EAF1;

- ***Presence of free CaO and MgO***. The second critical issue in the reuse of EAFS as aggregate in concrete is related to the presence of free calcium oxide (CaO) and magnesium oxide (MgO). Although they are present in smaller quantities than the concentration in BOFS, they still contribute to the volumetric instability of the concrete, due to their hydration once they come in contact with the mixing water (hydration reactions of these two compounds and expansion phenomenon already exposed and discussed in Section 2.2.2.3). In the past, these volumetric instability phenomena were one of the main causes of the limited reuse of EAFS slag in concrete production. The continuous search for solutions to this problem has led to the development of functional method capable of reducing the content of these compounds in the slag. As was done for BOFS with Table 2-24, the different methods for reducing the content of free CaO and MgO in EAFS are summarised in Table 2-31.

Table 2-31: Main methods for reducing free-CaO and free-MgO contents in EAFS.

EAFS treatment methods	Results after treatments	Refs.
• Ageing for 3, 4 or 6 months in an open area	• Volumetric expansion is inversely proportional to the ageing time of the slag • To ensure acceptable volume stability, an ageing period of at least 2–3 months is recommended	[99,105,126]
• Weathering over several weeks	• Improvements in the expansive behaviour of the slag	[101]
• Exposure to weather and open air and regular water spraying for 90 days	• Performing a specific chemical analysis and tests (e.g. Autoclave test) to ensure that expansion does not occur	[104,108,132]
• Weathering in outdoor environment for at least 6 months	-	[112]

Table 2-31: Cont.

EAFS treatment methods	**Results after treatments**	**Refs.**
- Weathering in an open area for several months	- Reduction in lime content	[116]
- Ageing outdoor for at least 90 days and treated with water every day	- Slag volume stability determined using expansion tests	[128]
- Stockpiled for more than a year and dried for another 2 months in the laboratory	- Reduction in free CaO concentration	[129]
- Outdoor ageing of at least 90 days and some daily wetting/drying cycles	- Reduction of expansion phenomena due to the hydration of free CaO and MgO	[131]

As previously analysed, the hydration of free calcium oxide (free CaO) causes volumetric expansion at early age, while that of magnesium oxide (MgO) leads to further expansion in the long term. In addition to these phenomena, oxidation of the iron nodules embedded in the slag also contributes to further expansions and corrosion products [108]. As for BOFS, the treatments described in Table 2-31 are therefore necessary for EAFS prior to its reuse in a rigid matrix (e.g. concrete), in order to reduce the content of these compounds and to avoid the formation of cracks in the mix due to expansion phenomena, which could affect its durability.

In Table 2-32, the rheological, performance and durability properties of the **N**ormal **S**trength **C**oncrete ("***NSC***") with the addition of Electric Arc Furnace Slag from Carbon steel production ("*EAFS-C*") in **partial or total replacement of binder, fine and/or coarse aggregate** will be analysed, in order to understand how its addition can affect the behaviour of the concrete mix itself when compared with a reference concrete (i.e. without slag).

*Table 2-32: Behaviour of the **N**ormal **S**trength **C**oncrete ("**NSC**") made with Electric Arc Furnace Slag from Carbon steel production ("EAFS-C") as partial or total replacement of binder, fine and/or coarse aggregate compared to the reference concrete (without the addition of slag).*

Slag	**Used as**	**Property: *Workability***	**Ref.**
EAFS-C	Binder	- Lower	[20]
EAFS-C	Coarse aggregate	- Lower (100% substitution percentage)	[66]
EAFS-C	Fine / Coarse aggregate	- Lower at higher substitution percentages, perhaps due to the higher water absorption of the EAFS-C	[100]

Table 2-32: Cont.

Slag	**Used as**	**Property: *Workability* (cont.)**	**Ref.**
EAFS-C	Fine / Coarse aggregate	• Lower at higher substitution percentages	[101]
EAFS-C	Fine / Coarse aggregate	• Comparable, thanks to the addition of a fluidifying agent	[102,104]
EAFS-C	Fine / Coarse aggregate	• Lower	[108,126]
EAFS-C	Binder	• Lower at higher substitution percentages (maybe due to the surface roughness of the slag)	[110]
EAFS-C	Fine / Coarse aggregate	• Comparable (addition of a plasticizer admixture)	[111,123]
EAFS-C	Fine / Coarse aggregate	• Comparable (addition of a superplasticizer admixture), both for C25/30 and C30/37 concretes	[113]
EAFS-C	Fine / Coarse aggregate	• Comparable, thanks to the addition of a superplasticizer admixture	[125]
EAFS-C	Coarse aggregate	• Lower (increased with increasing in the coarse aggregate size)	[129]
EAFS-C	Coarse aggregate	• Comparable	[130]

Slag	**Used as**	**Property: *Air content***	**Ref.**
EAFS-C	Binder	• Lower	[20]
EAFS-C	Coarse aggregate	• Slightly lower (100% substitution percentage)	[66]
EAFS-C	Fine / Coarse aggregate	• Higher at higher substitution percentages	[100]
EAFS-C	Coarse aggregate	• Comparable	[103]
EAF-C	Fine / Coarse aggregate	• Higher, comparable and lower, depending on the mix considered	[108]
EAFS-C	Fine / Coarse aggregate	• Comparable or slightly lower, both for C25/30 and C30/37 concretes	[113]

Slag	**Used as**	**Property: *Density***	**Ref.**
EAFS-C	Coarse aggregate	• Higher (100% substitution percentage)	[66]

Table 2-32: Cont.

Slag	**Used as**	**Property:** ***Density*** **(cont.)**	**Ref.**
EAFS-C	Fine / Coarse aggregate	• Higher at higher substitution percentages	[100,104,119]
EAFS-C	Fine / Coarse aggregate	• Higher	[102,108,111,113,123,125,126]
EAFS-C	Coarse aggregate	• Higher, with great variability at different times	[103]

Slag	**Used as**	**Property:** ***Initial and final setting times***	**Ref.**
EAFS-C	Binder	• Delay in both setting times • The addition of gypsum slightly reduced the setting times, but did not produce a significant different in initial setting time • Setting times of EAFS-C slag concretes comparable with those of GGBFS concrete (positive result as GGBFS is already widely used as a cement substitute)	[20]

Slag	**Used as**	**Property:** ***Development of the strength***	**Ref.**
EAFS-C	Binder	• Slower, especially at early age • The addition of gypsum accelerated the development of the strength	[20]
EAFS-C	Fine / Coarse aggregate	• Faster	[100,102]
EAFS-C	Fine / Coarse aggregate	• Slower at early age, comparable or faster for longer periods	[101]
EAFS-C	Fine / Coarse aggregate	• Comparable	[104,125]
EAFS-C	Binder	• Slower at early age, comparable for longer periods (maybe due to a retardation effect on cement hydration)	[110]
EAFS-C	Fine / Coarse aggregate	• Slower at early age, faster for longer periods, both for C25/30 and C30/37 concretes	[113]
EAFS-C	Coarse aggregate	• Comparable	[129,130]

Table 2-32: Cont.

Slag	**Used as**	**Property:** ***Compressive strength***	**Ref.**
EAFS-C	Binder	• Lower at early age, comparable to 28 days	[20]
EAFS-C	Coarse aggregate	• Slightly higher (100% substitution percentage)	[66]
EAFS-C	Fine / Coarse aggregate	• Higher at higher substitution percentages	[100]
EAFS-C	Fine / Coarse aggregate	• Lower at early age, comparable after 90 days and 1 year	[101]
EAFS-C	Fine / Coarse aggregate	• Higher (increased by about 30% for a substitution percentage of ~85%)	[102]
EAFS-C	Fine / Coarse aggregate	• Comparable or slightly higher • Lower in mixes with 100% fine aggregate replacement	[104]
EAFS-C	Fine / Coarse aggregate	• Slightly higher, comparable and lower, depending on the mix considered	[108]
EAFS-C	Binder	• Lower at early age, comparable for longer periods, depending on the mix considered	[110]
EAFS-C	Fine / Coarse aggregate	• Lower at early age, higher for longer periods, both for C25/30 and C30/37 concretes	[113]
EAFS-C	Fine / Coarse aggregate	• Lower for substitution percentages of 45, 50 and 55%, higher for substitution percentages of 60 and 65%	[119]
EAFS-C	Fine / Coarse aggregate	• Higher (increased about 38%)	[123]
EAFS-C	Fine / Coarse aggregate	• Higher	[125]
EAFS-C	Coarse aggregate	• Higher	[129,130]

Slag	**Used as**	**Property:** ***Flexural strength***	**Ref.**
EAFS-C	Fine / Coarse aggregate	• Higher at higher substitution percentages	[100]
EAFS-C	Binder	• Lower, comparable or slightly higher, depending on the mix considered	[110]
EAFS-C	Fine / Coarse aggregate	• Lower for substitution percentages of 45, 50, 55 and 60%, higher for substitution percentage of 65%	[119]

Table 2-32: Cont.

Slag	**Used as**	**Property:** ***Flexural strength*** **(cont.)**	**Ref.**
EAFS-C	Fine / Coarse aggregate	• Comparable or slightly higher	[125]
EAFS-C	Coarse aggregate	• Slightly higher or higher	[130]

Slag	**Used as**	**Property:** ***Split tensile strength***	**Ref.**
EAFS-C	Binder	• Lower at early age, comparable to 28 days	[20]
EAFS-C	Coarse aggregate	• Lower (100% substitution percentage)	[66]
EAFS-C	Fine / Coarse aggregate	• Higher at higher substitution percentages	[100]
EAFS-C	Fine / Coarse aggregate	• Higher	[102]
EAFS-C	Fine / Coarse aggregate	• Slightly higher	[104,123]
EAFS-C	Binder	• Lower or slightly lower, depending on the mix considered	[110]
EAFS-C	Fine / Coarse aggregate	• Higher or slightly higher, both for C25/30 and C30/37 concretes	[113]
EAFS-C	Fine / Coarse aggregate	• Lower for substitution percentages of 45, 50, 55 and 60%, slightly higher for substitution percentage of 65%	[119]
EAFS-C	Coarse aggregate	• Slightly higher or higher	[130]

Slag	**Used as**	**Property:** ***Elastic modulus***	**Ref.**
EAFS-C	Fine / Coarse aggregate	• Higher at higher substitution percentages	[100]
EAFS-C	Fine / Coarse aggregate	• Higher	[102,108, 125,126]
EAFS-C	Fine / Coarse aggregate	• Comparable or slightly higher	[104]
EAFS-C	Binder	• Comparable or higher, depending on the mix considered	[110]
EAFS-C	Fine / Coarse aggregate	• Comparable	[123]

Table 2-32: Cont.

Slag	**Used as**	**Property:** ***Pores volume***	**Ref.**
EAFS-C	Fine / Coarse aggregate	• Lower volume of permeable voids	[119]
EAFS-C	Fine / Coarse aggregate	• Comparable	[123]

Slag	**Used as**	**Property:** ***Porosity***	**Ref.**
EAFS-C	Fine / Coarse aggregate	• Slightly higher	[101]
EAFS-C	Fine / Coarse aggregate	• Higher or slightly higher	[123]

Slag	**Used as**	**Property:** ***Water absorption***	**Ref.**
EAFS-C	Fine / Coarse aggregate	• Lower or slightly lower, depending on the mix and the size of the slag in the mix considered	[101]
EAFS-C	Fine / Coarse aggregate	• *Capillary absorption of water*: comparable, slightly higher or slightly lower, depending on the mix considered, both for C25/30 and C30/37 concretes	[113]
EAFS-C	Fine / Coarse aggregate	• Lower	[119]
EAFS-C	Coarse aggregate	• Lower or slightly lower coefficient of water absorption • Lower sorptivity coefficient	[130]

Slag	**Used as**	**Property:** ***Autogenous and drying shrinkage***	**Ref.**
EAFS-C	Binder	• Both autogenous and drying shrinkage higher	[20]
EAFS-C	Coarse aggregate	• Higher drying shrinkage (100% substitution percentage)	[66]
EAFS-C	Fine / Coarse aggregate	• Higher drying shrinkage at higher substitution percentages	[100]
EAFS-C	Fine / Coarse aggregate	• Comparable drying shrinkage	[125,126]

Table 2-32: Cont.

Slag	Used as	Property: *Chloride penetration*	Ref.
EAFS-C	Fine / Coarse aggregate	• Comparable or higher • Higher corrosion of the steel bars embedded in slag concrete (attention to the negative effect of the iron nodules present in the slag on the resistivity and on the corrosion potential measurement)	[111]
EAFS-C	Fine / Coarse aggregate	• Lower, both for C25/30 and C30/37 concretes	[113]
EAFS-C	Coarse aggregate	• Slightly lower	[130]

Slag	Used as	Property: *Sulphate attack*	Ref.
EAFS-C	Fine / Coarse aggregate	• A sulphate resistant cement was selected in order to assessing the potential reactions of sulphates with the slag • Mortar samples were cast for the test • Less expansion after one year of exposure. Over time, these slag mortars showed an increase in compressive strength • Absence of internal damage and zero reactivity of the EAF slag fine fraction	[111]
EAFS-C	Coarse aggregate	• Better resistance to sulphate attack	[130]

Slag	Used as	Property: *Carbonation depth*	Ref.
EAFS-C	Fine / Coarse aggregate	• One to six time higher (high risk of steel bars corrosion in case of reinforced concrete)	[108]
EAFS-C	Fine / Coarse aggregate	• Lower, both for C25/30 and C30/37	[113]

Slag	Used as	Property: *Penetration of water under pressure*	Ref.
EAFS-C	Fine / Coarse aggregate	• Higher, due to the greater porosity of slag compared to that of natural aggregate	[108]
EAFS-C	Fine / Coarse aggregate	• Lower depth of water penetration	[111,123]
EAFS-C	Coarse aggregate	• Lower depth of water penetration	[130]

Table 2-32: Cont.

Slag	Used as	Property: *Behaviour after freeze-thaw cycles*	Ref.
EAFS-C	Fine / Coarse aggregate	• Greater strength loss and various degrees of damage of slag concretes after testing • The use of air-entraining admixtures should increase the resistance to freezing	[101]
EAFS-C	Fine / Coarse aggregate	• Increase in density (about +1.4%) and loss of strength (about –7.3%) after freeze-thaw cycles repeated for 25 days	[102]
EAFS-C	Fine / Coarse aggregate	• Increase both in density and compressive strength after freeze-thaw cycles repeated for 25 days	[104]
EAFS-C	Fine / Coarse aggregate	• Comparable	[108]
EAFS-C	Fine / Coarse aggregate	• Better behaviour both in term of strength and degradation	[111]
EAFS-C	Fine / Coarse aggregate	• Better behaviour in term of mass losses, both for C25/30 and C30/37 concretes	[113]

Slag	Used as	Property: *Behaviour after wet-dry cycles*	Ref.
EAFS-C	Fine / Coarse aggregate	• Comparable or slightly higher	[101]
EAFS-C	Fine / Coarse aggregate	• Increase in density and loss of strength after wetting and drying cycles repeated for 30 days	[102,104]
EAFS-C	Fine / Coarse aggregate	• During the test, the water tends to mobilize the products of the corroded iron nodules present in the slag and deposit them on the surface of the specimens with the consequent formation of stains (important in case of elements with aesthetic function or exposed to water) • Slightly higher expansive potential	[108]

Slag	Used as	Property: *High temperature resistance*	Ref.
EAFS-C	Fine / Coarse aggregate	• Slag concrete was more stable with regard to linear expansion and contraction, with no appreciable signs of deterioration or strength losses	[111]

Table 2-32: Cont.

Slag	Used as	Property: *Alkali-aggregate reaction*	Ref.
EAFS-C	Fine / Coarse aggregate	• Low (possible overlap of the effect of free CaO, MgO and sulphates, if present in the slag, to the alkali-aggregate expansive reaction, contributing to the total expansion at the end of the test)	[101]
EAFS-C	Fine / Coarse aggregate	• The expansion of the slag concrete did not exceed standard limits and the slag can be considered "non-reactive"	[111]

Slag	Used as	Property: *Corrosion of embedded steel bars*	Ref.
EAFS-C	Fine / Coarse aggregate	• Increase time for the start of reinforcement corrosion and cracking of slag concrete specimens	[119]

Slag	Used as	Property: *Leaching behaviour*	Ref.
EAFS-C	Slag, not added to concrete	• 45 EAFS samples analysed: all the samples met the standards to be considered "non-hazardous"	[50]
EAFS-C	Fine / Coarse aggregate	• Good results (the concentration of potentially harmful elements in the eluate did not exceed the limits established by the different standards)	[101,108,125]
EAFS-C	Fine / Coarse aggregate	• Despite compliance with reference standards, slag with smaller size produced a greater release of dangerous substances than larger size slag • Occlusion effect of the concrete matrix on the slag (greater for greater slag sizes), which limits the release of possible contaminants	[101]
EAFS-C	Slag, not added to concrete	• In general, slag with smaller size produced a greater release of elements	[114]

In addition to the reuse for the production of standard structural concrete, EAFS-C can also be reused for the production of "*non-ordinary*" concretes, such as **pervious**, **self-compacting**, **high-performance** and **fibre-reinforced concretes**. Table 2-33 shows a summary of the main results found in the literature and obtained from the inclusion of EAFS-C in these types of concrete.

Table 2-33: Main results on the behaviour of ***"non-ordinary" concretes*** *made with Electric Arc Furnace Slag from Carbon steel production ("EAFS-C") and comparison with reference concrete of the same type (without the addition of slag).*

"Non-ord." **concretes**	**Main results**	**Ref.**
EAFS-C used as coarse aggregate for ***industrial pavement concrete*** production	• 100% slag-natural coarse aggregate substitution percentage • Higher compressive strength, dynamic modulus of elasticity, flexural strength, toughness and impact resistance • Lower mass loss after freeze-thaw cycles • With regard to environmental aspects, slightly reduction (-2%) of Global Warming Potential (GWP) • Slightly higher production costs (+4%)	[112]
EAFS-C used as fine and coarse aggregate for ***pervious concrete*** blocks production	• 100% slag-natural coarse and fine aggregates substitution percentage • Comparable results in terms of compressive strength, modulus of elasticity and splitting tensile strength • Lower flexural strength • Higher resistance to abrasion • Slightly higher mass loss after freeze-thaw cycles • With regard to environmental aspects, reduction of Global Warming Potential (GWP) and production costs (-14% and -10%, respectively)	[112]
EAFS-C used as fine and coarse aggregate for ***heavyweight steel fibre-reinforced concrete*** production	• 100% slag-natural coarse and fine aggregates substitution percentage • Higher compressive strength, compressive strength after exposure to high temperature (500°C), flexural strength and modulus of elasticity • With regard to environmental aspects, reduction (-44%) of Global Warming Potential (GWP)m ,mainly due to the reduction of the cement content (-25%) • Lower production costs (-58%)	[112]
EAFS-C used as fine and coarse aggregate for ***pervious concrete*** production	• Higher water permeability • Higher compressive strength • The porous nature of the slag allowed a greater porosity in the unit volume • The possible expansion of the slag was not so significant due to the designed porosity of the concrete • Reduced possibility of heavy metal ions leaching due to the slag incorporation effect in the matrix • Higher anti-skid capability • Pervious concrete can be used for engineering applications where structural strength and high water permeability are required	[117]

Table 2-33: Cont..

"Non-ord." **concretes**	**Main results**	**Ref.**
EAFS-C used as fine and coarse aggregate for ***self-compacting concrete*** production	• Comparable slump • Higher density (both in fresh and hardened state) • Comparable compressive strength and stiffness modulus • Higher porosity • SEM analysis showed the existence of regions of good and bad adhesion between slag and cement paste • Good slag-cement paste adhesion on hydrophilic slag compounds (gehlenite, olivine, calcite, etc.) • Negative role on slag-cement paste adhesion given by hydrophobic iron oxides (wustite, etc.) emerging on slag surface contours • Through the appropriate use of compatible chemical admixtures, it is possible to made good quality self-compacting concretes with the addition of slag	[118]
EAFS-C used as fine and coarse aggregate for ***high-strength concrete*** production	• Higher unit weight • Higher 7-, 28- and 365-days compressive strength • Higher 28-days splitting tensile strength, flexural strength and fracture toughness • Comparable or lower depth of penetration of water under pressure • Higher abrasion resistance • Slightly lower porosity • When slag is used as a fine aggregate, a finer sand must also be used to improve the overall aggregate gradation • Destination of the concrete analysed: non-reinforced concrete applications (e.g. precast concrete paving blocks, maritime, shipbuilding and defence constructions)	[121]
EAFS-C used as fine and coarse aggregate for ***fibre-reinforced concrete*** production	• Inclusion of both steel and synthetic fibres • Higher 28-days compressive and flexural strengths • Slightly lower, comparable and higher 28-days splitting tensile strength, depending on the mix considered • Slightly lower or lower depth of penetration of water under pressure, depending on the mix considered • Higher toughness (greater post-cracking strength and higher ductility provided by metallic fibres) • Higher impact strength of the mixes with steel fibres • Poor workability: a water/cement ratio of more than 0.5 and the use of plasticising additives, as well as the addition of silica sand are recommended	[124]

From the previous Tables, it is evident that the reuse of electric arc furnace slag in concrete represents a valid alternative, with many studies already present in the literature. The interest in this type of reuse is also demonstrated by the **in-depth study** of several Authors on **particular and important aspects of the material behaviour beyond the mere and simple characterisation** by means of specimens. Some results of these studies are shown in Table 2-34.

*Table 2-34: Main results on **particular aspects** of the behaviour of concrete made with Electric Arc Furnace Slag from Carbon steel production ("EAFS-C") beyond the simple characterisation and comparison with reference concrete (without the addition of slag).*

Parameter	Main results	Ref.
Compressive stress distribution in slag concrete	• EAFS-C used as a partial replacement of fine and coarse aggregates • For the determination of the compressive stress distribution in concrete (basis for the evaluation of flexural performance), eccentric loading tests were conducted on C-type specimens • Proposed stress-strain relationship • Higher modulus of elasticity of slag concrete before peak stress, with gradual decrease in capacity after peak stress • When the compressive stress distribution was replaced with an area up to the point of ultimate strain, the compressive strength of slag concrete specimens was higher • Higher ultimate strain	[120]
Resistance of slag concrete ***to high temperatures exposure***	• EAFS-C used as a partial replacement of coarse aggregate in 4 percentages (15, 30, 50, 100%) • Exposure to high temperature (400–800°C) for different durations (1–2 hours) • Lower strength loss in slag mixes and good overall residual behaviour for both compressive and tensile strengths • Significant reduction in bond between steel bar and concrete matrix from 400 to 800°C exposure (with temperatures held constant for 1.5 hours) • Slight difference in bond once the specimens were exposed at 600°C for durations of 1, 1.5 and 2 hours	[127]

Table 2-34: Cont.

Parameter	Main results	Ref.
Bond between steel reinforcement and slag concrete	• EAFS-C fully replaced natural coarse aggregates • Pull-out tests performed • Higher compressive strength (behaviour observed in concretes with a lor w/c ratio) • The mechanical properties and chemical composition of the slag improved the Interfacial Transition Zone (ITZ) • Higher bond between concrete matrix and ribbed bars • Few differences between concretes with high w/c ratio • Greater dispersion of results with regard to the bond between concrete matrix and smooth bars • Existing equations are conservative for high-strength concretes, whereas they fit better for low-strength concretes • The fib MC2010 equation provides conservative values for the bond between concrete matrix and smooth bars	[131]

The different investigations on the physical, chemical, mineralogical and mechanical properties of the electric arc furnace slag, the studies on the characteristics of standard and "*non-ordinary*" concretes, both in fresh and hardened state and the analysis of some of their specific behaviour have contributed to the progress of the research on the reuse of this type of material in concrete. There are studies in the literature concerning the "*last step*" in the reuse of EAFS for concrete production, i.e. the analysis of the behaviour of **full-scale elements** made of concrete with the addition of electric arc furnace slag in different percentages. Table 2-35 therefore shows some of the main results obtained from the literature.

Table 2-35: Main results of the behaviour of ***full-scale concrete elements*** *with Electric Arc Furnace Slag from Carbon steel production ("EAFS-C") and comparison with reference concrete (without the addition of slag).*

Full-scale element	Main results	Ref.
Beam-column joints tested under ***cyclic loading***	• EAFS-C fully replaced natural coarse aggregates for the production of full-scale exterior beam-column joints, tested under horizontal reversed cycling loading (applied in quasi-static conditions) • Higher compressive strength and elastic modulus • Same failure mode and overall hysteretic behaviour • Higher loads reached by slag concrete samples • Comparable reduction in stiffness during the load history and higher initial secant stiffness • Comparable dissipated energy and less crack development	[132]

Table 2-35: Cont.

Full-scale element	Main results	Ref.
Bond performance of ***RC beams***	• EAFS-C replaced natural fine and coarse aggregates • 4 simple RC beams tested to induce bond failure before flexural and shear failures • Better bond behaviour • Bond behaviour of the lower bars was 30% higher than that of the upper bars • Higher bond behaviour of the bars positioned more externally in the cross-section than that of the internal bars (greater confining effect of the transverse reinforcement bars for the external bars) • Good prediction of the bond behaviour given by existing formulae (however, results underestimated by about 1.8 times by ACI equation if the contribution of transverse reinforcement is neglected to simplify design)	[135]
Flexural behaviour of ***high-strength RC beams***	• EAFS-C replaced natural fine and coarse aggregates • 8 RC beams tested (test variables: aggregate types, tension reinforcement ratios and compressive strength of concrete) • Significant ductile behaviour of slag concrete specimens as compressive strength and tension reinforcement ratio decreased • Higher modulus of rupture (less crack propagation and extension) • Yield and ultimate moments comparable to those of natural aggregate specimens • Good prediction of flexural strength by using current code equations • Higher displacement ductility factor for normal and high-strength concretes	[139]
RC columns subjected to ***combined bending and axial loads***	• EAFS-C replaced natural fine and coarse aggregates • 6 RC columns subjected to reversed cyclic antisymmetric moment (test variables: aggregate types and axial loads) • Comparable flexural strength, regardless of axial load • Good prediction of yield and ultimate moments by existing bending theory (strength requirements of ACI 318-11 code safely met) • Better ductility capacity (displacement ductility index were 1.5 and 2.6 times higher when axial force ratio was set at 20 and 30%, respectively)	[140]

Table 2-35: Cont.

Full-scale element	Main results	Ref.
Flexural behaviour of ***RC beams***	• EAFS-C replaced natural fine and coarse aggregates • 4 RC beams tested (test variable: aggregate types) • Comparable flexural strength • Flexural strength of slag concrete RC beams met the structural requirements proposed by ACI 318-08 code • Based on the analytical and experimental results, the flexural performance of slag concrete RC beams (in terms of first crack, yield and ultimate moments and moment-curvature response) can be reasonably predicted using existing flexural theory • The deflection of slag concrete RC beams under service loads can be successfully predicted using the effective moment of inertia recommended by ACI 318-08 code	[141]
Flexural and shear behaviour of ***RC beams***	• EAFS-C partially replaced natural coarse aggregates • 12 RC beams tested to induce flexural and shear failure modes (test variables: aggregate types, upper and lower longitudinal reinforcement, stirrups and failure modes) • Higher compressive and flexural strength, elastic modulus and specific weight • Lower workability and higher water demand (addition of plasticisers admixtures to adjust the mix) • Higher ultimate capacity in both bending and shear • Reduced crack widths and comparable cracking patterns • EAFS-C can fully replace the natural coarse aggregate (however, attention to the higher density of the concrete)	[142]
Effects of compressive stress distribution on the flexural behaviour of ***RC beams***	• EAFS-C replaced natural fine and coarse aggregates • 18 RC simply supported beams tested to verify the effects of compressive stress distribution on flexural behaviour (test variables: aggregate types, compressive strength, tension and compression reinforcement ratios) • Lower bending at yielding of tension reinforcement (this is due to the higher elastic modulus of slag concrete compared to concrete with natural aggregates) • Better prediction of experimental results by ACI 318M-14 criteria • Generally well-predicted experimental results when comparing the calculated ultimate resistant moment with the criteria of the main countries • Better displacement ductility ratio of slag concrete beams	[143]

2.3.1.4 Discussion

The good physico-chemical and mechanical properties of Electric Arc Furnace Slag from Carbon steel production ("*EAFS-C*") make it suitable for several reuses in the construction sector. A considerable portion is reused for road construction due to its good resistance to polishing and abrasion and its equally good affinity to bitumen. Besides the road sector, this material can also be reused for concrete production. There are several studies in the literature on the addition of EAFS-C slag as partial or total replacement of binder and/or fine and/or coarse aggregate for the production not only of normal strength concrete but also of so-called "*non-ordinary*" concretes (pervious, fibre-reinforced, high or ultra-high performance, self-compacting, etc.). The lower free calcium and magnesium oxides content of EAFS-C in comparison, for example, with BOFS, makes it easier to limit the problem of volumetric instability prior to its addition to the concrete mix (the literature provides several methods for reducing these expansive phenomena). As far as the rheological properties are concerned, workability is penalised as the substitution percentage of the natural aggregate with EAFS-C increases; however, the addition of a suitable additive in the right quantities allows workability to be controlled and the target slump to be achieved. The air content of the mix is comparable or slightly lower than that of the reference ordinary concrete, while the density increases as the substitution percentage increases, due to the higher density of EAFS-C compared to the natural aggregate. The development of strength is slightly slower and good results were obtained with regard to compressive strength (lower at early age but with comparable and/or higher values for longer periods, depending on the mix composition and the substitution percentage). The texture and the mechanical properties of the EAFS-C are probably the main factors that allow concrete to achieve good compressive strengths, many time exceeding even those of the reference concrete. Good results were also obtained in terms of flexural and tensile strengths and elastic modulus. Lower water absorption and smaller pores volume were also recorded, as well as a general increase in drying shrinkage of the slag concrete compared to the reference one. With regard to durability, there are rather conflicting results in the literature, especially in terms of chloride penetration, carbonation depth and penetration of water under pressure. In contrast, concretes with EAFS-C showed good behaviour in terms of resistance to high temperatures and sulphate attack. Finally, leaching tests performed on both granular slag and monolithic samples have demonstrated the non-hazardous nature of this material. This type of slag provides significant advantages in the case of reuse for concrete production, with good results also obtained in terms of concrete durability. Further tests and research still need to be carried out on this latter aspect, as it is of fundamental importance for the proper reuse of the material and for obtaining concretes with good performances not only at early age but also in the long periods.

2.4 Steel refining

The steel produced in a Basic Oxygen Converter (“*BOF*”) or in an Electric Arc Furnace (“*EAF*”) undergoes the so-called “*secondary metallurgy processes*” or “*out-of-furnace treatments*”. The main purpose of these processes is to correct and refine the composition and characteristics of the steel according to production requirements. There are several out-of-furnace treatments and they generally take place in a “*container*” separated from the main furnace (BOF or EAF), known as **L**adle **F**urnace (“***LF***”). The separation of the steel refining processes from the actual production cycle frees the producer from the conditioning of having to meet production requirements each time in the main production furnace, which may vary from casting to casting [5]. In the following, the main steel refining operations in the ladle furnace will be summarised and the properties and possible reuses of the resulting slag will be described in detail.

2.4.1 Ladle Furnace (“LF”)

2.4.1.1 Steel refining processes in Ladle Furnace (“LF”) and Ladle Furnace Slag (“LFS”) production

The **L**adle **F**urnace (“***LF***”) can be seen as a kind of electric arc furnace in miniature, equipped with 3 electrodes connected to a transformer and lined internally with refractory material (a permanent inner layer and an outer layer to be replaced approximately every 40 casts). On the other hand, the bottom and the part in contact with the molten steel (maintained at temperatures around 1600°C) are made of dolomite. Bricks made of magnesite (more resistant to corrosion) are usually used to cover the part in contact with the slag. In addition to the slag (described in detail below), fumes also originate during the refining processes, which are captured and sent to the fume extraction and treatment system [1,54]. Figure 2-23 shows an example of a ladle furnace [6].

As previously mentioned, the are several processes for refining steel in the ladle furnace, each characterised by a different purpose [5,6]:

- Adjustment of temperature and chemical composition of the steel by the addition of special alloys, so as to produce steels with different characteristics;
- Improvement of steel purity by reducing the content of non-metallic inclusions (inclusions of smaller size and of the least harmful type possible for the final steel);
- Final desulphurisation, which consists of eliminating sulphur by adding specific substances (Mn, CaO, etc.) or desulfurizing agents (Mg, CaSi, CaC_2, 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, which can be achieved, for example, by providing the ladle furnace 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 continuously stirred in order to bring the metal that is deep into the surface and vice versa. The stirring is achieved by argon injection from the bottom of the ladle furnace or by an electromagnetic action;
- Completion of decarburization (very thorough decarburization for the manufacture of ultra-low carbon steels (C<0.01%), while avoiding excessive oxidation of the metal;
- Possibility of heating the molten steel (and maintaining the temperature) in order to favour a steel storage system and facilitate flow management between steel mill and continuous casting.

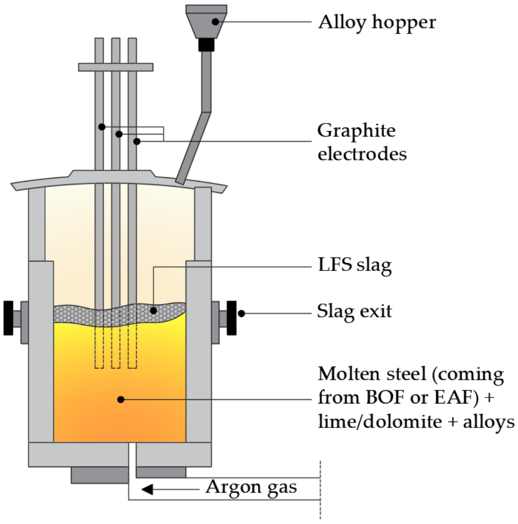


Figure 2-23: Schematic representation of a Ladle Furnace ("LF", adapted from [6]).

As for the different production processes of pig iron and steel illustrated above, the refining processes also generate residues, the so-called **L**adle **F**urnace **S**lag ("***LFS***" or "*white slag*", a name due to their colour, which, for example, is quite different from the black slag from electric arc furnace). Like BFS, BOFS and EAFS, LFS are deposited on top of the liquid steel bath and help to protect the furnace refractories, collect inclusions and other undesirable elements in the composition of the final steel and thermally insulate the steel bath while protecting it from oxidation.

The multitude of out-of-furnace treatment processes possible in a ladle furnace results in different steels in terms of properties and composition. Consequently, the resulting slags will also have different properties and composition depending on the process considered. The quantity of LFS slag produced per tonne of steel are lower than for the other types of slags described in the previous Sections, amounting to **30–50 kg of LFS per tonne of steel refined** [6,18].

In the following, the physical, chemical, mineralogical and performance properties of LFS will be explained in detail and its possible reuse will be described (although their characteristics make their reuse very complicated).

2.4.1.2 *Ladle Furnace Slag ("LFS"): types, properties and possible reuses*

The composition and final characteristics of ladle furnace slag depend essentially on the refining process considered and the properties of the steel to be produced. Table 2-36 summarises the main **physical properties** of the Ladle Furnace Slag ("*LFS*").

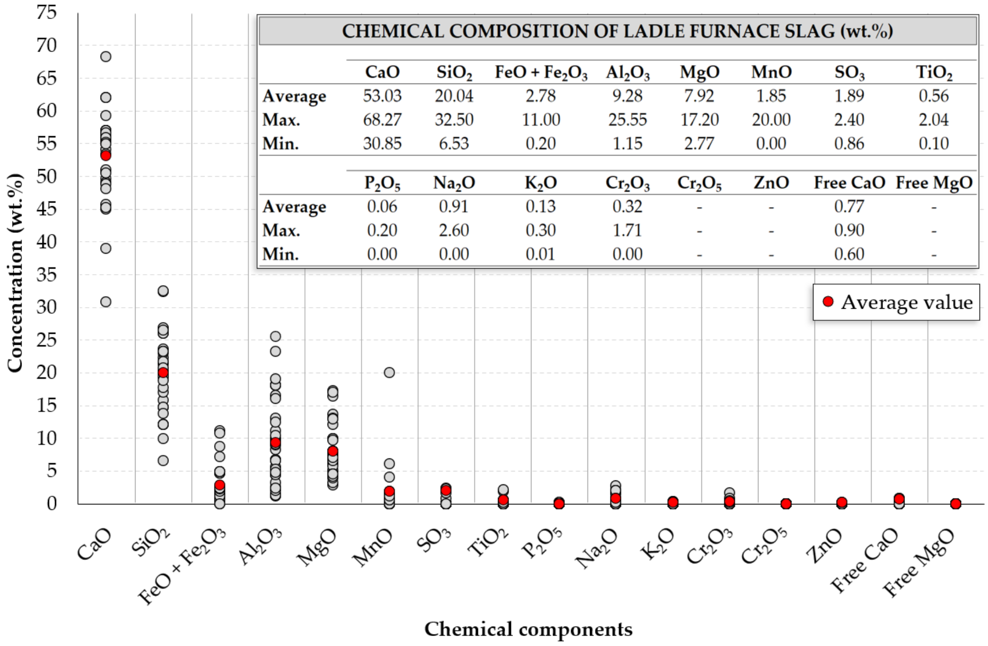
Table 2-36: Main Ladle Furnace Slag ("LFS") physical properties.

Ladle Furnace Slag ("LFS") physical properties			
Property	**Units**	**Values**	**References**
Dimension	[mm]	0.025–8.00	[18,19,113,144,145,146,147,148,149,150,151,152,153,154,155]
Density	[kg/m^3]	2730–3300	[113,146,147,148,151,153,156]
Apparent density	[kg/m^3]	2555–2650	[112,144,152]
Specific surface area	[cm^2/g]	2820–8490	[152]
Fineness R$_{45}$	[%]	20; 22	[112,144]
Fineness modulus	[-]	4.2	[151]
Le Chatelier expansion	[mm]	0.49	[112]
Volumetric expansion	[%]	22; 37	[156]
Loss on ignition (LOI)$^{(*)}$	[%]	4.00–7.1	[144,147,150]
Blaine specific surface area	[cm^2/g]	1200–5000	[145,151,153]
Rigden voids	[%]	38.5; 41.7	[146]
Sand equivalent	[%]	50	[151]
Colour	[-]	Greyish-white	[151]
Sand equivalent	[%]	50	[151]

$^{(*)}$ *Property that typically accompanies the chemical composition of the slag, shown in this table for a better comprehension*

Figure 2-24 shows the typical **chemical composition** of Ladle Furnace Slag (“*LFS*”). For better understanding, the graph is accompanied by a table in which the minimum, maximum and average values are indicated for each component (the average value is also marked by a red dot on the graph). From each paper consulted, the chemical compositions of the slag used were obtained, represented by the grey dots in the graph [18,19,73,112,113,144–150,152–157].

Compared to the chemical composition of the other types of slags described in the previous Sections, there is a greater variation in the chemical composition of LFS, due to the multitude of refining processes that can be carried out in the ladle furnace, which allow steels with different characteristics to be obtained and thus also slags with equally different and variable composition. From a comparison, it can be seen that calcium oxide (CaO) is the main component, followed by silica (SiO_2) and alumina (Al_2O_3). There are also important concentrations of magnesium oxide (MgO). Other elements present in low concentrations (or even in traces or absent) are iron oxides (FeO and Fe_2O_3), manganese oxide (MnO), sulphuric anhydride (SO_3), titanium dioxide (TiO_2), phosphoric anhydride (P_2O_5), sodium oxide (Na_2O), potassium oxide (K_2O), chromium oxides (Cr_2O_3, Cr_2O_5), zinc oxide (ZnO), free-CaO and free-MgO. Finally, the Sulphur (S) content of the slag, varying between 0.2 and 1.65%, is also noteworthy.



CHEMICAL COMPOSITION OF LADLE FURNACE SLAG (wt.%)

	CaO	SiO_2	FeO + Fe_2O_3	Al_2O_3	MgO	MnO	SO_3	TiO_2
Average	53.03	20.04	2.78	9.28	7.92	1.85	1.89	0.56
Max.	68.27	32.50	11.00	25.55	17.20	20.00	2.40	2.04
Min.	30.85	6.53	0.20	1.15	2.77	0.00	0.86	0.10

	P_2O_5	Na_2O	K_2O	Cr_2O_3	Cr_2O_5	ZnO	Free CaO	Free MgO
Average	0.06	0.91	0.13	0.32	-	-	0.77	-
Max.	0.20	2.60	0.30	1.71	-	-	0.90	-
Min.	0.00	0.00	0.01	0.00	-	-	0.60	-

Figure 2-24: Chemical composition of Ladle Furnace Slag (LFS) [18,19,73,112,113,144–150,152–157].

With regard to **mineralogical properties**, the main constituents of Ladle Furnace Slag are shown in Table 2-37.

Table 2-37: Mineral constituents of Ladle Furnace Slag.

Constituent	Formula	References
Belite (dicalcium silicate)	C_2S (or Ca_2SiO_4)	[145,147,149,150,152,155,157]
Portlandite (calcium hydroxide)	$Ca(OH)_2$	
Alite (tricalcium silicate)	C_3S (or Ca_3SiO_5)	[155]
Calcite (calcium carbonate)	$CaCO_3$	[147,150,152]
Amorphous phase	-	[147,152]
Fluorite	CaF_2	[149,150,152,155,157]
Wustite	FeO	[147]
Merwinite	$Ca_3Mg(SiO_4)_2$	[147,157]
Gehlenite	$Ca_2Al_2SiO_7$	
Anorthite	$CaAl_2Si_2O_8$	[73,157]
Mayenite	$Ca_{12}Al_{14}O_{33}$	[147,150,157]
Wollastonite	C_3A (or $Ca_3Al_2O_6$)	[73]
Calcium sulphide	CaS	
Calcium magnesium silicate	$Ca_5MgSi_3O_{12}$	[149]
Calcium aluminium oxide fluoride	$Ca_{12}Al_{14}O_{32}F_2$	
Cuspidine	$Ca_4Si_2O_7F_2$	
Nordstrandite	$Al(OH)_3$	
Tricalcium aluminate	C_3A (or $Ca_3Al_2O_6$)	[157]
Akermanite	$Ca_2MgSi_2O_7$	
Brownmillerite	$Ca_2(Al,Fe)_2O_5$	
Monticellite	$CaMgSiO_4$	
Melilite	$(Ca,Na)_2(Al,Mg,Fe{+}{+})(Si,Al)_2O_7$	
Augite	$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$	
Diopside	$CaMgSi_2O_6$	
Tremolite	$Ca_2Mg_5(Si_8O_{22})(OH)_2$	
Halloysite	$Al_2Si_2O_5(OH)_4$	

As can be seen from Table 2-37, the mineralogical composition (as well as the chemical composition) of LFS is quite differentiated due to the several refining treatments that can take place in the ladle furnace and the addition of alloys to obtain the desired steel.

In contrast to the slags described in the previous Sections, the reuse of LFS is rather complicated due to its characteristics and behaviour after slagging procedure. They are in fact rich in lime (CaO) and dicalcium silicate (Ca_2SiO_4 or C_2S), which undergoes a series of transformations during the cooling operations, referred as phases (α, α'_H, α', β and γ in descending order). The most interesting phases are undoubtedly the β- and γ-phases, since the β-dicalcium silicate (β-C_2S) transforms into γ-dicalcium silicate (γ-C_2S) at temperature around 500°C. This transformation causes an increase in volume of about 12–15%, leading to an accumulation of internal stresses in the slag that result in its disintegration. This tendency of the slag to self-pulverise during the cooling processes causes problems in terms of dust formation at the workplace but, above all, in terms of the severe limitation of possible future reuse options, thus leading to the disposal of almost of it in landfills [158]. There are several studies in the literature that propose alternatives to reduce or avoid the disintegration phenomenon of LFS, such as chemical stabilisation with addition of special additives (P_2O_5, BaO, Na_2O, boron compounds, etc.), modification of the chemical composition of the slag (addition of silica, MgO, etc.), or rapid cooling (so as to stop the dicalcium silicate in its β form and avoid the formation of γ-C_2S) [158,159]. The latter technique is mainly used in the cement production industry, since the γ phase is hydraulically inactive and would therefore require special additives (NaOH or Na-silicate activators) for appropriate activation of the slag, so that it can be used as a cement substitute in concrete production [91,155].

These issues strongly limit the possible reuse applications of LFS, almost all of which is inevitably destined for landfill. In light of this, interest in the search for possible methods to implement the reuse of this type of slag has increased significantly in recent years, also through the birth and development of cooperation between public (e.g. universities) and private institutions (producers or final reusers), in order to create synergy to increase the possibilities of recovery.

Despite the difficulties of reuse, the are some studies in the literature that show how LFS can be recovered, although sometimes in limited quantities, in different sectors: as "*fluxes*" or "*correctives*" by reintroducing the slag into the steel production cycle (e.g. as a partial replacement of lime) [159], in road construction (e.g. for asphalt production) [73,146,149,151], for soil stabilisation [150], as a binder for cement pastes [147], as a binder and/or sand replacement for mortars [112,145,153,156], in addition to raw materials for the production of Portland cement clinker [154], as partial replacement of binder, filler and/or fine aggregate for concrete production [18,19,112,113,144]. In particular, the reuse of LFS for concrete production will be discussed in more detail in the following paragraph.

2.4.1.3 Ladle Furnace Slag ("LFS"): reuse for concrete production

In light of the difficulties in the reuse of LFS discussed in the previous paragraph (especially with regard to its low hydraulic properties if not properly treated), several studies have tried to reuse this type of slag in the construction sector, as a partial or total replacement of binder and/or fine aggregate for concrete production. The results obtained from these studies are summarized in the table below (Table 2-38).

*Table 2-38: Behaviour of the **N**ormal **S**trength **C**oncrete ("**NSC**") made with Ladle Furnace Slag ("LFS") as a partial or total replacement of binder and/or fine aggregate compared to the reference concrete (without the addition of slag).*

Slag	Used as	Property: *Workability*	Ref.
LFS_1(*)	Binder	• Slightly lower	[18]
LFS_2(*)	Binder	• Lower, extreme dry consistency (concrete with cavities that affected its properties)	
LFS	Fine aggregate	• Comparable for C25/30 concrete • Comparable or slightly lower for C30/37 concrete	[113]

Slag	Used as	Property: *Air content*	Ref.
LFS	Fine aggregate	• Comparable for both C25/30 and C30/37 concretes	[113]

Slag	Used as	Property: *Density*	Ref.
LFS_1(*)	Binder	• Lower (lower at higher substitution percentage)	[19]
LFS_2(*)	Binder	• Comparable or slightly higher	
LFS	Fine aggregate	• Slightly higher for both C25/30 and C30/37 concretes	[113]

Slag	Used as	Property: *Development of the strength*	Ref.
LFS_1(*)	Binder	• Slower at early age, comparable after 28 days	[18]
LFS_2(*)	Binder	• Slower	
LFS	Fine aggregate	• Faster for both C25/30 and C30/37 concretes	[113]

Slag	Used as	Property: *Compressive strength*	Ref.
LFS_1(*)	Binder	• Lower	[18]
LFS_2(*)	Binder	• Lower	
LFS_1(*)	Binder	• Lower (lower at higher substitution percentage)	[19]
LFS_2(*)	Binder	• Lower (lower at higher substitution percentage)	

Table 2-38: Cont.

Slag	Used as	Property: *Flexural strength*	Ref.
LFS_1(*)	Binder	- Lower (lower at higher substitution percentage)	[19]
LFS_2(*)	Binder	- Lower (lower at higher substitution percentage)	

Slag	Used as	Property: *Split tensile strength*	Ref.
LFS	Fine aggregate	- Comparable for both C25/30 and C30/37 concretes	[113]

Slag	Used as	Property: *Porosity*	Ref.
LFS_1(*)	Binder	- Higher (higher at higher substitution percentage)	[19]
LFS_2(*)	Binder	- Lower	

Slag	Used as	Property: *Water absorption*	Ref.
LFS	Fine aggregate	- *Capillary absorption of water*: comparable or slightly lower, depending on the mix considered, both for C25/30 and C30/37 concretes	[113]

Slag	Used as	Property: *Chloride penetration*	Ref.
LFS	Fine aggregate	- Lower for both C25/30 and C30/37 concretes	[113]

Slag	Used as	Property: *Carbonation depth*	Ref.
LFS	Fine aggregate	- Lower for both C25/30 and C30/37 concretes	[113]

Slag	Used as	Property: *Penetration of water under pressure*	Ref.
LFS_1(*)	Binder	- Comparable	[18]
LFS_2(*)	Binder	- Higher, due to the extreme dry consistency of the mix (and the consequent lack of cohesion between particles)	

Slag	Used as	Property: *Behaviour after freeze-thaw cycles*	Ref.
LFS	Fine aggregate	- Better behaviour in term of mass losses, both for C25/30 and C30/37 concretes	[113]

Table 2-38: Cont.

Slag	Used as	Property: *Leaching behaviour*	Ref.
LFS_1(*)	Binder	- Good results (the concentration of potentially harmful elements in the eluate did not exceed the limits established by the different standards)	[19]
LFS_2(*)	Binder		

(*) *For each research, two types of concretes were produced with two types of LFS slags, from two different production plants and with different compositions [18,19].*

2.4.1.4 Discussion

LFS is a residue from the refining of steel in the ladle furnace and is a material with particular characteristics, completely different from those of other slags from the actual iron and steel production processes. Its volumetric instability, combined with its tendency to self-pulverise during the cooling process and its poor hydraulic properties, greatly complicate its recovery possibilities. The reuse of LFS as a partial replacement of cement for the production of concrete is rather difficult and the few studies in the literature offer very conflicting results, with performance mostly dependent on the chemical and mineralogical composition of the slag and its percentage added as a replacement for natural raw materials (binder, filler, fine aggregate). In view of the general penalisations in terms of mechanical properties and the rather satisfactory preliminary results regarding durability, LFS could nevertheless be reused as a partial replacement of cement in concrete for civil engineering applications requiring low mechanical strength, using special alkaline activators. However, certain aspects related to the rheological properties of concrete and its durability should be studied more in detail before investigating reuse for real applications. It is evident how the reuse of LFS in "*ordinary*" concrete is possible but not the preferential recovery application for this type of slag. In fact, some studies show how it can be reused in other sectors, such as in the iron and steelmaking industry itself by reintroducing it into the steel production cycle as a source of lime (partially replacing natural "*correctives*"), in the road construction sector (e.g. for the production of bituminous mixes), for soil stabilisation, for the production of Portland cement and cement-based mortars, i.e. those sectors where the critical aspects illustrated above can be more easily solved or even neglected.

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3. REGULATORY FRAMEWORK

3.1 *Introduction*

In Section 2, the different types of slags resulting from the most globally widespread pig iron and steel production processes have been described in detail. These materials differ in terms of physical, chemical, mineralogical, mechanical and environmental properties and their suitability for reuse in various applications. This mainly results from differences in terms of raw materials (iron ore, scrap, additives, etc.) and furnace conduct. In order to define a general regulatory framework for the recovery and reuse of slags in the construction sector, it is therefore necessary to consider, on the one hand, the existing environmental regulations and, on the other hand, the technical standards of each application and recovery sector. Firstly, there are several implications arising from the legal classification of slags as "***by-product***", "***product***" or "***waste***". According to current Italian legislation, slags, once produced and subjected to preliminary treatments in the production plant, can be classified as follow:

- "***By-product***" (definition according to Legislative Decree 152/2006, Art. 183, paragraph 1, letter qq)) and related conditions for a production residue to be attributed the status of "by-product" (Legislative Decree 152/2006, Art. 184–bis) [1]);
- "***Waste***" (definition according to Legislative Decree 152/2006, Art. 183, paragraph 1, letter a)), destined for disposal or recovery operations (Legislative Decree 152/2006, Art. 182 and 184-ter, respectively) [1].

Figure 3-1 shows a summary diagram concerning the production, management, treatment, classification and marking of steel slags, adapted from [2]. The different steps will be discussed in detail later.

3.2 *Steelmaking slags classified as "by-product"*

In order to distinguish waste from what actually cannot be considered as such, the European Commission, though **Communication COM(2007)59**, has provided some clarifications and guideline criteria with regard to residues deriving from a production process, thus adopting the three conditions indicated by the European Court of Justice. The aforementioned conditions are useful in order to be able to make a distinction between materials that are not the primary purpose of a production process, but can still be considered "*by-products*" and not "*waste*" [3]:

1. The reuse of the material is certain and not only possible;
2. The material can be reused without prior processing;

3. The preparation of the material for the reuse takes place during the production process.

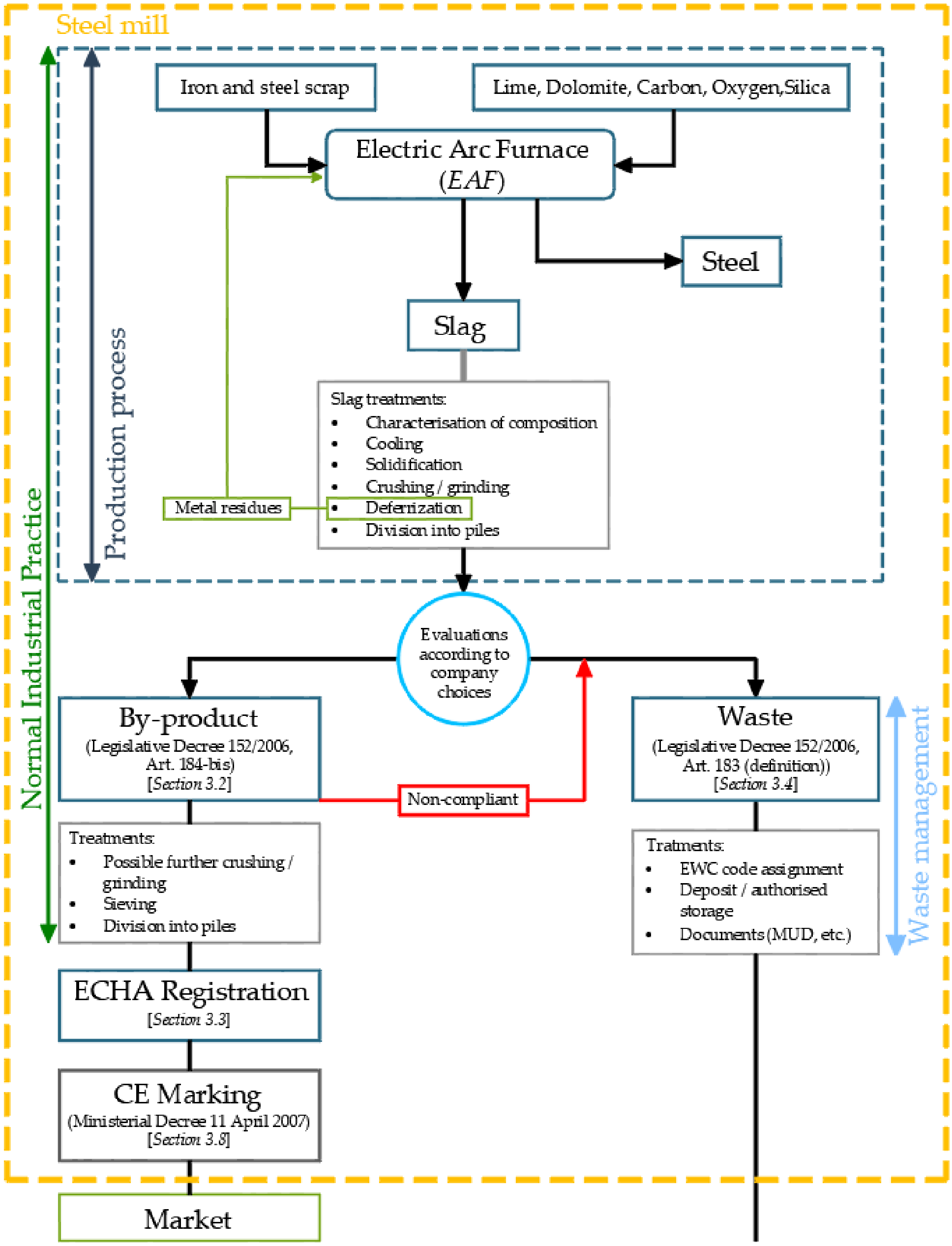


Figure 3-1: Summary diagram concerning the production, management, treatment, classification and marking of steel slags (adapted from [2]).

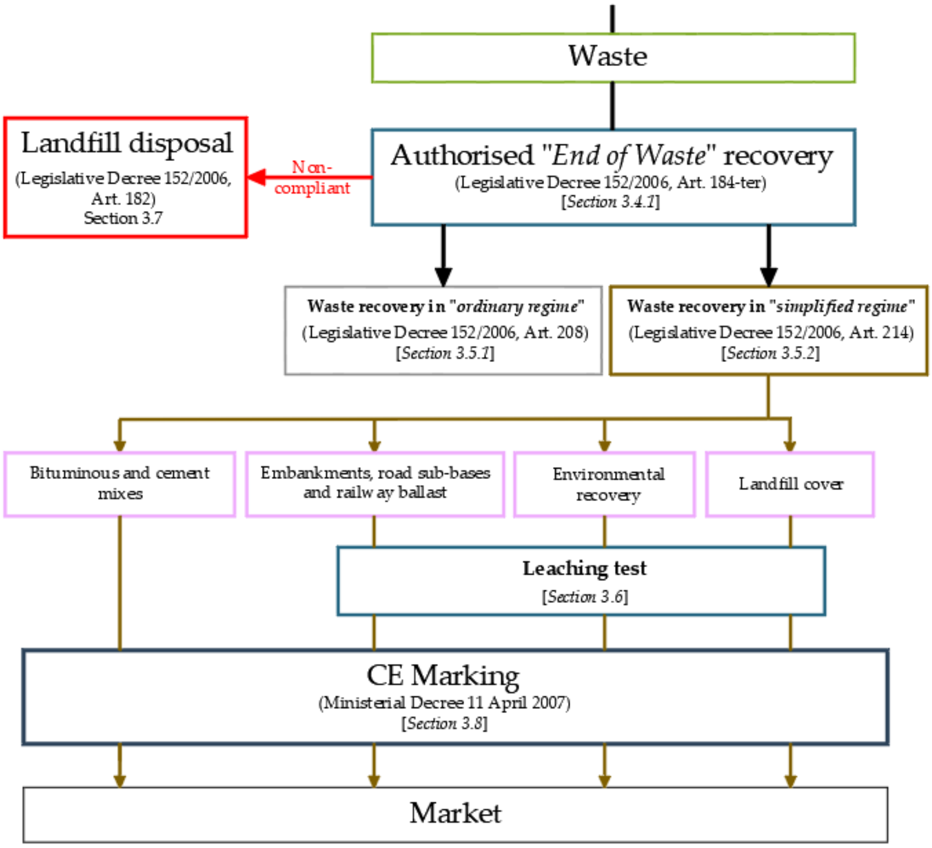


Figure 3-1: Cont.

In order to better understand these three criteria and thus facilitate their application, the Commission has included a number of examples of materials which, due to their production process and resulting characteristics, can assume the status of *"by-product"*. The best example is that of blast furnace slag (*"BFS"*): the Commission recognises that in most cases this process is adapted from the early stages, introducing specific analysis and controls to ensure that the slag has the technical characteristics required for the specific reuses for which it is destined, thus allowing the material obtained to be reused directly without any processing that is not already an integral part of the process (criterion 3 fulfilled). Blast furnace slag has already been a much appreciated material in the construction industry for many years (see Section 2.2.1.2) and therefore there are no doubts about its *"certainty of reuse"* (criterion 1 satisfied), following of course appropriate controls in compliance with the technical regulations of the sector [3].

The transposition in Italy of **Directive 2008/98/EC** [4] through **Legislative Decree 205/2010** [5], has modified **Legislative Decree 152/2006** [1] introducing a new definition of "*by-product*". It is contained in **Art. 184-bis**, which specifies and lists the conditions for a residue to be considered a "*by-product*": "*A by-product, and not a waste, is any substance or object that meets the following conditions:*

(a) The substance or object originates in a production process, of which it is an integral part, and whose primary purpose is not the production of that substance or object;
(b) It is certain that the substance or object will be used, in the same or a subsequent production or use process, by the producer or a third party;
(c) The substance or object may be used directly without any further processing other than "normal industrial practice";
(d) The further use is legal, i.e. the substance or object fulfils, for the specific use, all relevant product, health and environmental protection requirements and will not lead to overall harmful impacts on the environment or human health".

Steel slags can therefore be classified as "*by-product*" if the above conditions are met. Table 3-1 reproduces, as an example, Table 4 included in **Resolution n. XI / 5224** of the Lombardy Region (Italy), in which the conditions for classification as a "*by-product*" in the specific case of electric arc furnace slag from carbon steel production (EAFS-C) are reported [2].

Table 3-1: Conditions of the Art. 184-bis of the Legislative Decree 152/2006 for classification as "by-product" declined for EAFS-C (adapted from [2]).

Conditions		**Applications to EAFS-C**
(a)	*The substance or object originates in a production process, of which it is an integral part, and whose primary purpose is not the production of that substance or object*	In the production process, steel is the so-called "*primary product*" and slag originates at the same time. It is therefore an integral part of the production process but not its primary product, fulfilling condition (a)
(b)	*It is certain that the substance or object will be used, in the same or a subsequent production or use process, by the producer or a third party*	The certainty of use of steel slag-derived aggregates in different sectors can be demonstrated by the existence of commercial or contractual relationships between the producer and the end users. In the absence of such relationships, the certainty of use can be demonstrated by the provision of technical documentation, in which the types of activities or utilisation plants to which the material is destined and the management methods (including collection and storage) are indicated
(c)	*The substance or object may be used directly without any further processing other than "normal industrial practice"*	The "*normal industrial practice*" will be discussed in more detail in Section 3.2.1

Table 3-1: Cont.

Conditions		Applications to EAFS-C
(d)	*The further use is legal, i.e. the substance or object fulfils, for the specific use, all relevant product, health and environmental protection requirements and will not lead to overall harmful impacts on the environment or human health"*	The requirements of condition (d) are fulfilled by the CE marking of the steel slag-derived aggregate, which implies compliance with both the technical regulations for each specific use and the parameters of respect and protection of the environment and human health

If the slag does not meet one or more of the aforementioned conditions, it will not be classified as "*by-product*" and will have to follow the procedure for the residues classified as "*waste*" (detailed in Section 3.4).

3.2.1 "Normal industrial practice" treatments

The **Art. 6** ("*Direct use without treatments other than normal industrial practice*") of the **Ministerial Decree 13 October 2016, n. 264** [6] states:

1. *"For the purposes and effects of Art. 4, paragraph 1, letter c) (i.e. Art. 184-bis of Legislative Decree 152/2006), the processes and operations necessary to make the environmental characteristics of the substance or object suitable for satisfying, for the specific use, all the relevant requirements concerning products and environmental and health protection and not leading to overall negative impacts on the environment do not constitute normal industrial practice, unless they are carried out in the same production cycle, as provided for in paragraph 2";*
2. *"In any case, activities and operations that are an integral part of the production cycle of the residue, even if designed and carried out for the specific purpose of making the environmental or health characteristics of the substance or object suitable for and conducive to all the relevant requirements concerning products and environmental and health protection for the specific use and not leading to overall negative environmental impacts, are part of normal industrial practice".*

In the absence of an established legal interpretation to unambiguously identify those treatments that are included in the definition of "*normal industrial practice*", a possible reference can be the content of the **B**est Available Techniques (BAT) **REF**erence Document for Iron and Steel Production ("***BREF***", [7]). It is a technical reference document at EU level which, under the **I**ntegrated **P**ollution **P**revention and **C**ontrol ("***IPPC***") legislation, identifies and describes, for each industrial sector, the **B**est **A**vailable **T**echniques ("***BAT***") in the environmental sector. The BREF undergoes periodic revisions and updates in order to incorporate the possible development of new techniques and /or technologies and is derived from the work of the **T**echnical **W**orking **G**roup ("*TWG*"), a working group at European level coordinated by the **E**uropean **I**ntegrated **P**revention **P**ollution and **C**ontrol **B**ureau ("*EIPPCB*"), in which representatives of the Member States and of the industrial sector considered participate. As far as slag from steel production is concerned, in addition to highlighting the importance of its appropriate use in civil engineering and road construction, the BREF also contains a section on so-called "*normal industrial practice*" and the treatments to which slag is generally subjected for its reuse in the aforementioned applications. As an example and for a better understanding, the following are the commonly adopted industrial practices for slag from electric arc furnace steel production, as explained in the BREF [7]:

- *"Slag cooling can be improved by water sprays";*
- *"If slag is poured onto the floor, after solidification it is crushed with excavators or shovels and taken to an external storage area";*
- *"After a certain period, the slag is processed in crushing and screening devices to give it the desired consistency for further use in construction";*
- *"During this operations, the metal particles contained in the slag are separated magnetically, manually of by digging, crushing and screening to be recycled in the steel production process".*

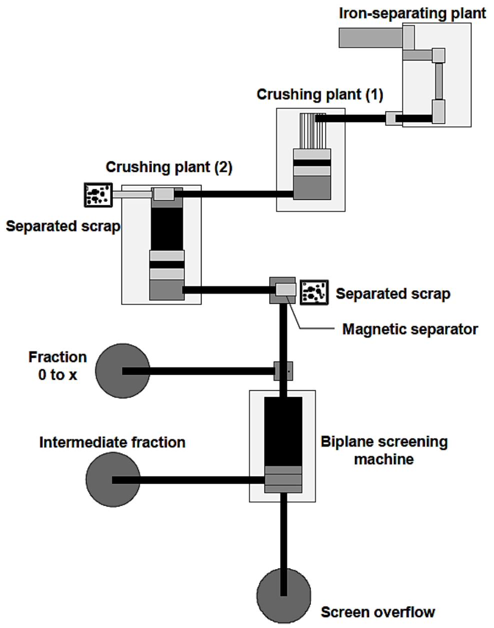


Figure 3-2: Processing scheme of a plant for slag preparation [7].

Figure 3-2 resumes Figure 8.21 of the BREF and shows a processing scheme of a plant for slag preparation [7].
Some operations that can be considered "*normal industrial practice*" for steel slags are given as example (non-exhaustive list) [2]:

- Transport of the liquid slag from the furnace to the processing area;
- Spilling of the liquid slag onto a slag bed;
- Creation of overlapping layers that solidify in a stratified manner;
- Cooling by water jets;
- Coarse crushing-granulation of the successive slag layers by means of a mechanical shovel and separation of any leachates present;
- Removal of slag from the bed and direct processing;
- Processing of the cooled and coarsely crushed slag (secondary crushing-granulation through crushers/mills, screening, deferrization with recovery of the leachates/metallic parts and subsequent sending of these to the scrap yard for re-melting);
- Arrangement of the granulated material obtained in heaps, identified by production batch or product type (different grain size) for subsequent chemical, geotechnical and performance characterisation analysis;
- Loading of the sols material (complying with technical and analytical specifications) onto a transport vehicle by mean of a mechanical shovel and radiometric control at the exit.

In summary, the so-called "*normal industrial practice*" operations for the EAFS-C by-product are mechanical processing, with the aim of obtaining the best size for its subsequent characterisation and reuse. Once the treatments and the characterisation are completed, in order to market the EAFS-C slag-derived aggregate it is necessary to register it at the **E**uropean **CH**emical **A**gency ("***ECHA***"), in accordance with the REACH regulation and the CE marking, as provided by **Presidential Decree 21 April 1993, n. 246** [8] (repealed by **Legislative Decree 16 June 2017, n. 106** [9]).

3.3 REACH Regulation and ECHA registration

3.3.1 Introduction

REACH (EC n. 1907/2006, "***R****egistration,* ***E****valuation,* ***A****uthorisation and restrictions of* ***CH****emical substances*") is a regulation that became effective on 1st June 2007 and was adopted to improve human health and the environment from the risks that chemical substances may cause [10]. It covers the registration, evaluation, authorisation and restriction of chemical substances and requires European producers and importers to study the chemical, physical, toxicological and eco-toxicological properties of the substances they produce or import. REACH does not apply to waste and there is no registration requirement for substances produced or imported in quantities of less than 1 tonne per year. In addition, other substances exempt from the registration obligation are those used for the **P**roduct and **P**rocess **O**riented **R**esearch and **D**evelopment (“***PPORD***”), although used in quantities greater than 1 tonne (the exemption is valid for a period of 5 years, after submission of a PPORD notification to ECHA).

In principle, REACH applies to all chemical substances, both those used in industrial processes and those in daily use (cleaning products, paints, etc.). It also aims to promote alternative methods for hazard assessment in order to reduce the number of animal experiments. For this reason, this regulation has an impact on the majority of companies in the EU.

REACH places the burden of proof on companies to identify and manage the risks associated with the substances they produce and market in the EU, to demonstrate to ECHA how they use these substances and to communicate risk management measures to the users. ECHA authorities and scientific committees assess whether such management is possible; if not, they may restrict their use or make it possible only after authorisation. For companies that may be involved, the regulation provides the following roles [10]:

- Producer, one who produces chemicals, either for his own use or to supply them to others;
- Importer, who may import either single chemicals or mixtures for subsequent slae or finished products;
- Final users, who must verify their obligations if they use any chemicals in their industrial or professional activities;
- Companies established outside the EU are not subjected to REACH regulation, even if they export their products to the customs territory of the EU. REACH obligations are applied to importers established in the EU or the exclusive representative of a non-EU producer.

3.3.2 Substance identification

The accurate determination of a substance is a prerequisite for most of the processes required by the REACH regulations and ensure the proper preparation of collective registrations and the adequacy of experimental data, so that the risks and hazards of registered substances can be fully assessed. Proper identification also makes it possible to assess whether a substance is included in the list of substances subjected to authorisation and/or restriction or has harmonised classification and labelling [10]. As an example, for EAFS-C the “*substance identity*” is expressed through:

- Name (the name on the register is “*Slags, steelmaking, elec. Furnace (carbon steel production)*”);

- Number (“*932-275-6*”);
- Chemical composition derived from previously performed chemical analyses.

In order to avoid the risk of the same substance being registered several times, companies planning to register such a substance must check whether an application for registration has already been submitted or whether it has even already been registered (through an application made to ECHA). If a registration is already planned or the substance has already been registered, the companies involved will be put in contact with each other to ensure appropriate data sharing. The step of “*substance registration*” is thus based on the principle “*one substance, one registration*” (also called the “*sameness principle*”). This principle is fulfilled if producers demonstrate the same requirements within the production process, in the mineralogical components and in the placement of the chemical composition in the ternary diagram [10]. Finally, the substance identification process also aims to define the scope of collective registration, facilitating the development of the **S**ubstance **I**dentify **P**rofile (“***SIP***”) and the indication of the boundary composition.

3.3.3 Procedures and Assessments

The REACH regulation consists of 4 main steps [10]:

- “*Registration*”: by means of a registration dossier, the company producing or importing the substance must communicate to ECHA the required information regarding possible hazards and risks from the use of that substance and how to manage them. Registration is based on the “sameness principle” mentioned above, with producers and importers of the same substance required to submit their registration together. A registration requires the payment of a fee;
- “*Evaluation*”: ECHA and Member States examine the registration dossiers, assessing the information contained in them. The evaluation also aims to identify whether a particular substance represents a risk to human health and the environment. Once the assessment has been carried out, registrants may be asked to provide further information on the substance under consideration;
- “*Authorisation*”: this process starts when a Member State or ECHA, at the request of the Commission, proposes a substance to be identified as a **S**ubstance of **V**ery **H**igh **C**oncern (“***SVHC***”). The main objective of this procedure is to ensure that substances of very high concern are progressively replaced by less hazardous substances. The “*substance identification*” process as an SVHC first involves a 45-days consulting period, so that it can be among the possible candidates. This entails

immediate obligations for the substance suppliers, including the adoption of a **S**afety **D**ata **S**heet (“*SSD*”), communication of guidelines and instructions for the safe use of the substance, responding to any requests from consumers within 45 days and informing ECHA in the case of an article containing a substance classified as SVHC in concentration greater than 0.1% (w/w) or if the quantity produced and/or imported is greater than 1 tonne per year;

- “*Restriction*”: is the instrument adopted to protect human health and the environment from risks from chemicals. Restrictions are normally used to limit or ban the production and/or import of the substance on its own, as a component of a mixture or in products, and can also be enforced by imposing any relevant conditions such as technical measures or special labelling.

The application of REACH is a national responsibility and each EU Member State must therefore provide, plan and ensure the existence of an official control system and establish legislation specifying sanctions for non-compliance with REACH provisions.

3.3.4 Registration for steelmaking slags

For each type of slag resulting from iron and steel production processes, the **R**EACH **F**errous **S**lag **C**onsortium (“***RFSC***”), led by the German Research Institute for Iron and Steel Slags (“***FEhS – Institut für Baustoff-Forschung***”), defined the qualitative and quantitative parameters of the substances and their eluate, in order to unify the characterisation of the slag (on which the REACH regulation studies were then developed) [2]. Table 3-2 shows the slag families, i.e. subdivision of the main types of slags according to the production process from which they originate and accompanied by a **CAS** (“*Chemical Abstract Service*”) and **EINECS** (“*European Inventory of Existing Commercial Chemical Substances*”) numbers [2,11].

Table 3-2: Slag families and corresponding CAS and EINECS numbers (adapted from [2,11]).

Family no.	**Common name**		**EINECS name**	**CAS no. / EINECS no.**
1	**G**ranulated **B**last furnace **S**lag	GBS	Slag, ferrous metal, blast furnace (granulated)	65996-69-2 / 266-002-0
	Air-cooled **B**last furnace **S**lag	ABS	Slag, ferrous metal, blast furnace (air-cooled)	65996-69-2 / 266-002-0
2	**B**asic **O**xygen furnace **S**lag (converter slag)	BOS	Slag, steelmaking, converter	91722-09-7 / 294-409-3

Table 3-2: Cont.

Family no.	Common name		EINECS name	CAS no. / EINECS no.
3a	**E**lectric **A**rc **F**urnace slag (from **C**arbon steel production)	EAF-C	Slag, steelmaking, elec. furnace (carbon steel production)	(91722-10-0 / 294-410-9)(*) / 932-275-6(**)
3b	**E**lectric **A**rc **F**urnace slag (from **S**tainless/high alloy steel production)	EAF-S	Slag, steelmaking, elec. furnace (stainless/high alloy steel production)	(91722-10-0 / 294-410-9)(*) / 932-476-9
4	**S**teel**m**aking **S**lag	SMS	Slag, steelmaking	65996-71-6 / 266-004-1

(*) *Old CAS and EINECS numbers [11].*

(**) *New EINECS number [2,11].*

The steel mills must prove that the studies carried out on the slags they produce and reported in the registration dossier are representative of production. The analysis of all steel slags placed on the market makes it possible to create an area on a ternary diagram (i.e. the representation of a system of 3 variables arranged on an equilateral triangle and used to represent the variations in the physico-chemical properties of a system consisting of 3 components as the composition of the system changes [12]).

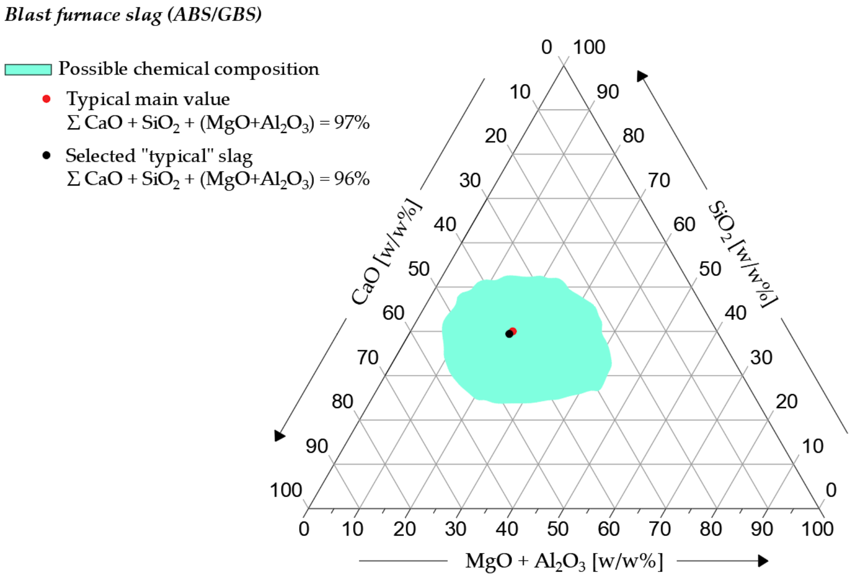


Figure 3-3: Ternary diagram of blast furnace slag (ABS/GBS), adapted from [12]).

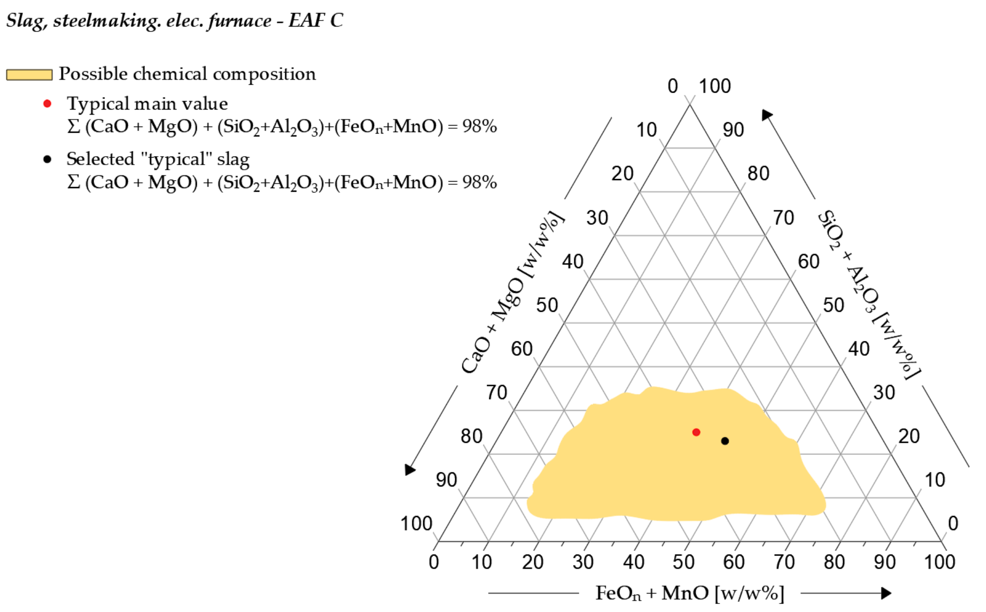


Figure 3-4: Ternary diagram of electric arc furnace slag from carbon steel production (EAF-C), adapted from [12]).

On this ternary diagram, the average of the values and the composition chosen for toxicological and eco-toxicological tests are identified. As an example, Figure 3-3 and Figure *3-4* show the ternary diagrams for the two types of blast furnace slags (GBS/ABS) and electric arc furnace slag from carbon steel production (EAF-C), respectively. The red and black dots represent the mean values and the composition chosen to carry out toxicological and eco-toxicological tests, respectively. X-ray diffraction (XRD) with a defined radiant source is the classical method for analysing the mineralogical components of steel slags.

3.3.5 The Chemical Safety Report ("CSR")

The **C**hemical **S**afety **R**eport ("***CSR***") of a registered substance contains a summary of information on its properties that could represent a risk to the environment and human health and, where necessary, an exposure and risk assessment. For EAFS-C, the document received input from the scientific community and was signed by 97% of European producers. It is deposited at ECHA and available for consultation and comment by stakeholders [10].

According to the CSR, slag does not show any hazardous characteristics and is therefore not classified of the **G**lobally **H**armonised **S**ystem of Classification and Labelling of Chemicals ("***GHS***") and the hazardous substances directive. Introduced in 2002 and continuously updated, the GHS is a system adopted by the

United Nations to identify, classify and label hazardous chemicals and inform users about the risk (by introducing communication elements such as labels and safety data sheets), in order to improve the protection of human health and the environment during the handling, transport and use of these substances [12].

3.3.6 CLP Regulation

The **CLP Regulation** (EC) No. 1272/2008 [13], in force since 20 January 2009, progressively replaced **Directives 67/548/EEC** [14] and **1999/45/EC** [15], both repealed on 1 June 2015, and aligned previous EU legislation with the GHS. The CLP Regulation also modified the REACH Regulation No. 1907/2006 and, as of 1 June 2015, is the only regulation in force in the EU for the classification and labelling of substances and mixtures. All Member States are legally bound to comply with the CLP Regulation, which is applicable to all industrial sectors, requiring producers, importers and users to classify, label and package hazardous chemicals appropriately before they are placed on the market [13].

Among the many objectives of the CLP Regulation, the main one is undoubtedly the determination of the properties that allow a substance or mixture to be classified as "*hazardous*". A hazard class and category (physical, human health, environmental, etc.) are assigned if the information on a substance or mixture (e.g. toxicological data) meets the CLP criteria. Identified hazards must be communicated to other actors in the supply chain (including consumers).

With regard to labelling, the CLP Regulation established detailed criteria for the elements and information that must be included on the label: pictograms, warnings and statements that allow rapid identification and understanding of the hazard, prevention, reaction, storage and disposal of each hazard class and category. In addition, the CLP Regulation forms the basis of numerous legislative provisions on risk management of chemicals. Finally, the CLP also includes harmonised classification and labelling processes, alternative chemical names in mixtures, C&L inventory and poison control centres [13].

3.3.7 REACH Regulation: example of a safety data sheet

In the particular case of steelmaking slags, the REACH regulation reports the conclusions derived from their characterisation with regard to physical, chemical, toxicological and eco-toxicological aspects in order to assess their possible impact on humans and environment. The toxicological tests performed on the slags comply with the protocols developed by the **O**rganisation for **E**conomic **C**ooperation and **D**evelopment ("***OECD***") and expressed in periodically updated guidelines. Recognised standards were also used to derive the **P**redicted **N**o **E**ffect

Concentration ("***PNEC***") values, i.e. those values within which no adverse effects on the environment can be expected [10].

The information contained in the steel mill report for the actors in the supply chain is transmitted by means of a safety data sheet, produced in accordance with the REACH Regulation. As steelmaking slag is not a hazardous substance, it does not require a safety data sheet. On the ECHA website there are "brief profiles" containing the characteristics of the different types of slag (GBS/ABS [16], BOS [17], EAF-C [18], EAF-S [19] and SMS [20]):

- Substance identity;
- Hazard classification and labelling;
- Regulatory context (REACH);
- Classification Labelling and Packaging (CLP);
- About the substance (general, consumer uses, article service life, widespread uses by professional workers, formulation or re-packing, uses at industrial sites, manufacture, precautionary measures and safe use);
- Registrants/suppliers (active and inactive);
- Substance name (CAS names, IUPAC names, Trade names, other identifiers);
- Scientific properties (physical and chemical properties, environmental fate and pathways, eco-toxicological information, toxicological information.

3.4 Steelmaking slags classified as "waste"

Legislative Decree 152/2006 [1], **Art. 183**, **paragraph 1**, **letter a)**, updated by **Legislative Decree 205/2010** [5], **Art. 10**, defines "*waste*" as "*any substance or object which the holder discards or intends or is required to discard*". If the steel mill decides to adopt the status of "*waste*" for the slag produced, it will be assigned an EWC code, referring to the European Waste Catalogue (**Commission Decision 2000/532/EC** [21]), i.e. a number consisting of three pairs of two digits (in the case of waste considered "*hazardous*", the symbol * is added to the end of the code):

- The first pair of number, called "*Class*", identifies the sector of activity from which the waste originates (for steelmaking slags, the class is 10 "*waste from thermal processes*");
- The second pair of numbers, called "*Subclass*", identifies the production process (for steelmaking slags, two subclasses are identified: 02 "*waste from the steel industry*" and 09 "*waste from casting of ferrous materials*");
- The third pair of numbers, called "*Category*", indicates the name or description of the waste.

Thus, as far as steelmaking slags are concerned, the EWC codes under which they are commonly classified are [21]:

- EWC 10.02.01 – "*Waste from the processing of slag*";
- EWC 10.02.02 – "*Unprocessed slag*";
- EWC 10.09.03 – "*Furnace slag*".

The assignment of EWC code to the slag effectively certifies its status as "*waste*" which is then destined for recovery or disposal operations. There may be situations in which the slag produced is assigned the status of "*waste*" despite having all the characteristics to be considered a "*by-product*". The reason are many and are the result of purely business choices, such as commercial agreements with external companies authorised for recovery, lack of necessary personnel and/or adequate storage space, insufficient slag production for the economic sustainability of direct by-product production, etc.

Legislative Decree 152/2006 [1], **Art. 183, paragraph 1, letter a)**, updated by **Legislative Decree 205/2010** [5], **Art. 10**, defines "*recovery*" as "*any operation the main result of which is to enable waste to play a useful role, by replacing other materials that would otherwise be used to perform a particular function or to prepare them to perform that function within the plant or in the economy in general*". In cases where slag is attributed the status of "*waste*" and sent for recovery treatment at authorised plants, it will be their responsibility to comply with the provision of **Legislative Decree 152/2006, Art. 184-ter** "*End of Waste*".

3.4.1 End of Waste

The term "*End of Waste*" refers to a process performed on a waste, at the end of which it loses this status and acquires that of "*product*". The methodology comes from the revision of the European legislation on waste contained in **Directive 2006/12/EC** [22], repealed by **Directive 2008/98/EC**, which attempts to attribute a vision of waste not limited to the disposal and recovery phase, but relates to the entire life cycle [4]. **In Art. 4**, **Directive 2008/98/EC** also defines a priority scale of waste management methods ("*Waste hierarchy - 1. The following waste hierarchy shall apply as the order of priority of waste prevention and management legislation and policy: 1.a) prevention, 1.b) preparing for reuse, 1.c) recycling, 1.d) other recovery, e.g. energy recovery, 1.e) disposal [...]*").

On a practical level, a waste ceases to be "*waste*" when it has undergone recovery operations and fulfils the conditions established in **Directive 2008/98/EC**, **Art. 6**: "*Certain specified wastes cease to be waste within the meaning of Art. 3(1), when they have undergone a recovery operation, including recycling, and fulfil specific criteria to be developed in accordance with the following conditions:*

(a) *The substance or object is commonly used for specific purposes;*
(b) *There is a market or demand for that substance or object;*
(c) *The substance or object meets the technical requirements for the specific purposes and complies with existing legislation and standards applicable to products;*
(d) *The use of the substance or object will not lead to overall adverse environmental or human health impacts*".

In particular, with regard to the first three points:

(a) "*The substance or object is commonly used/used for specific purposes*": these must therefore be widespread products, applied in known areas and intended to perform known and defined functions;
(b) "*There is a market or demand for that substance or object*": the existence of a market shows that the recovered object is unlikely to be abandoned or disposed of illegally;
(c) "*The substance or object meets the technical requirements for the specific purpose and complies with existing legislation and standards applicable to products*": the performance required during use and/or consumption of the object must be ensured in accordance with both the legal and technical standards applicable to the specific substance or object.

The EU Commission, in its Communication to the Council and the European Parliament on waste and by-products (**COM(2007)59** [3]), underlines that: "*the fact that a producer can sell a specific material at a profit indicates a greater probability that this material will be reused, even if this element is not a sufficient indication*": i.e. a possible profit is not in itself an indication of reuse. The economic value of the material is therefore not essential for the purposes of the recovery process (as required by the previous **Art. 181-bis** of **Legislative Decree 152/2006** [1] concerning secondary raw materials, repealed by **Legislative Decree 205/2010**, **Art. 7** [5]). Once all the above conditions are met, the material classified as "*waste*" becomes to all effects a "*product*".

Italian environmental legislation, which finds reference in **Legislative Decree 152/2006** [1], has been enriched with a new ad hoc provision: **Art. 184-ter** "***End of Waste***" (introduced for the first time by **Legislative Decree 205/2010** [5], **Art. 12**). The provision literally adopts the conditions of **Art. 6** cited above, and adds, in **paragraph 2**, that "*the recovery operation may consist simply in checking the waste to see if it meets the criteria developed in accordance with the above conditions*", thus confirming what has already been suggested by the Community Legislator [1].

In summary, the control carried out on a material classified with the status of "*waste*", aimed at verifying its characteristics so that it may cease to be such, is a recovery operation to all effects and therefore requires authorisation in accordance with the procedures set out in Part Four of the aforementioned **Legislative Decree**

152/2006 [1]. On the other hand, at the European level, **Art. 6** of **Directive 2008/98/EC** [4] has been updated by **Directive (EU) 2018/851** [23], **Art. 1**, **paragraph 6**, transposed in Italy through **Legislative Decree 116/2020** [24].

As described in Table 3-1 for the case of EAFS-C classified as "*by-product*", the conditions of **Art 184-ter** of **Legislative Decree 152/2006** [1] are also declined for those classified as "*waste*" (Table 3-3).

Table 3-3: Conditions of the Art. 184-ter of the Legislative Decree 152/2006 for classification as "waste" declined for EAFS-C (adapted from [2]).

Conditions		Applications to EAFS-C
(a)	*The substance or object is commonly used for specific purposes*	The possibility of reusing aggregate from EAFS-C in different applications in the construction sector has been established for decades in Italy as well as in EU countries
(b)	*There is a market or demand for that substance or object*	
(c)	*The substance or object meets the technical requirements for the specific purposes and complies with existing legislation and standards applicable to products*	The CE marking of the EAFS-C aggregate proves that all technical requirements of the construction sector are met
(d)	*The use of the substance or object will not lead to overall adverse environmental or human health impacts*	Requirements for the protection of health and the environment met after leaching tests

3.5 *Waste recovery*

As mentioned before, the definition of "*recovery*" is provided by **Legislative Decree 152/2006** [1], **Art. 183**, **paragraph 1**, **letter t)**, updated by **Legislative Decree 205/2010** [5], **Art. 10**: "*Any operation the main result of which is to enable waste to play a useful role, by replacing other materials that would otherwise be used to perform a particular function or to prepare them to perform that function within the plant or in the economy in general*". A non-exhaustive list of recovery operations is included in **Legislative Decree 152/2006** [1], **Part IV**, **Annex C**, replaced by **Legislative Decree 205/2010** [5], **Annex C** (shown in Table 3-4).

Table 3-4: Recovery operations (Legislative Decree 205/2010, Annex C) [5].

Recovery operations	
R1	Main use as a fuel or other source of energy
R2	Solvent regeneration/recovery
R3	Recycling/recovery of organic substances not used as solvents (including composting and other biological transformations)
R4	Recycling/recovery of metals or metal compounds

Table 3-4: Cont.

Recovery operations	
R5	Recycling/recovery of other inorganic substances
R6	Regeneration of acids and bases
R7	Recovery of products used to capture pollutants
R8	Recovery of products from catalysts
R9	Regeneration or other reuse of oils
R10	Land spreading for agricultural or ecological benefit
R11	Utilisation of waste obtained from any of the operations listed from R1 to R10
R12	Exchange of waste for submission to any of the operations listed from R1 to R11
R13	Storage of waste for submission to any of the operations listed from R1 to R12 (excluding temporary storage, prior to collection, at the location where they are produced)

Italian law provides for a dual regime for recovery: "*ordinary regime*" and "*simplified regime*".

3.5.1 Waste recovery in "ordinary regime"

The recovery in "*ordinary regime*" is disciplined by **Legislative Decree 152/2006** [1], **Art. 208** "*Single authorisation for new waste disposal and recovery plants*", updated by **Legislative Decree 205/2010** [5], **Art. 22**. In summary, actors intending to set up new disposal or recovery plants (including for hazardous substances) have to:

- Submit an application to the Region (attaching the final design of the plant and the technical documentation);
- Within 30 days of receiving the application, the Region identifies the person in charge of the procedure and convenes the Services Conference in order to acquire documents and information;
- Within 90 days of the convocation, the Services Conference proceeds to assess the projects, acquires and evaluates all the elements relating to their compatibility (including the environmental compatibility assessment, where required by law) and transmits the acts with its conclusions to the Region;
- Within 30 days of receiving the conclusions, the Region authorises the construction and management of the plant in case of a positive assessment.

The procedure is then concluded within 150 days from the submission of the initial application, with the granting of the single authorisation or the reasoned refusal.

3.5.2 Waste recovery in "simplified regime"

The recovery in "*simplified regime*" is disciplined by **Legislative Decree 152/2006** [1], **Art. 214** "*Determination of the activities and characteristics of waste for admission to simplified procedures*", which establishes that a high level of environmental protection must be ensured, in any case, both through rules fixing types and quantities of waste and through conditions according to which recovery and disposal activities (of non-hazardous waste) are subjected to simplified procedures.

The **Legislative Decree 152/2006** [1], **Art. 216** "*Recovery operations*", modified by **Legislative Decree 4/2008** [25], **Art. 2**, **paragraph 36** and by **Legislative Decree 205/2010** [5], **Art. 30**, specifies: "*Provided that the technical standards and specific prescriptions referred to in Art. 214, paragraphs 1, 2 and 3 are complied with, waste recovery operations can be started after ninety days from the communication of the start of activity to the Province with territorial jurisdiction*".

According to subsection 3 of the aforementioned article, the Province shall register in a special register the companies that make the start-of-activity notification and, within 90 days, shall verify the existence of conditions and requirements. A report will be attached to the notification of the start of activity, which must show compliance with the technical standards and specific conditions, possession of the subjective requirements for waste management, the recovery activities to be performed, the establishment, the recovery capacity and the treatment or combustion cycle in which the waste is to be recovered, as well as the use of any mobile facilities and the characteristics of the products resulting from the recovery cycles.

In particular, the conditions and technical standards mentioned above and referred to in the article are subdivided according to whether they are considering:

- Non-hazardous waste (maximum quantities that can be used, origin, types, characteristics and requirements necessary to ensure that the waste is recovered without risk to human health and without using processes or methods that could have consequences for the environment);
- Hazardous waste (maximum quantities that can be used, origin, types, characteristics, specific conditions with regard to limit values of hazardous substances it contains, emission limit values for each type of waste and type of activity and facility used, requirements necessary to perform different forms of recovery and to ensure that the waste is recovered without risk to human health and without using processes or methods that could have consequences for the environment).

The report has to be renewed every five years or if there is a substantial change in the recovery operations.

3.5.2.1 Recovery operations in "simplified regime"

Recovery operations in "*simplified regime*" are specified in **Ministerial Decree 5 February 1998** [26], modified and updated by **Ministerial Decree 5 April 2006, n. 186** [27] for non-hazardous waste and by **Ministerial Decree 12 June 2002, n. 161** [28] for hazardous waste.

The **Art. 1** of **Ministerial Decree 5 February 1998** ("*General principles*") states that the activities and processes for the recovery of each type of waste identified by the Decree must not represent a risk to human health and the environment.

Art. 3 of **Ministerial Decree 5 February 1998** ("*Material recovery*") defines the technical and environmental performance that the final product must have, specifying: "*The activities, processes and methods of recycling and material recovery identified in Annex 1 must guarantee the obtaining of products or raw or secondary raw materials with commodity characteristics that comply with the technical standards of the sector or, in any case, in the forms usually marketed. In particular, the products, raw materials and secondary raw materials obtained from the recycling and recovery of waste identified by this Decree must not have hazard characteristics that are superior to those of the products and materials obtained from the processing of virgin raw materials*".

Sub-annex 1 of the aforementioned **Annex 1** defines the "*General technical standards for the recovery of materials from non-hazardous waste*". This section of the Decree is characterised by a list of recoverable waste, for each of which the conditions under which the operation is subjected to simplified procedure are identified. In particular, under **Section 4** of the Sub-annex 1 ("*Metal-containing waste from furnace, melting and refining of metals*"), there are, at **Point 4.4**: "*Steelmaking slags, slags from melting in electric furnaces, combustion furnaces or oxygen converters of ferrous metal alloys and their subsequent refining treatments [10.02.02], [10.09.03], [10.02.01]*".

The waste characteristics, identified in **Section 4.4.2** of the Sub-annex 1, are: "*Granulated or non-granulated slags with more than 80% by weight of* SiO_2, CaO, Al_2O_3, MgO, FeO". For this type of waste, the recovery activities are defined:

(a) Cement factory [R5];
(b) Production of cement and bituminous mixtures for construction and bricks [R5];
(c) Glass industry [R5];
(d) Steel mills and primary and secondary smelting foundries for the recovery of ferrous and non-ferrous materials [R4];
(e) Formation of embankments, road sub-bases and railway ballast [R5];
(f) Use for environmental recovery [R10];
(g) Use for covering MSW landfills (the percentage of waste that can be mixed with the raw material must not exceed 30% by weight [R5].

For points e), f) and g), the Decree also specifies: "*The recovery is subordinate to the execution of the leaching test on the waste as it is according to the method in Annex 3 to this Decree*" [26].

The waste sampling procedure for future characterisation is described in **Ministerial Decree 5 February 1998** [26], **Art. 8** ("*Sampling and analysis*"). This operation must be carried out on the waste as it is, in order to obtain a representative sample according to standard **UNI 10802**: "*Waste – Manual sampling, sample preparation and analysis of eluates*" (standardised methods recognised at national, EU and international level [29]). In addition to sampling, analyses are also carried out by the producer using standardised methods and performed at the first transfer to the recovery plant and thereafter every 2 years (or whenever substantial changes occur in the waste production process).

The execution of the leaching test is regulated through **Ministerial Decree 5 February 1998** [26], **Art. 9**, with sampling that, as before, is carried out on the waste as it is (to obtain a representative sample always according to UNI 10802 standard). The leaching test is carried out at least at the beginning of each activity and, subsequently, every 12 months (or whenever substantial changes occur in the waste production process) and the methods of execution are defined in **Annex 3** of **Ministerial Decree 5 February 1998** ("*Criteria for determining the leaching test*").

Sub-annex 1 of **Annex 4** of the **Ministerial Decree 5 February 1998**: "*Determination of the maximum quantities of non-hazardous waste referred to in Sub-annex 1 of Annex 1 of Ministerial Decree 5 February 1998*", establishes, for each recovery activity, the maximum admissible quantities (tonnes/year). With regard to waste type **4.4** ("*Steelmaking slags, slags from melting in electric furnaces, combustion furnaces or oxygen converters of ferrous metal alloys and their subsequent refining treatments [10.02.02], [10.09.03], [10.02.01]*"), included in the Decree, Table 3-5 shows the maximum quantities that can be recovered.

Table 3-5: Maximum quantities of non-hazardous waste for each recovery operation (Sub-annex 1 of Annex 4 of Ministerial Decree 5 February 1998) for the type in point 4.4 [26].

Recovery activities	**Quantity (t/y)**
Steel industry	145000
Production of cement mixtures	15000
Production of bituminous mixtures	25000
Cement factory	25000
Brick industry	77620
Use of waste for road embankments and sub-bases	303580
Use of waste for landfill cover	15000
Use of waste for environmental recovery	303590
Put in reserve	3500

Another case of interest concerns the type of waste described in **Point 5.17** (**Sub-annex 1** of **Annex 1** of **Ministerial Decree 5 February 1998**): "*Granulated blast furnace slag not meeting the standards of UNI ENV 197/1 [10.02.02]*". This particular slag "*originates from the iron and steel industry dedicated to the production of pig iron in a blast furnace by smelting coke and iron ore in the presence of fluxes*". This slag appears as a "*glassy matrix solid in granular form or medium-coarse-grained sand, varying in colour from grey to yellowish, consisting of silica > 30%, calcium oxides > 40%, aluminium oxides, magnesium oxides*". The following recovery activities are identified for this type of waste [26]:

(a) Cement factory [R5];
(b) Glassy industry [R5]
(c) Production of concrete, cement and bituminous mixtures [R5];
(d) Production of catalysed hydraulic mixes [R5];
(e) Formation of embankments, road sub-bases and railway ballast, even when mixed with other waste for which this type of recovery is planned [R5];
(f) Use for environmental recovery [R10];

For points e) and f), the Decree also specifies: "*The recovery is subordinate to the execution of the leaching test on the waste as it is according to the method in Annex 3 to this Decree*" [26].

As previously done for waste type 4.4, also for waste type 5.17 **Sub-annex 1** of **Annex 4** of the **Ministerial Decree 5 February 1998**: "*Determination of the maximum quantities of non-hazardous waste referred to in Sub-annex 1 of Annex 1 of Ministerial Decree 5 February 1998*", establishes, for each recovery activity, the maximum admissible quantities (tonnes/year). With regard to waste type **5.17** ("*Granulated blast furnace slag not meeting the standards of UNI ENV 197/1 [10.02.02]*"), included in the Decree, Table 3-6 shows the maximum quantities that can be recovered.

Table 3-6: Maximum quantities of non-hazardous waste for each recovery operation (Sub-annex 1 of Annex 4 of Ministerial Decree 5 February 1998) for the type in point 5.17 [26].

Recovery activities	**Quantity (t/y)**
Cement factory	25000
Use of waste for road embankments and sub-bases	1000
Use of waste for environmental recovery	3000

3.6 Leaching test

The reuse of steelmaking slags in different applications must also take into account the possible impacts that this material could have on human health and the environment. The **leaching test** is a test that simulates the process of transferring chemical constituents, carried out by placing a solid in contact with a separator agent (*"leaching agent"* or *"leachant"*) for a certain period of time, and then separating the two phases to obtain an eluate, which will then be tested for the chemical constituents. Current legislation regulates various types of leaching tests, depending on the type of material to be analysed (*"waste"*, *"by-product"*, *"EoW"*, *"construction product"*), its structure (granular or monolithic material) and its destination. In particular, the destination of the material is one of the most significant parameters since whether the test is mandatory or not may depend on it. Table 3-7, Table 3-8, Table 3-9 and Table 3-10 show a (non-exhaustive) list of the main regulations and methods concerning leaching tests. The tests have been divided first according to the European Committee for Standardisation (*"**C**omité **E**uropéen de **N**ormalisation"* or *"**CEN**"* [30]) **T**echnical **C**ommittees (*"**CEN/TC**"*), then by Working Groups (*"**WG**"*) and finally according to whether they are tests for the characterisation of *"waste"*, *"by-products"* or *"construction products"*.

Table 3-7: (Non-exhaustive) list of the main regulations and methods concerning leaching tests (according to CEN/TC 351 "Construction products – Assessment of release of dangerous substances", WG 1 "Release from construction products into soil, ground, water and surface water").

Name	**Material**	**Title**	**Ref.**
CEN/TS 16637-1:2018	Construction products	Construction products – Assessment of release of dangerous substances – Part 1: Guidance for the determination of leaching tests and additional testing steps	[31]
CEN/TS 16637-2:2014	Construction products	Construction products – Assessment of release of dangerous substances – Part 2: Horizontal dynamic surface leaching test	[32]
CEN/TS 16637-3:2016	Construction products	Construction products – Assessment of release of dangerous substances – Part 3: Horizontal up-flow percolation test	[33]
CEN/TR 17105:2017	Construction products	Construction products – Assessment of release of dangerous substances – Guidance on the use of ecotoxicity tests applied to construction products	[34]

TS: Technical Specifications.
TR: Technical Reports.

Table 3-8: (Non-exhaustive) list of the main regulations and methods concerning leaching tests (according to CEN/TC 351 "Construction products – Assessment of release of dangerous substances", WG 5 "Content and eluate analysis in construction products").

Name	**Material**	**Title**	**Ref.**
CEN/TS 17331:2019	Construction products	Construction products – Assessment of release of dangerous substances – Content of organic substances – Methods for extraction and analysis	[35]
CEN/TS 17332:2019	Construction products	Construction products – Assessment of release of dangerous substances – Analysis of organic substances in eluates	[36]
CEN/TS 17195:2018	Construction products	Construction products – Assessment of release of dangerous substances – Analysis of inorganic substances in eluates	[37]

TS: Technical Specifications.

Table 3-9: (Non-exhaustive) list of the main regulations and methods concerning leaching tests (according to CEN/TC 444 "Environmental characterisation", WG 1 "Leaching tests").

Name	**Material**	**Title**	**Ref.**
EN 12920:2006 + A1:2008	Waste	Characterization of waste – Methodology for the determination of the leaching behaviour of waster under specified conditions	[38]
CEN/TS 15364:2006	Waste	Characterization of waste – Leaching behaviour tests – Acid and base neutralization capacity test	[39]
EN 12457-1:2002	Waste	Characterization of waste – Leaching – Compliance test for leaching of granular waste materials and sludges – Part 1: One stage batch test at a liquid to solid ratio of 2 l/kg for materials with high solid content and with particle size below 4 mm (without or with size reduction)	[40]
EN 12457-2:2002	Waste	Characterization of waste – Leaching – Compliance test for leaching of granular waste materials and sludges – Part 2: One stage batch test at a liquid to solid ratio of 10 l/kg for materials with particle size below 4 mm (without or with size reduction)	[41]
EN 12457-3:2002	Waste	Characterization of waste – Leaching – Compliance test for leaching of granular waste materials and sludges – Part 3: Two stage batch test at a liquid to solid ratio of 2 l/kg and 8 l/kg for materials with high solid content and with particle size below 4 mm (without or with size reduction)	[42]

Table 3-9: Cont.

Name	Material	Title	Ref.
EN 12457-4:2002	Waste	Characterization of waste – Leaching – Compliance test for leaching of granular waste materials and sludges – Part 4: One stage batch test at a liquid to solid ratio of 10 l/kg for materials with particle size below 10 mm (without or with size reduction)	[43]
EN 14405:2017	Waste	Characterization of waste – Leaching behaviour test – Up-flow percolation test (under specified conditions)	[44]
CEN/TS 16660:2015	Waste	Characterization of waste – Leaching behaviour test – Determination of the reducing character and the reducing capacity	[45]
EN 15863:2015	Waste (monolithic)	Characterization of waste – Leaching behaviour test for basic characterization – Dynamic monolithic leaching test with periodic leachant renewal, under fixed conditions	[46]
EN 14429:2015	Waste	Characterization of waste – Leaching behaviour test – Influence of pH on leaching with initial acid/base addition	[47]
EN 14997:2015	Waste	Characterization of waste – Leaching behaviour test – Influence of pH on leaching with continuous pH control	[48]
CEN/TS 15862:2012	Waste (monolithic)	Characterization of waste – Compliance leaching test – One stage batch leaching test for monoliths at fixed liquid to surface area ratio (L/A) for test portions with fixed minimum dimensions	[49]

TS: Technical Specifications.

Table 3-10: (Non-exhaustive) list of the main regulations and methods concerning leaching tests (according to CEN/TC 154 "Aggregates", Subcommittee ("SC") 6 "Test methods").

Name	Material	Title	Ref.
EN 1744-3:2002	Aggregates	Tests for chemical properties of aggregates – Part 3: Preparation of eluates by leaching of aggregates	[50]

The leaching test used to assess the release of chemical constituents and possible contaminants from steelmaking slags is **EN 12457-2:2002** [41] (transposed in Italy by the **UNI EN 12457-2:2004**). As reported by the **Lombardy Region Council Resolution n. XI/5224 of 13 September 2021** [2] for EAFS-C, the leaching test is required whenever the slag aggregate is destined for reuse in unbound applications (e.g. road embankments and sub-bases, landfill capping, etc.), while is not required for reuse in bound applications (e.g. hydraulically bound layers, concrete, bituminous mixtures, etc.). However, as pointed out by the same document, in addition to the numerous advantages, the use of the aforementioned leaching test generates doubts and some difficulties among operators. Table 3-11 shows a comparison is made between 2 leaching tests applicable to EAFS-C, based on the observation contained in the Lombardy Region Council Resolution n. XI/5224 of 13 September 2021 [2].

Table 3-11: Comparison between 2 leaching tests applicable to EAFS-C, based on the observation contained in the Lombardy Region Council Resolution n. XI/5224 [2].

	EN 12457-2:2002 [41]	**EN 1744-3:2002 [50]**
Fields of application	Granular waste and sludge	Aggregates for unbound applications
Material classification	Waste	By-product or EoW
Grain size	At least 95% (mass) < 4mm (with or without reduction)	< 32mm
Test portions preparation	In case of samples > 4 mm, grinding (possibly not finely so as not to increase the fine content of the sample)	• Aggregates must comply the grain size in which they are supplied • Grains > 32 mm crushed and the 16/32 mm fraction isolated (to be added in percentage in which the > 32 mm fraction was present in the original sample)
Liquid/Solid ratio (L/S)	10 l/kg dry matter	10 l/kg dry matter
Duration	• Waste-leachant (demineralised water) contact for at least 24h • Setting time of 15 minutes • Filtration at 0.45 µm • Chemical characterisation	• Material-water contact (agitated using a mechanical immersion agitator) for 24h ± 10 minutes • 10 minutes decantation • Extraction of eluate • Analysis
Limit values	• Imposed by Ministerial Decree 186/2006 [27] • Addition of molybdenum to the parameters (Lombardy Region Council Resolution n. XI/5224 [2])	• Imposed by Ministerial Decree 186/2006 [27] • Addition of molybdenum to the parameters (Lombardy Region Council Resolution n. XI/5224 [2])

Table 3-11: Cont.

	EN 12457-2:2002 [41]	**EN 1744-3:2002 [50]**
Main reference standards	UNI 10802:2013 [29], indicates that the test alone cannot characterise all properties of the waste, as specified in EN 12920:2008 [38] (applicable to disposal and recovery scenarios)	UNI EN 13242:2008 [59], indicates UNI EN 1744-3 for testing leaching behaviour
Advantages	• Cost-effectiveness • Simplicity of execution • Speed in obtaining results • Widespread presence of laboratories capable of doing this	• Test referred to materials independently classified as by-products or EoW • No reduction of sample size < 32 mm (no problems in managing the fine part, greater representativeness of the sample, less variability of results)
Disadvantages	• Lack of specific guidance on sample preparation criteria (particle size reduction, management of the fine part, excessive subjectivity and variability of the results, lack of representativeness of the sample) • Test referring specifically to waste	• Doubts about the treatment of the fine part resulting from any grinding processes

It is therefore of fundamental importance to know the characteristics of classification, structure and destination of the material considered, in order to identify the correct leaching test to per performed for its characterization.

For completeness, Table 3-12 shows the limit concentration values of the different components in the eluate. The limit values according to **Ministerial Decree 5 February 1998**, **Annex 3** [26], the **Ministerial Decree 5 April 2006**, **n. 186**, **Annex 3** [27] (which modified the Annex 3 of the Ministerial Decree 5 February 1998) and the proposal contained in the **Lombardy Region Council Resolution n. XI/5224 of 13 September 2021** [2] (specifically for EAFS-C), in which some elements have been excluded, are highlighted.

Table 3-12: Limit concentration values in the eluate according to Ministerial Decree 5 February 1998, Annex 3 [26], Ministerial Decree 5 April 2006, n. 186, Annex 3 [27] (which modified the Annex 3 of Ministerial Decree 5 February 1998) and the proposal contained in the Lombardy Region Council Resolution n. XI/5224 [2] for the leaching test performed specifically on electric arc furnace slag from carbon steel production (EAFS-C).

Parameters	**U.M.**	**Limit concentration values according to**		
		[26](*)	[27](*)	[2](**)
Nitrates	mg/l	50	50	-
Fluorides	mg/l	1.5	1.5	1.5
Sulphates	mg/l	250	250	-
Chlorides	mg/l	200	100	-
Cyanides	µg/l	50	50	-
Barium	mg/l	1	1	1
Copper	mg/l	0.05	0.05	0.05
Zinc	mg/l	3	3	3
Beryllium	µg/l	10	10	10
Cobalt	µg/l	250	250	250
Nickel	µg/l	10	10	10
Vanadium	µg/l	250	250	250
Arsenic	µg/l	50	50	50
Cadmium	µg/l	5	5	5
Total chromium	µg/l	50	50	50
Lead	µg/l	50	50	50
Selenium	µg/l	10	10	10
Mercury	µg/l	1	1	1
Asbestos	mg/l	30	30	-
COD(***)	mg/l	30	30	30
pH	-	5.5–12.0	5.5–12.0	9–13
Molybdenum	mg/l	-	-	0.15

(*) *Limit values for the results of the leaching test performed according to EN 12457-2:2002 [41].*

(**) *Proposal limit values for the results of the leaching test performed **specifically** on electric arc furnace slag from carbon steel production (**EAFS-C**), according to EN 1744-3:2002 [50].*

(***) *COD: Chemical Oxygen Demand.*

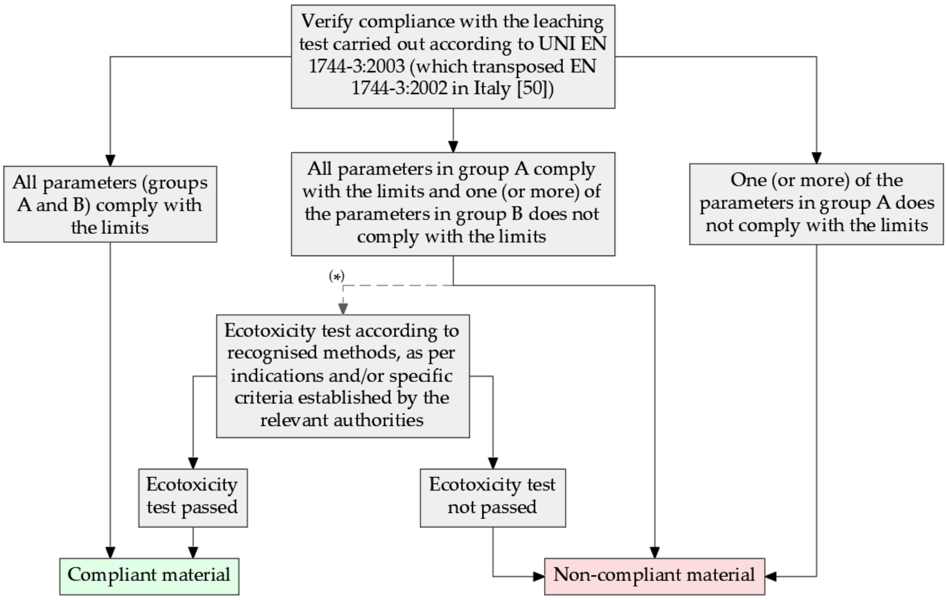
As the table shows, Annex 3 of Ministerial Decree 5 April 2006, n. 186 [27] did not make any changes to Annex 3 of Ministerial Decree 5 February 1998 [26] with regard to elements limit concentration values in the eluate, except for chlorides, which saw a reduction by half on the limit concentration (from 200 to 100 mg/l).

The third column of the table refers to the limit values proposed by the Lombardy Region Council Resolution n. XI/5224 of 13 September 2021 [2] for the leaching test performed specifically on electric arc furnace slag from carbon steel production (EAFS-C), according to the EN 1744-3:2002 method [50]. These values were identified from those contained in Annex 3 of the Ministerial Decree 5 February 1998, with the exclusion of some substances and the addition of "*molybdenum*". In particular [2]:

- Nitrates, sulphates, chlorides, cyanides and asbestos were excluded (tests and literature revealed concentrations that are typically absent or much lower than the limits imposed by the regulations, due to the production process of EAFS-C than does not allow or limit the formation of these compounds in the slag);
- The parameter "*molybdenum*" was added. This element is significant in terms of its ecotoxicity characteristics for the aquatic environment (as reported in the ECHA Registration dossier); the proposed concentration limit value is therefore 0.15 mg/l (two orders of magnitude lower than the **P**redicted **N**o **E**ffect **C**oncentration ("***PNEC***") value (12.7 mg/l) for the freshwater organisms).

In addition to the leaching test, there are also tests for verifying the environmental compatibility of a material by assessing direct interactions with the environment and the biological response of certain living organisms in contact with the eluate, so-called "***ecotoxicity tests***". They have the advantage of allowing global assessment of the impact of a material on the environment and quantifying any effects on living organisms (so-called "*sensitive indicator species*", e.g. Vibrio fischeri, Pseudokirchneriella sub-capitata, Daphnia Magna). On the other hand, they are not easy to perform, both in terms of time and the necessary equipment that a laboratory would need to set up. According to the Lombardy Region Council Resolution n. XI/5224 of 13 September 2021 [2], they could support the leaching tests in case a material should exceed one or more limits. In case a material does not comply with one or more limits with regard to leaching test, it will not be considered compliant and will be destined for disposal in landfill. By combining the leaching test with the ecotoxicity test, the real and direct environmental impact could be verified, perhaps leading to a recovery of the material that, based on the leaching test alone, would not have been possible [2].

Just as an example, Figure 3-5 shows an adaptation of the diagram in Figure 4 of the Lombardy Region Council Resolution n. XI/5224 of 13 September 2021 [2], which contains a proposal for the environmental conformity of electric arc furnace slag from carbon steel production (EAFS-C), placing the ecotoxicity test alongside the leaching test and dividing the parameters in column 3 of Table 3-12 of this document into two groups, A (substances of particular relevance to health and the environment, e.g. carcinogens and mutagens) and B (other substances).



(*) Possibility foreseen when defining the methods to be adopted
Group A elements: Arsenic, Beryllium, Cadmium, Cobalt, Total chromium, Mercury, Nickel, Lead
Group B elements: Barium, Fluorides, Molybdenum, Copper, Selenium, Vanadium, Zinc, COD, pH

Figure 3-5: Proposal for the environmental conformity of electric arc furnace slag from carbon steel production (EAFS-C), adapted from the diagram in Figure 4 of the Lombardy Region Council Resolution n. XI/5224 of 13 September 2021 [2].

3.7 Waste disposal

The definition of "*disposal*" is provided by **Legislative Decree 152/2006** [1], **Art. 183, paragraph 1, letter z)**, updated by **Legislative Decree 205/2010** [5], **Art. 10**: "*Any operation other than recovery even when the operation has a secondary consequence the recovery of substances or energy. Annex B to Part IV of this Decree contains a non-exhaustive list of disposal operations*". A non-exhaustive list of recovery operations is included in **Legislative Decree 152/2006** [1], **Part IV**, **Annex B**, replaced by **Legislative Decree 205/2010** [5], **Annex B** (shown in Table 3-13).

Table 3-13: Disposal operations (Legislative Decree 205/2010, Annex B) [5].

Disposal operations	
D1	Disposal on or in the soil (e.g. landfill)
D2	Treatment in the terrestrial environment (e.g. biodegradation of liquid waste or sludge in soils)
D3	Deep injection (e.g. injection of pumpable waste into wells, salt domes or natural geological faults)
D4	Surface impoundment (e.g. discharge of liquid waste or sludge into wells, ponds or lagoons, etc.)
D5	Specially engineered landfill (e.g. placement into ponds, separated, capped or isolated from each other and the environment)
D6	Discharge of solid waste into the water environment except immersion
D7	Immersion, including burial in the seabed
D8	Biological treatment not specified elsewhere in this Annex which results in final compounds or mixtures which are discarded by means of any of the operations numbered D1 to D12
D9	Physico-chemical treatment not specified elsewhere in this Annex which results in final compounds or mixtures which are discarded by means of any of the operations listed from D1 to D12 (e.g. evaporation, drying, calcination, etc.)
D10	Incineration on land
D11	Incineration in the sea
D12	Permanent storage (e.g. placement of containers in a mine)
D13	Preliminary repackaging prior to any of the operations listed from D1 to D12
D14	Reconditioning prior to any of the operations listed from D1 to D13
D15	Preliminary storage prior to any of the operations listed from D1 to D14 (excluding temporary storage, prior to collection, on the production site)

In case the "*End of Waste*" process fails, steelmaking slags have to be disposed of in a landfill. The definition of waste eligibility criteria in landfills is established by **Legislative Decree 3 September 2020**, **n. 121** [51], which repealed **Ministerial Decree 27 September 2010** [52] (in turn modified by **Ministerial Decree 24 June 2015** [53]). The aforementioned Legislative Decree modifies **Legislative Decree 13 January 2003**, **n. 36** [54], introducing **Art. 7-bis** ("*Basic characterisation*") which, in **Point 1**, specifies: "*In order to determine the acceptability of waste in each category of landfill, the waste producer is required to carry out the basic characterisation of each type of waste sent to the landfill. The characterisation must be carried out prior to landfilling or after the last treatment performed*". Characterisation is therefore mandatory for any type of waste and must be carried out in order to provide basic information on composition, consistency and any tendency to leachate. In particular, **Art. 7-quarter**

(“*Landfills for inert waste*”), establishes which waste can actually be destined for landfills for inert waste. As an example, Table 3-14 shows the limits that have to be complied with for eligibility for landfill for inert waste (as contained in Table 2 of Annex 4 of the Legislative Decree 3 September 2020 [51]).

Table 3-14: Limit values for landfill admissibility for inert waste (Table 2 of Annex 4 of Legislative Decree 3 September 2020, n. 121) [51].

Parameters	**U.M.**	**Limit values**
Antimony	mg/l	6
Fluorides	mg/l	1
Sulphates	mg/l	100
Chlorides	mg/l	80
Barium	μg/l	2
Copper	mg/l	0.2
Zinc	mg/l	0.4
Molybdenum	mg/l	50
Nickel	μg/l	40
Phenol index	μg/l	100
Arsenic	μg/l	50
Cadmium	μg/l	4
Total chromium	μg/l	50
Lead	μg/l	50
Selenium	μg/l	50
Mercury	μg/l	1
DOC(*)	μg/l	50
TDS(**)	μg/l	400
pH	-	5.5–12

(*) *DOC: Dissolved Organic Carbon.*

(**) *TDS: Total Dissolved Solids.*

3.8 CE Marking

The European Union has issued specific regulations for construction products (with the aim of creating a single market) through **Council Directive 21 December 1988 (89/106/EEC** or “*Construction Products Directive*” or “***CPD***” [55]), repealed by **European Regulation CPR 305/2011** [56]. Annex 1 of the aforementioned Council Directive establishes what the essential requirements of civil works should be:

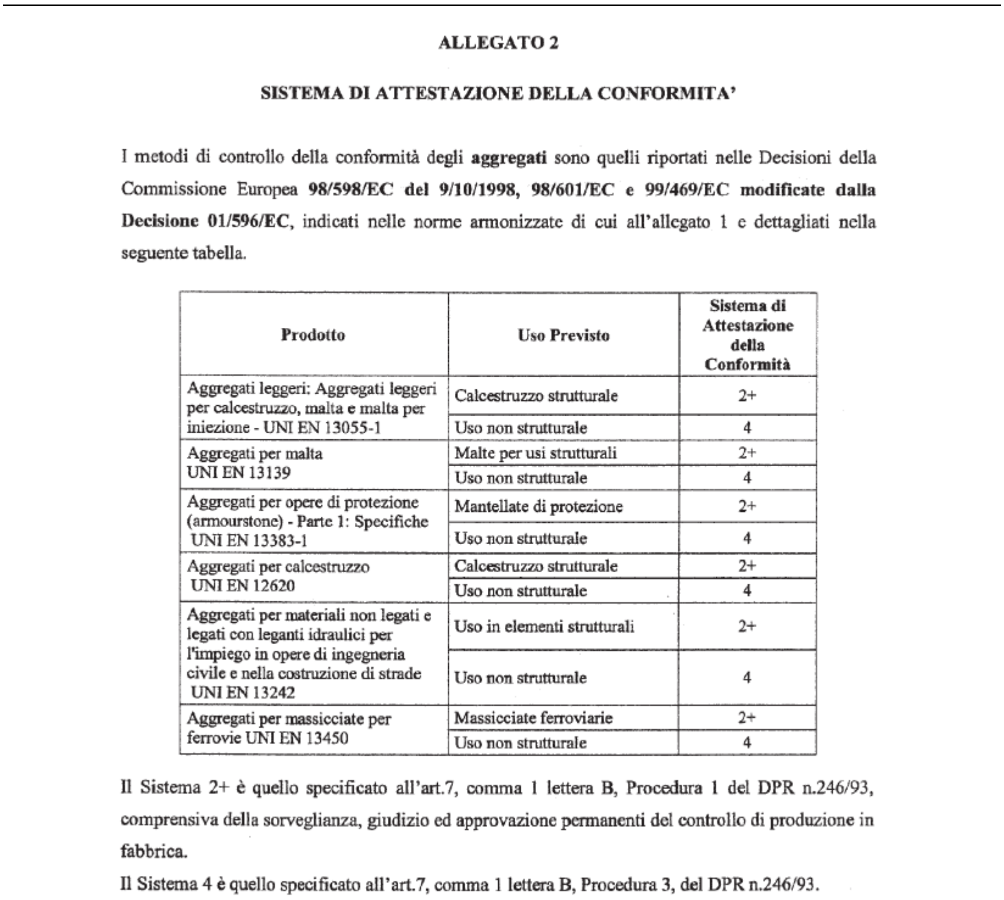
(a) “*Mechanical resistance and stability*”;

(b) *"Safety in case of fire"*;
(c) *"Hygiene, health and the environment"*;
(d) *"Safety in use"*;
(e) *"Protection against noise"*;
(f) *"Energy, economy and heat retention"*.

The **Ministerial Decree 11 April 2007** of the Ministry of Infrastructure [57] constitutes the application of Council Directive 21 December 1988 [55] on construction products, (transposed by **Presidential Decree 21 April 1993, n. 246** [8]). **Annex 1** identifies the products and the relevant harmonised reference standards for aggregates. On the other hand, **Annex 2** contains the methods for certifying the conformity of aggregates for each category (small extract in Figure 3-6), while **Annex 3** contains a list of technical characteristics to be declared by the producer, depending on the expected use (Figure 3-7 and Figure *3-8* show two extracts for aggregates destined for reuse in concrete as aggregate and as filler, respectively).

As highlighted in Section 2, the aggregate derived from steel slag is a material mechanically comparable to an inert natural aggregate and, as such, complies with the relevant technical standards:

- EN 12620 (*"Aggregates for concrete"*), transposed as UNI EN 12620 [58];
- EN 13242 (*"Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction"*), transposed as UNI EN 13242 [59];
- EN 13450 (*"Aggregates for railway ballast"*), transposed as UNI EN 13450 [60];
- EN 13043 (*"Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas"*), transposed as UNI EN 13043 [61];
- EN 13055 (*"Lightweight aggregates"*), transposed as UNI EN 13055 [62];
- EN 13139 (*"Aggregates for mortar"*), transposed as UNI EN 13139 [63];
- EN 13383-1 (*"Armourstone – Part 1: Specification"*), transposed as UNI EN 13383-1 [64].



ALLEGATO 2

SISTEMA DI ATTESTAZIONE DELLA CONFORMITA'

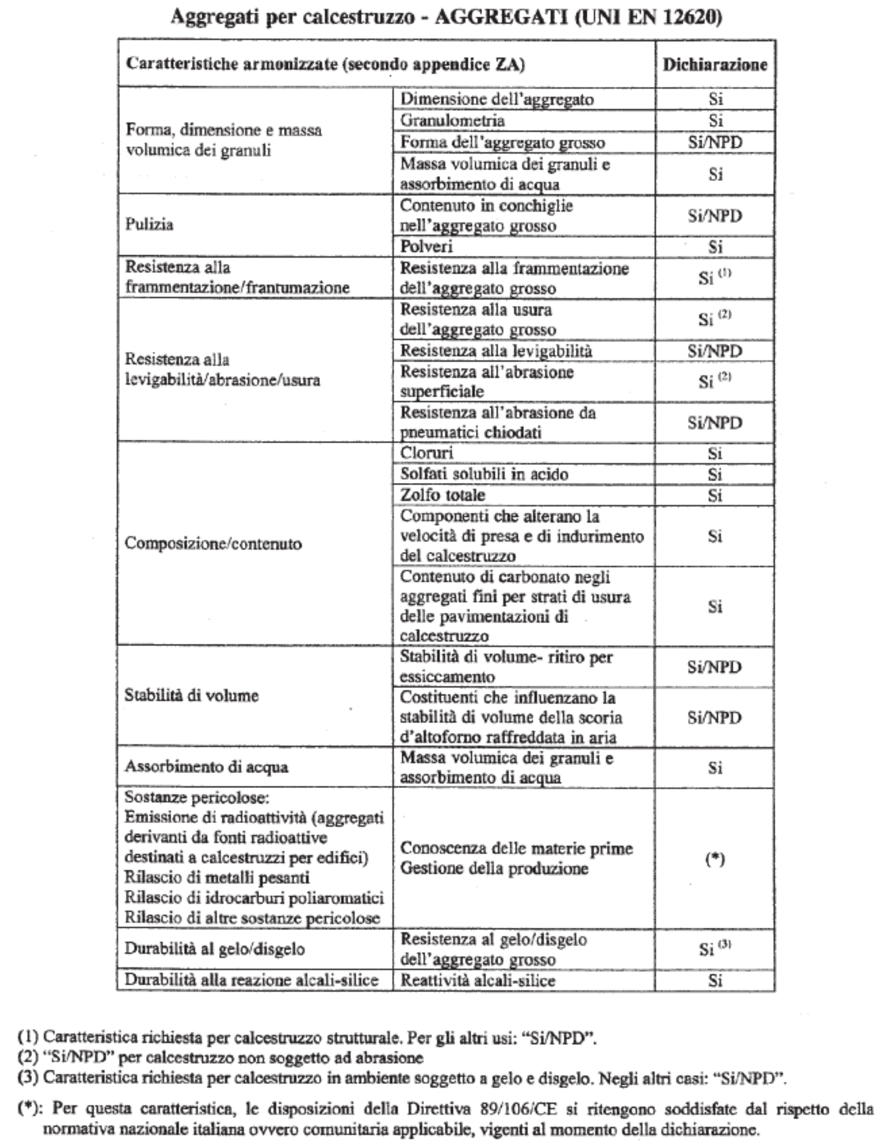
I metodi di controllo della conformità degli **aggregati** sono quelli riportati nelle Decisioni della Commissione Europea **98/598/EC del 9/10/1998, 98/601/EC e 99/469/EC modificate dalla Decisione 01/596/EC**, indicati nelle norme armonizzate di cui all'allegato 1 e dettagliati nella seguente tabella.

Prodotto	**Uso Previsto**	**Sistema di Attestazione della Conformità**
Aggregati leggeri: Aggregati leggeri per calcestruzzo, malta e malta per iniezione - UNI EN 13055-1	Calcestruzzo strutturale	2+
	Uso non strutturale	4
Aggregati per malta UNI EN 13139	Malte per usi strutturali	2+
	Uso non strutturale	4
Aggregati per opere di protezione (armourstone) - Parte 1: Specifiche UNI EN 13383-1	Mantellate di protezione	2+
	Uso non strutturale	4
Aggregati per calcestruzzo UNI EN 12620	Calcestruzzo strutturale	2+
	Uso non strutturale	4
Aggregati per materiali non legati e legati con leganti idraulici per l'impiego in opere di ingegneria civile e nella costruzione di strade UNI EN 13242	Uso in elementi strutturali	2+
	Uso non strutturale	4
Aggregati per massicciate per ferrovie UNI EN 13450	Massicciate ferroviarie	2+
	Uso non strutturale	4

Il Sistema 2+ è quello specificato all'art.7, comma 1 lettera B, Procedura 1 del DPR n.246/93, comprensiva della sorveglianza, giudizio ed approvazione permanenti del controllo di produzione in fabbrica.

Il Sistema 4 è quello specificato all'art.7, comma 1 lettera B, Procedura 3, del DPR n.246/93.

Figure 3-6: Extract from Annex 2 of Ministerial Decree 11 April 2007, containing the methods for certifying the conformity of aggregates for each category [57]).



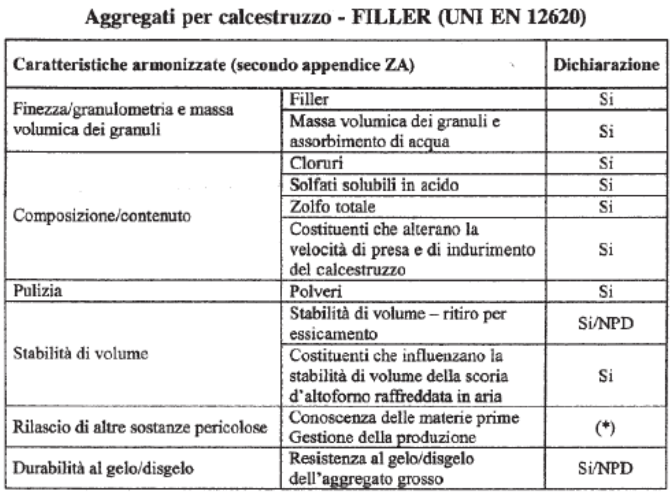
Aggregati per calcestruzzo - AGGREGATI (UNI EN 12620)

Caratteristiche armonizzate (secondo appendice ZA)		Dichiarazione
Forma, dimensione e massa volumica dei granuli	Dimensione dell'aggregato	Si
	Granulometria	Si
	Forma dell'aggregato grosso	Si/NPD
	Massa volumica dei granuli e assorbimento di acqua	Si
Pulizia	Contenuto in conchiglie nell'aggregato grosso	Si/NPD
	Polveri	Si
Resistenza alla frammentazione/frantumazione	Resistenza alla frammentazione dell'aggregato grosso	Si (1)
Resistenza alla levigabilità/abrasione/usura	Resistenza alla usura dell'aggregato grosso	Si (2)
	Resistenza alla levigabilità	Si/NPD
	Resistenza all'abrasione superficiale	Si (2)
	Resistenza all'abrasione da pneumatici chiodati	Si/NPD
Composizione/contenuto	Cloruri	Si
	Solfati solubili in acido	Si
	Zolfo totale	Si
	Componenti che alterano la velocità di presa e di indurimento del calcestruzzo	Si
	Contenuto di carbonato negli aggregati fini per strati di usura delle pavimentazioni di calcestruzzo	Si
Stabilità di volume	Stabilità di volume- ritiro per essiccamento	Si/NPD
	Costituenti che influenzano la stabilità di volume della scoria d'altoforno raffreddata in aria	Si/NPD
Assorbimento di acqua	Massa volumica dei granuli e assorbimento di acqua	Si
Sostanze pericolose: Emissione di radioattività (aggregati derivanti da fonti radioattive destinati a calcestruzzi per edifici) Rilascio di metalli pesanti Rilascio di idrocarburi poliaromatici Rilascio di altre sostanze pericolose	Conoscenza delle materie prime Gestione della produzione	(*)
Durabilità al gelo/disgelo	Resistenza al gelo/disgelo dell'aggregato grosso	Si (3)
Durabilità alla reazione alcali-silice	Reattività alcali-silice	Si

(1) Caratteristica richiesta per calcestruzzo strutturale. Per gli altri usi: "Si/NPD".
(2) "Si/NPD" per calcestruzzo non soggetto ad abrasione
(3) Caratteristica richiesta per calcestruzzo in ambiente soggetto a gelo e disgelo. Negli altri casi: "Si/NPD".

(*): Per questa caratteristica, le disposizioni della Direttiva 89/106/CE si ritengono soddisfate dal rispetto della normativa nazionale italiana ovvero comunitaria applicabile, vigenti al momento della dichiarazione.

Figure 3-7: Extract from Annex 3 of Ministerial Decree 11 April 2007, containing the technical characteristics to be declared for the reuse of aggregates as aggregates for concrete production [57]).

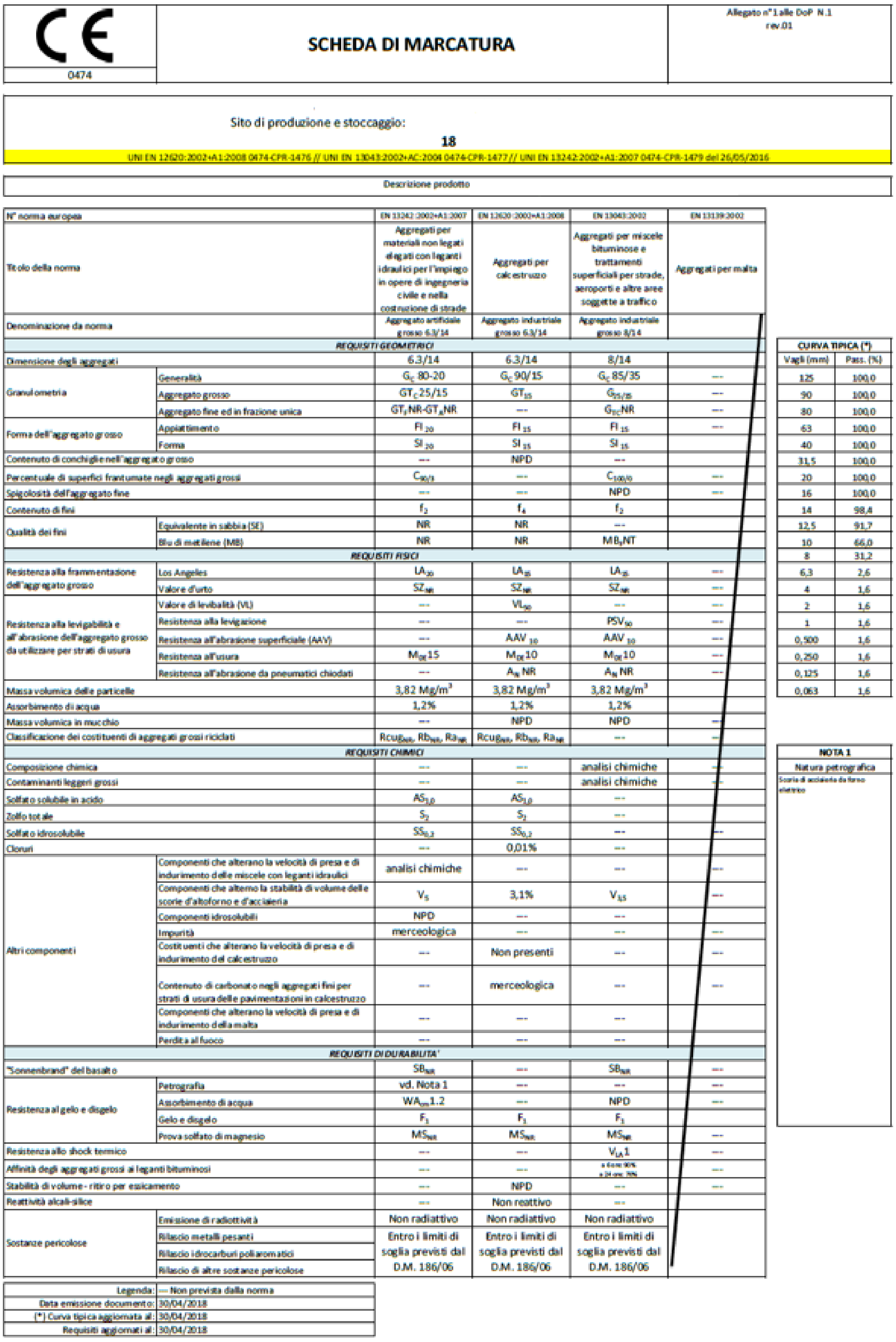


Aggregati per calcestruzzo - FILLER (UNI EN 12620)

Caratteristiche armonizzate (secondo appendice ZA)		Dichiarazione
Finezza/granulometria e massa volumica dei granuli	Filler	Si
	Massa volumica dei granuli e assorbimento di acqua	Si
Composizione/contenuto	Cloruri	Si
	Solfati solubili in acido	Si
	Zolfo totale	Si
	Costituenti che alterano la velocità di presa e di indurimento del calcestruzzo	Si
Pulizia	Polveri	Si
Stabilità di volume	Stabilità di volume – ritiro per essicamento	Si/NPD
	Costituenti che influenzano la stabilità di volume della scoria d'altoforno raffreddata in aria	Si
Rilascio di altre sostanze pericolose	Conoscenza delle materie prime Gestione della produzione	(*)
Durabilità al gelo/disgelo	Resistenza al gelo/disgelo dell'aggregato grosso	Si/NPD

Figure 3-8: Extract from Annex 3 of Ministerial Decree 11 April 2007, containing the technical characteristics to be declared for the reuse of aggregates as filler for concrete production [57]).

Therefore, the producer of EAFS-C aggregate places a material on the market that must be CE marked, demonstrating that the characteristics comply with the technical reference standards. The CE marking thus represents a guarantee for the purchaser that the aggregate simultaneously meets the essential safety requirements and the technical reference standards. Figure 3-9 shows an example of a CE marking sheet.



CE
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SCHEDA DI MARCATURA

Allegato n°1 alle DoP N.1
rev.01

Sito di produzione e stoccaggio:
18

UNI EN 12620:2002+A1:2008 0474-CPR-1476 // UNI EN 13043:2002+AC:2004 0474-CPR-1477 // UNI EN 13242:2002+A1:2007 0474-CPR-1479 del 26/05/2016

Descrizione prodotto

N° norma europea		EN 13242:2002+A1:2007	EN 12620:2002+A1:2008	EN 13043:2002	EN 13139:2002
Titolo della norma		Aggregati per materiali non legati e legati con leganti idraulici per l'impiego in opere di ingegneria civile e nella costruzione di strade	Aggregati per calcestruzzo	Aggregati per miscele bituminose e trattamenti superficiali per strade, aeroporti e altre aree soggette a traffico	Aggregati per malta
Denominazione da norma		Aggregato artificiale grosso 6.3/14	Aggregato industriale grosso 6.3/14	Aggregato industriale grosso 8/14	
REQUISITI GEOMETRICI					
Dimensione degli aggregati		6.3/14	6.3/14	8/14	
Granulometria	Generalità	G_C 80-20	G_C 90/15	G_C 85/35	---
	Aggregato grosso	GT_C 25/15	GT_{15}	$G_{25/15}$	---
	Aggregato fine ed in frazione unica	GT_FNR-GT_ANR	---	G_{TC}NR	---
Forma dell'aggregato grosso	Appiattimento	FI_{20}	FI_{15}	FI_{15}	---
	Forma	SI_{20}	SI_{15}	SI_{15}	
Contenuto di conchiglie nell'aggregato grosso		---	NPD	---	
Percentuale di superfici frantumate negli aggregati grossi		$C_{90/3}$	---	$C_{100/0}$	---
Spigolosità dell'aggregato fine		---	---	NPD	---
Contenuto di fini		f_2	f_4	f_2	
Qualità dei fini	Equivalente in sabbia (SE)	NR	NR	---	
	Blu di metilene (MB)	NR	NR	MB_FNT	
REQUISITI FISICI					
Resistenza alla frammentazione dell'aggregato grosso	Los Angeles	LA_{20}	LA_{25}	LA_{25}	---
	Valore d'urto	SZ_{NR}	SZ_{NR}	SZ_{NR}	---
Resistenza alla levigabilità e all'abrasione dell'aggregato grosso da utilizzare per strati di usura	Valore di levibalità (VL)	---	VL_{50}	---	---
	Resistenza alla levigazione	---	---	PSV_{50}	---
	Resistenza all'abrasione superficiale (AAV)	---	AAV_{10}	AAV_{10}	---
	Resistenza all'usura	M_{DE}15	M_{DE}10	M_{DE}10	---
	Resistenza all'abrasione da pneumatici chiodati	---	A_N NR	A_N NR	---
Massa volumica delle particelle		3,82 Mg/m³	3,82 Mg/m³	3,82 Mg/m³	
Assorbimento di acqua		1,2%	1,2%	1,2%	
Massa volumica in mucchio		---	NPD	NPD	---
Classificazione dei costituenti di aggregati grossi riciclati		$Rcug_{NR}$, Rb_{NR}, Ra_{NR}	$Rcug_{NR}$, Rb_{NR}, Ra_{NR}	---	---
REQUISITI CHIMICI					
Composizione chimica		---	---	analisi chimiche	---
Contaminanti leggeri grossi		---	---	analisi chimiche	---
Solfato solubile in acido		$AS_{1,0}$	$AS_{1,0}$	---	
Zolfo totale		S_2	S_2	---	
Solfato idrosolubile		$SS_{0,2}$	$SS_{0,2}$	---	---
Cloruri		---	0,01%	---	
Altri componenti	Componenti che alterano la velocità di presa e di indurimento delle miscele con leganti idraulici	analisi chimiche	---	---	---
	Componenti che alterno la stabilità di volume delle scorie d'altoforno e d'acciaieria	V_5	3,1%	$V_{3,5}$	---
	Componenti idrosolubili	NPD	---	---	
	Impurità	merceologica	---	---	---
	Costituenti che alterano la velocità di presa e di indurimento del calcestruzzo	---	Non presenti	---	---
	Contenuto di carbonato negli aggregati fini per strati di usura delle pavimentazioni in calcestruzzo	---	merceologica	---	---
	Componenti che alterano la velocità di presa e di indurimento della malta	---	---	---	
	Perdita al fuoco	---	---	---	
REQUISITI DI DURABILITA'					
"Sonnenbrand" del basalto		SB_{NR}	---	SB_{NR}	---
Resistenza al gelo e disgelo	Petrografia	vd. Nota 1	---	---	---
	Assorbimento di acqua	WA_{cm}1.2	---	NPD	---
	Gelo e disgelo	F_1	F_1	F_1	
	Prova solfato di magnesio	MS_{NR}	MS_{NR}	MS_{NR}	---
Resistenza allo shock termico		---	---	V_{LA}1	---
Affinità degli aggregati grossi ai leganti bituminosi		---	---	[illegible]	---
Stabilità di volume - ritiro per essicamento		---	NPD	---	---
Reattività alcali-silice		---	Non reattivo	---	
Sostanze pericolose	Emissione di radiottività	Non radiattivo	Non radiattivo	Non radiattivo	
	Rilascio metalli pesanti	Entro i limiti di soglia previsti dal D.M. 186/06	Entro i limiti di soglia previsti dal D.M. 186/06	Entro i limiti di soglia previsti dal D.M. 186/06	
	Rilascio idrocarburi poliaromatici				
	Rilascio di altre sostanze pericolose				

CURVA TIPICA (*)	
Vagli (mm)	Pass. (%)
125	100,0
90	100,0
80	100,0
63	100,0
40	100,0
31,5	100,0
20	100,0
16	100,0
14	98,4
12,5	91,7
10	66,0
8	31,2
6,3	2,6
4	1,6
2	1,6
1	1,6
0,500	1,6
0,250	1,6
0,125	1,6
0,063	1,6

NOTA 1
Natura petrografica
Scoria di acciaieria da forno elettrico

Legenda:	--- Non prevista dalla norma
Data emissione documento:	30/04/2018
(*) Curva tipica aggiornata al:	30/04/2018
Requisiti aggiornati al:	30/04/2018

Figure 3-9: Example of a CE marking sheet.

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4. MATERIAL FLOW ANALYSIS (“*MFA*”)

4.1 Introduction

In addition to the knowledge of the properties of the different types of steel slags and the regulatory processes they have to comply with in order to be reused (and disposed), it is also essential to understand how production is distributed throughout the national territory and how the different actors of the supply chain (from producer to final user) are interconnected. **M**aterial **F**low **A**nalysis (“*MFA*”) is therefore a very useful and used tool in the field of sustainability and circular economy. By means of accurate processing of data from different sources and depending on the available and desired information, it allows to outline the state of the art of a well-defined system at different levels of detail.

In particular, this section will show the processing of data from different sources and relating to the production, treatment, management, marketing and reuse of steel slags at both national and local levels, with a special focus on the Lombardy region (Italy) and the province of Brescia (Italy). The quantities of slag produced in the territory will be identified, which will then be subdivided according to the type of slag, classification (“*by-product*” or “*waste*”), destination (“*recovery*” or “*disposal*”) and final reuses. Thanks to these processing, it was also possible to choose the most suitable type of steel slag for the development of the subsequent experimental campaign.

4.2 World steel and steelmaking slags production

Figure 4-1 shows the development of steel production worldwide over the years, starting from 2000 up to the last available annual data (2021). Total production is indicated by a box above each column of the histogram. The graph also subdivides the total production according to the major producing countries to show who contributes most to production [1].

As shown, the global steelmaking industry has seen a significant increase in production, from 0.84 billion tonnes in 2000 to 1,95 billion tonnes in 2021 (an increase of approximately 130%). It can be seen that Asian countries are the world’s largest steel producers, with China alone producing about 53% (as of 2021). The European countries have been merged into a single group due to their low production compared to that of the Asian countries (a further subdivision has been made between European countries, distinguishing between EU and non-EU countries, naming the “other Europe”, as indicated in [1]).

However, great care must be taken when comparing these data and keep in mind the “*changes*” (including cultural and geopolitical changes) that occur over time. For example, the EU has seen the entry of several new countries in the last twenty years, thus increasing its production share (in 2000 there were 15 Member States and all of them contributed the necessary data, while in 2021 there were 27 Member States but only 21 provided production data).

The figure also shows that the years 2009 and 2015 were characterised by a more or less significant reduction in production, due to the economic crisis, which was later overcome by the continued growth of the sector. 2020 was also a particularly complicated year, due to the SARS-CoV-2 pandemic. While China still managed to increase its production, albeit to a limited extent, many other leading steel producing countries (e.g. India, Japan, the US, etc.) experienced a sharp decline.

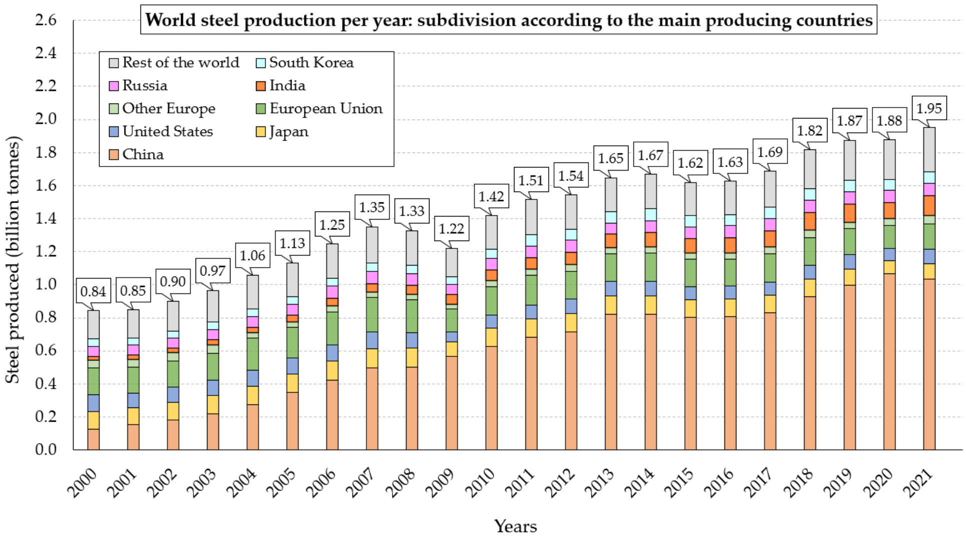


Figure 4-1: Development of steel production worldwide over the years (from 2000 to 2021), subdivided according to the major producing countries (total production is indicated by a box above each column). Values in billion tonnes (x10^9) [1].

Figure 4-2 shows the annual world steel production subdivided, however, according to the production process adopted. As previously mentioned, steel production takes place according to two different cycles: "*integral cycle*" (in which steel is produced in a basic oxygen converter starting from pig iron produced in a blast furnace) and "*electric cycle*" (single production step in an electric arc furnace).

It can be seen that the integral cycle, i.e. the production of steel by means of a basic oxygen converter (for more details on production processes, see Section 2), is the most widespread technique worldwide, with production percentages of around 70% (as of 2021) [1].

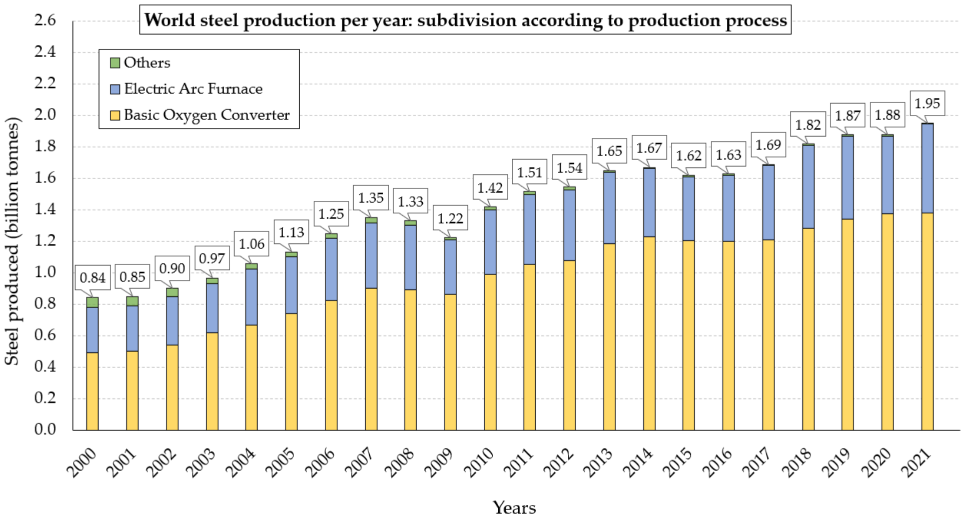


Figure 4-2: Development of steel production worldwide over the years (from 2000 to 2021), subdivided according to the production process (total production is indicated by a box above each column). Values in billion tonnes (x10^9) [1].

The factors that lead to the choice of a production process rather than another are many and can be very different even within the same country. The most important include the historicity of the production method and local customs, the raw materials available, the choices of individual companies, the bureaucracy and the decision of individual governments, possible import/export agreements with other countries, waste management and reuse, etc.

As an example, a subdivision of the different steel production processes by macro-areas is shown in Figure 4-3 for the year 2021. A great difference can be seen in the use and spread of the different technologies. Steel production by basic oxygen converter is widespread on the Asian continent, which alone produces about 82% of global steel from basic oxygen converter (Figure 4-3(b)). On the other hand, electric cycle technology is slightly more uniformly spread, with “only” 48% of the total produced coming from Asian countries (Figure 4-3(c)). Some technologies other than those previously analysed and certainly less widespread are however used in the regions of Russia and Ukraine and in Central and South America (Figure 4-3(d)) [1].

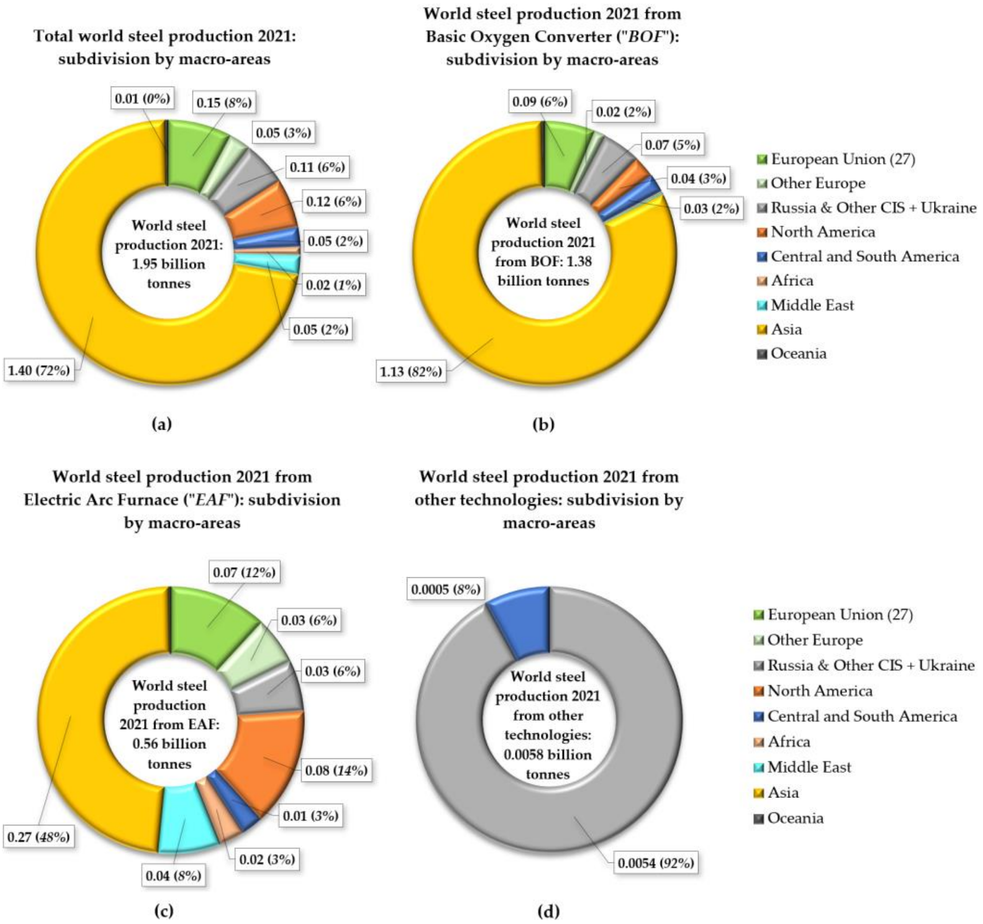


Figure 4-3: Subdivision of the different steel production processes by macro-areas: total world production (a); production by basic oxygen converter (b); production by electric arc furnace (c) and production by "other technologies" (d). Values in billion tonnes (x10^9) [1].

With regard to **global steelmaking slags production**, no precise values exists. Using the steel production described above and appropriately divided between the different processes and the slag production per tonne of steel produced (described in Section 2), it is possible to estimate the amount of steelmaking slags produced globally. For example, for the year 2021, the (**estimated**) production of **BOFS** (from the production of steel in basic oxygen converter) is between **140 and 200 million tonnes** (assuming 100–150 kg of slag per tonne of steel produced), while **EAFS** (from the production of steel in electric arc furnace) is between **56 and 84 million tonnes** (assuming 100 – 150 kg of slag per tonne of steel produced).

4.3 *Italian steel and steelmaking slags production*

Figure 4-4 shows the annual Italian steel production subdivided according to the production process adopted (basic oxygen converter or an electric arc furnace, the only two methods currently used).

With a total steel production of about 24.4 million tonnes in 2021, Italy is currently the second largest steel producer in Europe after Germany, without considering Turkey (which is not classified in the "EU27"countries in the World Steel Association statistics [1]). However, it must be considered that the 2021 data, even though it is the latest available year, is not fully representative of Italian production trend. As can be seen from the figure, the SARS-CoV-2 pandemic has had a significant negative impact on the steel sector, with a reduction of around 12% in total steel production from 2019 to 2020 (a reduction not comparable to that which occurred with the economic crisis of 2009, but which has still accentuated the fluctuating production trend production trend of the past twenty years).

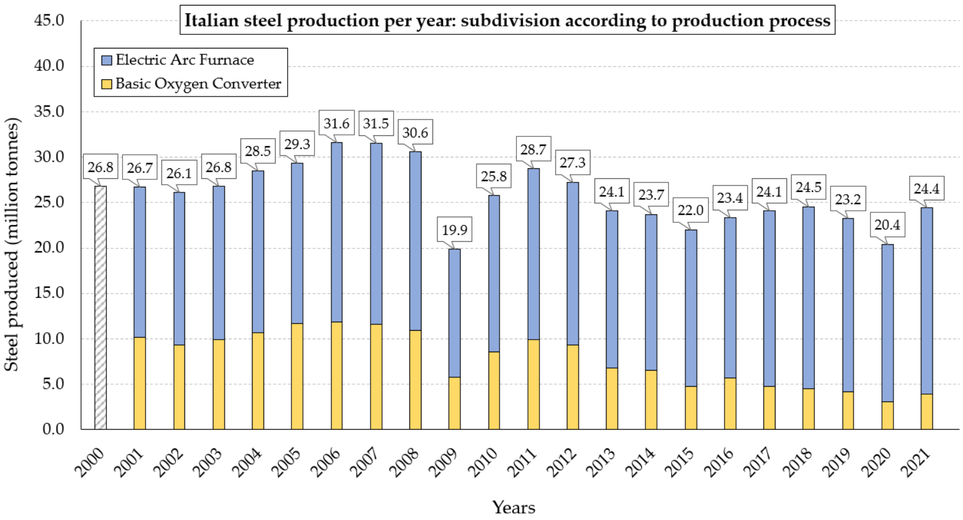


Figure 4-4: Development of steel production in Italy over the years (from 2000 to 2021), subdivided according to the production process (total production is indicated by a box above each column). Values in million tonnes (x10^6) [1].

The subdivision of Italian steel production according to production processes is quite different from that shown for world production. While for the latter the most widespread process is that of production in basic oxygen converter (thus exploiting the second step of the "*integral cycle*"), in Italy the trend is totally opposite. In fact, over the last twenty years, Italian steel mills have equipped their plants with electric arc furnaces, thus adopting the single-step production process of the "*electric cycle*". Today, about 85% of Italian steel production is carried out by electric arc furnace (20.5 million tonnes in 2021), making Italy the leading producer of electric furnace steel in Europe (without considering Turkey, which is not classified in the "EU27"countries in the World Steel Association statistics [1]).

Several factors influence the choice of one production process over another. Between the end of the 20th and the beginning of the 21st century, Italy experienced a gradual transition from the integral cycle to the electric technology, anticipating it compared to other European countries. At that time, Italian plants operating on an integral cycle were all publicly owned and favoured size and high employment requirements over the profitability of the plant itself. On the other hand, steel plants operating with the electric cycle were all managed by private capital, which considered the electric option simpler and more flexible. In addition to the purely bureaucratic aspect, over the years, the decision to adopt electric arc furnace technology was also influenced by the scarcity of raw materials available in Italy to supply the blast furnaces and the consequent need to invest in infrastructure to guarantee their movement and retrieval [2].

With regard to **Italian steelmaking slags production**, no precise values exists. Using the steel production described above and appropriately divided between the different processes and the slag production per tonne of steel produced (described in Section 2), it is possible to estimate the amount of steelmaking slags produced in Italy. For example, for the year 2021, the (**estimated**) production of **BOFS** (from the production of steel in basic oxygen converter) is between **0.40 and 0.60 million tonnes** (assuming 100–150 kg of slag per tonne of steel produced), while **EAFS** (from the production of steel in electric arc furnace) is between **2.10 and 3.10 million tonnes** (assuming 100–150 kg of slag per tonne of steel produced).

4.4 Data analysis – Methodology

4.4.1 Overview on national and local steel production

Once the importance of analysing data at a global and national level (albeit with the aid of estimates) has been established, it is of fundamental utility to investigate the production of steelmaking slags also at a local level. In particular, the production and management of slags in the Lombardy Region (Italy) and, more specifically, in the Province of Brescia (Italy) were considered as case studies, as Brescia is the most representative province in Italy in terms of steel production and the location of the university where this research was conducted.

While the retrieval of data and estimates at a national level is easier, it is more difficult to consult them at a local scale, thus requiring support through the direct involvement of supply chains actors.

First, an analysis was conducted on the location of steel mills at local levels, also highlighting their production technologies. By consulting special databases and integrating and processing data of different provenance, it was then possible to obtained a detailed picture of steelmaking slags production and management at regional and provincial level. The **M**aterial **F**low **A**nalysis (“***MFA***”) criterion was used in order to understand more intuitively the interconnection among producers, treatment and recovery plants and final reusers of steelmaking slags. In particular, the results of the processing carried out will be shown below, which have contributed to providing a particularly detailed overview of production (both within the Province of Brescia, outside the Province and outside the Lombardy Region), treatment, import/export among provinces and regions, reuse and disposal of steelmaking slags.

Italian steel production takes place in 42 production sites (including non-operational ones), divided as follows [3]:

- 3 Blast Furnaces, located in Taranto, Piombino and Trieste (the latter closed in 2020 and demolished in 2022);
- 2 Oxygen Converters, located in Taranto and Piombino;
- 37 Electric Furnaces, located in Aosta, Bergamo, Brescia, Catania, Cremona, Cuneo, Padua, Potenza, Reggio Emilia, Turin, Terni, Trento, Udine, Varese, Verona and Vicenza.

As previously mentioned in Section 4.3, 85% of Italian steel production takes place in electric arc furnaces, most of which are located in Northern Italy and in particular in the Lombardy Region (where there are 19 steel mills). One of the most virtuous provinces concerning the Italian steel sector is undoubtedly the Province of Brescia (in Lombardy), which has 11 steel mills located on its territory, contributing approximately to the 30–35% of the national steel produced. In parallel with steel production, there is also the production of a large quantity of slags (electric arc (EAF) + ladle furnace (LFS)), with average values around 1.1 million tonnes. Unfortunately, a considerable part of these slags is not recovered and is still disposed in landfills, despite their good performance properties and different possibilities of reuse, generating numerous problems in material management. Figure 4-5 shows the location of the steel producers in Italy in 2021 (including non-operational sites), with a focus on the Lombardy Region and the Province of Brescia (for the latter, in addition to the steel mills, treatment/recovery plants and disposal plants are also shown) [4].

The use of slags as alternative materials could be promoted through regional Industrial Symbiosis (“*IS*”) agreements that can support companies in terms of competitiveness, in order to:

- Reduce the environmental impact associated with their daily activities [5];

- Use platforms and systems to facilitate the identification of certified resources on the territory and their use also in the context of green public procurement [6,7];
- Use the tools developed to minimise transport in resource and waste management [8].

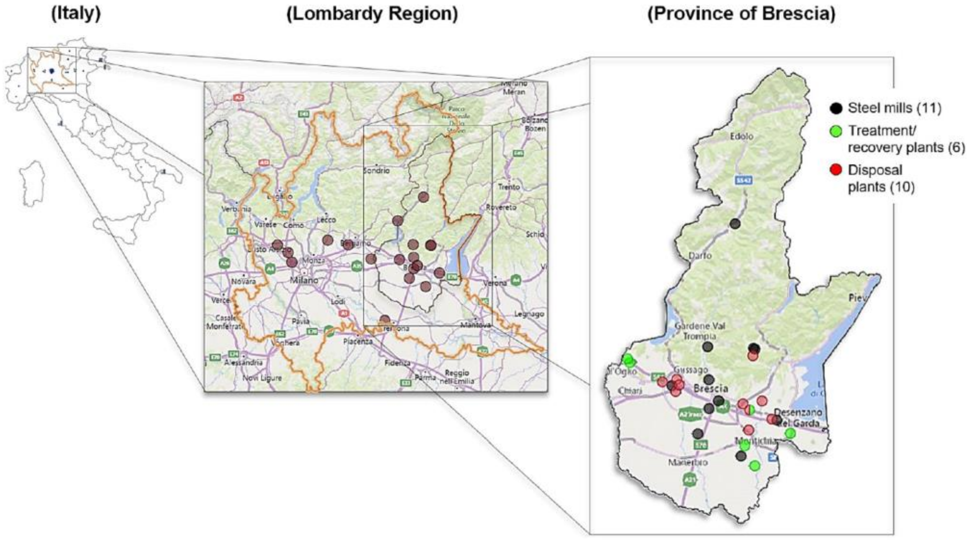


Figure 4-5: Location of the steel producers in Italy, with a focus on Lombardy Region and Province of Brescia. For the Province of Brescia, there is also a subdivision of plants into steel mills, treatment/recovery and disposal plants [4].

Symbiotic activities can be applied at different levels [9]: they can involve a single firm or organization (micro-level), companies located in the same area (meso-level) and finally the entire regional or national production system (macro-level). Several Industrial Symbiosis applications have been developed at different scales [10] and different methodologies and tools have been developed and improved through the study of real applications to support IS implementation [11]. The greatest benefits are found to be achieved at meso-level, where the clustering of complementary companies provides a complexity of functions [9,12]. This is a situation compatible with the provincial dimensions and particularly with the productive system of the Province of Brescia, consisting of a broad complementarity and number of companies.

4.4.2 Regional and provincial scale database analysis

As already explained in Section 3, according to Legislative Decree 152/2006 and subsequent amendments and updates [13]) and depending on the choices made by each steel mill, the slag can be classified either as “*waste*” or as “*by-product*”, with consequent differences in terms of management and treatment. The Lombardy Region, through the **A**genzia **R**egionale per la **P**rotezione dell’**A**mbiente (“***ARPA***”), provides a database called **M**odello **U**nico di **D**ichiarazione ambientale (“***MUD***”), consisting of a set of declarations that all producers, transporters, treatment/recovery plants and disposers of waste must submit every year and in which waste is distinguished according to type, producer, origin and source [14]. For each of the 12 provinces of Lombardy Region, the original version of the database is divided into 29 tables (exportable in the desired format or consultable by means of special software), each containing one or more information and identified by two letters. Depending on the purpose of the research and the waste of interest, and using special filters, the database provides the desired information. The sections consulted for this research were:

- **Section AA** – “*Company and Local Unit Master Data*”, containing the master data of each company that has submitted the annual declaration of waste production, management, treatment or disposal. Among the most important data in this section, in addition to the name and the address of the company, there is the **C**odice di **I**dentificazione **U**nivoca provinciale (“***CIU***”), i.e. a code assigned to each declarant for its easier and immediate identification in the other sections of the database;
- **Section BA** – “*Waste Communication*”, containing, for each reporting company, the main information on waste produced, managed, treated or disposed (total quantities produced and destined for third parties, stocks, etc.), subdivided by EWC code (see Section 3.4);
- **Section BB** – “*Attachments to Section BA*”, containing information on incoming and outgoing flows from each company. This section is subdivided into three different modules: module “*RT*” – “*waste received from third parties*”, module “*DR*” – “*waste delivered to third parties*”, module “*TE*” – “*waste transported by third parties*” and, for each module, the quantity of waste, the name and the address of the sender or receiver company are indicated;
- **Section BD** – “*Waste management, disposal operations*”, containing information on waste destined for disposal: quantities, name and address of the destination company and disposal category (in accordance with Annex B of Legislative Decree 152/2006 [13]);
- **Section BE** – “*Waste management, recovery operations*”, containing information on waste destined for recovery: quantities, name and address of the destination company and recovery category (in accordance with Annex C of Legislative Decree 152/2006 [13]).

As previously mentioned, the distinction between the different types of waste in the database is made possible by the assignment of an EWC code (see Section 3.4). As regards the steel slags examined in this study, they were classified by the producers using the following EWC codes:

- EWC 10.02.01 – "*Waste from the processing of slag*";
- EWC 10.02.02 – "*Unprocessed slag*";
- EWC 10.09.03 – "*Furnace slag*".

However, since the database consists of numerous tables and a huge amount of data, even a simple consultation is complex and onerous. In order to simplify the processes of visualization and interpretation, further analyses were carried out, first extrapolating the data of interest and deleting superfluous information, and then processing them in more detail, with the aim of representing and identifying, in a quicker, simpler, more intuitive and interactive manner all possible information contained for the type of waste of interest.

4.4.3 Limitations of the Regional database

The analysis of the MUD database can provide a lot of information on the production and destination of steelmaking slags in a given territory. However, by consulting the MUD alone, there is the risk of obtaining an inaccurate representation of the real situation of the steel industry, due to some weaknesses in the database design, that, unfortunately, contribute to providing useful but incomplete data:

- The database contains information only on steelmaking slags classified as "*waste*"; there is no information on slags classified as "*by-product*" (which, on further investigation, accounts for a large portion of the slags produced);
- Although the database allows searches to be carried out using the EWC code of interest, it is not possible to distinguish between slag from electric arc furnace (EAFS) and slag from ladle furnace (LFS). This is due to the fact that the two types of slag are classified under the same EWC code by most of the steel mills operating in the area, despite the fact that they are totally different in every aspect (see Sections 2.3.1.2 and 2.4.1.2);
- By analysing sections BD and BE of the database, only partial information can be obtained on the disposal and recovery of slag classified as "*waste*". In fact, disposal and recovery are only identifiable by the codes in Legislative Decree 152/2006, Annexes B and C of Part IV, from D1 to D15 for disposal and from R1 to R13 for recovery, respectively [13] (see Tables Table 3-4 and Table 3-13). There is therefore no further information about

the actual fields of reuse of the examined slags (e.g. road construction, concrete mixes, etc.).

4.4.4 Analysis of big data obtained from consortia and operators in the supply chain

In the light of what was stated in the previous paragraph, further research was therefore carried out trying to fill the limitations in the database and provide a picture of steelmaking slags management in the Province of Brescia as close to reality as possible. In order to do this, both sector consortia and operators were directly involved. The first by means of discussion and in-depth meetings on the topic, the latter by sending questionnaires (customised for each company), with the aim of obtaining more information about the part of slag classified as a “*by-product*”, a subdivision of the slags in Electric Arc Furnace slag (EAFS) and Ladle Furnace Slag (LFS) and an update of the data to the year 2020. In particular, steel mills and treatment/recovery plants were directly involved. While the participation of steel mills in the survey was not very active, remarkable results were obtained from the treatment/recovery plants (out of 6 recovery plants in the Province of Brescia, 4 actively participated in the data collection, representing about 80% of the total slags treated and recovered in the province). Consequently, it was possible to go into detail on the production and management of steelmaking slags by subdividing the different quantities produced and treated in the Province of Brescia. For each year (2017–2020) [4]:

- Subdivision of the slags by classification: “*by-product*”, “*waste*” and “*End of Waste*”;
- Subdivision of the slags by type: Electric Arc Furnace slag (EAFS or “*black slag*”) and Ladle Furnace Slag (LFS or “*white slag*”);
- Subdivision of the slags by origin: slag produced in the Province of Brescia, slag produced in the Lombardy Region excluding the Province of Brescia, slag produced outside the Lombardy Region;
- Further subdivision of slags classified as “*waste*” according to recovery or disposal destination;
- Further subdivision of slags classified as “*waste*” and destined to recovery, according to EWC classification codes (10.02.01, 10.02.02, 10.09.03);
- Subdivision of slags according to the different reuse applications.

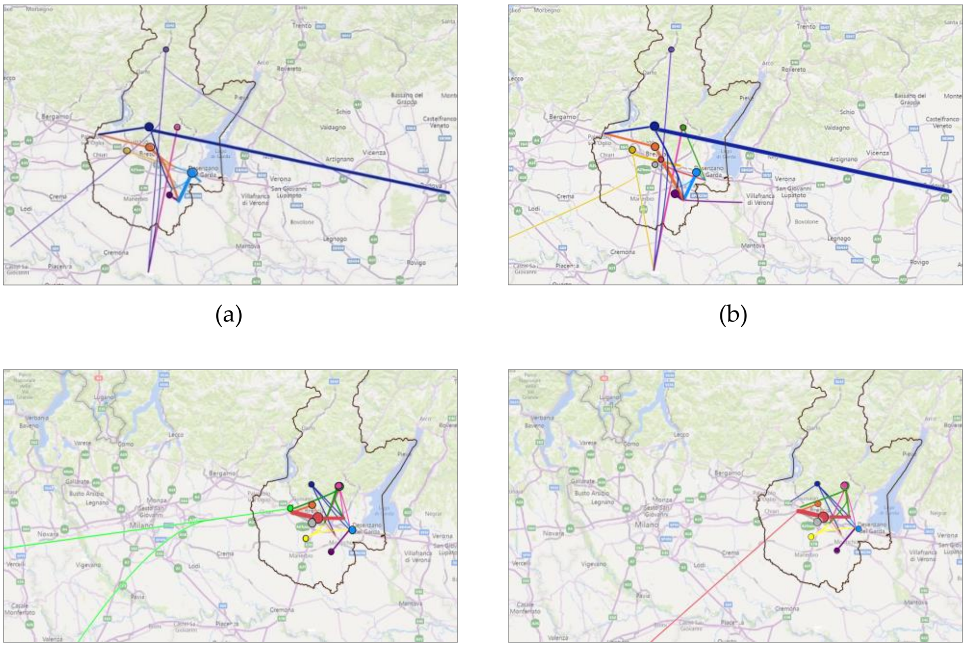
This made it possible to outline a situation much closer to the real situation regarding the production, management, treatment, recovery, reuse and disposal of steelmaking slags in the province, compared to consulting only the MUD database.

4.5 Results

4.5.1 Results from MUD Database analysis

The Province of Brescia is located in the eastern part of the Lombardy Region and is one of the most virtuous provinces in Italy as regards the steel sector. There are 11 steel mills on its territory, equipped with one or more electric arc furnaces and one or more ladle furnaces, depending on the company's management system. The total steel production in the Province of Brescia has undergone a significant increase in the last 10 years, reaching about 6 million tons in 2019 (last useful data for comparison, before the 2020 production drop caused by the pandemic). In parallel to this steel production, high quantities of slags are also generated, reaching about 825 thousand tonnes of electric arc furnace (EAF) slag and 285 thousand tonnes of ladle furnace (LFS) slag in 2019, for a total of about 1.1 million tonnes (as before, last useful data for comparison before the 2020 production drop caused by the pandemic). Analyses of not only the overall production data, but also the slag flows in the province, from the producer to the final treatment/recovery plant and/or to the disposer, obtained by consulting the MUD database for the last two years available: 2017 and 2018, are shown below. Further analysis and data processing made it possible to map the flows of steelmaking slags produced in the Province of Brescia, highlighting both the quantities that remain within the province and those destined for recovery and/or disposal outside the province.

Figure 4-6 shows an example of processing through which it was possible to identify the quantities of slags produced and destined for treatment operations at recovery plants or for disposal in landfills, located both inside and outside the province, for the years 2017 and 2018. In this figure, steel mills are identified with different coloured circles for better distinction and a thicker line corresponds to a larger quantity of slags going to a recovery and/or disposal plant [4].


(a) (b)

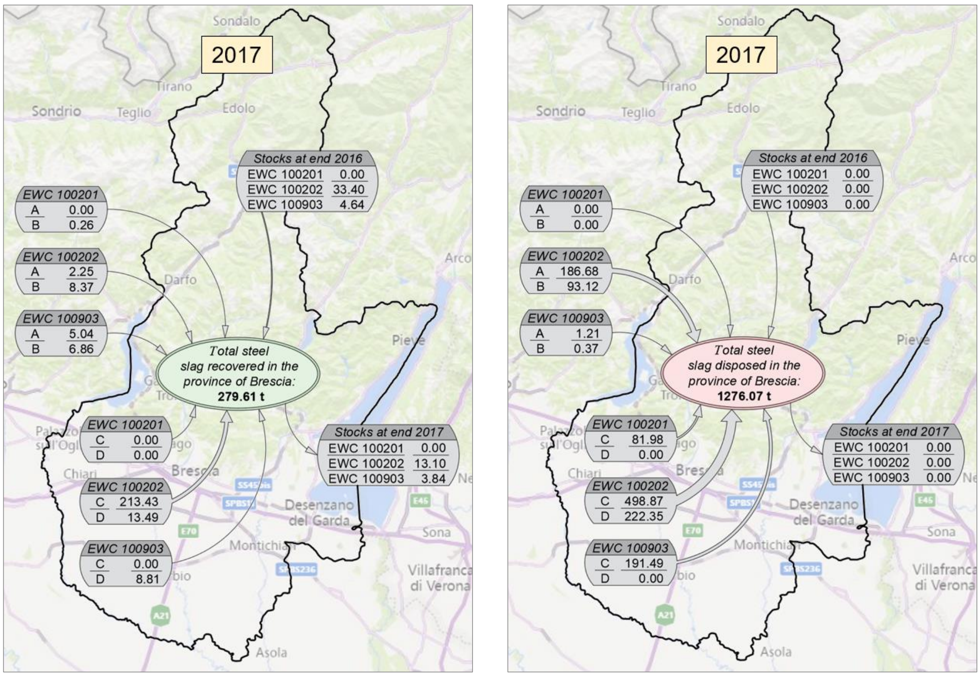
(c) (d)

Figure 4-6: Example of processing showing the quantities of steelmaking slags produced and destined for treatment operations, for the years 2017 (a) and 2018 (b), or for disposal in landfills, for the year 2017 (c) and 2018 (d). Treatment plants and landfills are located both inside and outside the province. Steel mills are marked with different coloured circles and a thicker line corresponds to a higher amount of slags going to a recovery plant [4].

Figure 4-7 and Figure 4-8 show the results of the analysis and processing carried out on the data extrapolated from the MUD database for the years 2017 and 2018, concerning the production of steelmaking slags both inside and outside the Province of Brescia and their destination (recovery or disposal) in the provincial territory. This helps to understand the amount of slags actually produced and managed in the province and the percentage of “*imported*” slags compared to that produced in the provincial territory. The data processing also includes the production of companies that generate slags and classify them with the three EWC codes seen above (10.02.01, 10.02.02, 10.09.03), but which are not strictly steel mills (this may be the case, for example, of steelmaking slags dumped in the past by now disused steel mills and re-emerging during excavations for the reclamation of land for new construction, which will be subject to controls and reports by the responsible company).

In the following figures, the different quantities have been marked with letters for a better visualisation and comprehension:

- Letter “A”: production only of steel mills located outside the province;
- Letter “B”: production of other companies different from steel mills and located outside the province;
- Letter “C”: production only of steel mills located inside the province;
- Letter “D”: production of other companies different from steel mills, located inside the province.



(a) (b)

Figure 4-7: Summary of the quantities of steelmaking slags produced both inside and outside the Province of Brescia (boxes located inside and outside the provincial boundary, respectively), subdivided by EWC classification code and destined for recovery (a) and disposal (b) in the provincial territory in 2017. A: production only of steel mills located outside the province; B: production resulting from other companies different from steel mills, located outside the province; C: production only of steel mills located inside the province; D: production resulting from other companies different from steel mills, located inside the province. Values in thousand tonnes (x10^3) [4].

As shown in Figure 4-7(a), steel slags recovered in 2017 in the Province of Brescia amounted to 279.61 thousand tonnes. Approximately 80% (226.92 thousand tonnes) were slags with EWC classification code 10.02.02 from production in the Province of Brescia, which are divided into production from steel mills alone (a large part of the total, 213.43 thousand tonnes) and production from companies other than steel mills. The contributions of slags classified with the other two EWC codes analysed, from both production in and outside the province, made up a very small part of the total amount of recovered slags (approximately 7%).

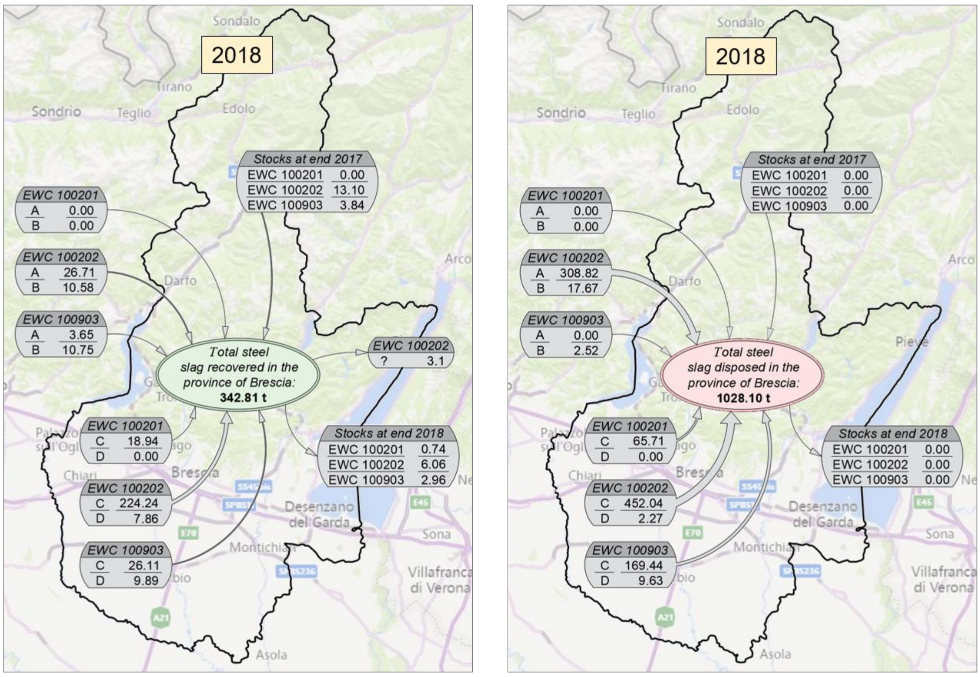
Figure 4-7(b) shows steel slags destined for landfill disposal in 2017 in the Province of Brescia. The total amounted to 1276.07 thousand tonnes. Unlike slags destined for recovery, in this case only 55% of the total were slags with EWC classification code 10.02.02 from the production in the provincial territory, which are divided into production from steel mills alone (498.87 thousand tonnes) and production from companies other than steel mills (222.35 thousand tonnes). In contrast to the case of recovered slags, significant contributions also derived from the production of slags classified as EWC 10.09.03 (191.49 thousand tonnes) and EWC 10.02.01 (81.98 thousand tonnes) by steel mills located within the province. As regards the slags produced outside the province, almost all of them consist of slags classified with EWC code 10.02.02, which made up about 20% of the total disposed.

From the analysis of the MUD database, for the year 2017, out of the total amount of steelmaking slags classified as "*waste*" (EWC codes 10.02.01, 10.02.02, 10.09.03), managed in the Province of Brescia and deriving from production both inside and outside the province, the quantity for disposal was unfortunately significantly higher than that destined for recovery. The ratio "*recovered slags to disposed slags*" is approximately 0.18 (i.e., out of the total amount of slags classified as waste managed in the Province of Brescia, only 18% was destined for treatment and recovery, the remainder was destined for disposal in landfills).

The same analysis was done for the year 2018, the latest available update of the MUD database. As shown in Figure 4-8(a), steelmaking slags recovered in 2018 in the Province of Brescia amounted to 342.81 thousand tonnes (+ 23% compared to previous year). Approximately 68% (232.10 thousand tonnes) were slags with EWC classification code 10.02.02 from production in the Province of Brescia, which are divided into production from steel mills alone (a large part of the total, 224.24 thousand tonnes) and production from companies other than steel mills. The contributions of slags classified with the other two EWC codes analysed, from both production in and outside the province, made up the 20% of the total amount of recovered slags, higher than in 2017.

Figure 4-8(b) shows steelmaking slags destined for landfill disposal in 2018 in the Province of Brescia. The total amounted to 1028.10 thousand tonnes (−19% compared to the previous year). Only the 44% of the total were slags with EWC classification code 10.02.02 from the production in the provincial territory, which are divided into production from steel mills alone (452.04 thousand tonnes) and production from companies other than steel mills (2.27 thousand tonnes). As in 2017, significant contributions also derived from the production of slags classified as EWC 10.09.03 (169.44 thousand tonnes) and EWC 10.02.01 (65.71 thousand tonnes) by steel mills located within the province. As regards the slags produced outside the province, almost all of them consist of slags classified with EWC code 10.02.02, which made up about 32% of the total disposed.

From the analysis of the MUD database, for the year 2018, out of the total amount of steelmaking slags classified as "*waste*" (EWC codes 10.02.01, 10.02.02, 10.09.03), managed in the Province of Brescia and deriving from production both inside and outside the province, the quantity for disposal was still significantly higher than that destined for recovery. However, the ratio "*recovered slags to disposed slags*" has increased from 0.18 of 2017 to 0.25 of 2018.



(a) (b)

Figure 4-8: Summary of the quantities of steelmaking slags produced both inside and outside the Province of Brescia (boxes located inside and outside the provincial boundary, respectively), subdivided by EWC classification code and destined for recovery (a) and disposal (b) in the provincial territory in 2018. A: production only of steel mills located outside the province; B: production resulting from other companies different from steel mills, located outside the province; C: production only of steel mills located inside the province; D: production resulting from other companies different from steel mills, located inside the province. Values in thousand tonnes (x10^3) [4].

It is clear that the amount of steelmaking slags destined for disposal in landfills, compared to that destined to recovery operations, is unfortunately still very high. However, an analysis of the MUD database alone is not sufficient to provide a complete picture of the problem of the management of these materials in the provincial territory, due to some limitations explained in the Section 4.4.3.

4.5.2 Results from Sector Consortia data: Impact of the slags classified as "by-product"

From data obtained from a sector consortium (raMET, "*Società consortile per le ricerche ambientale per la metallurgia*" [15]) and declared by 10 out of 11 steel mills in the Province of Brescia, it was possible to complete, albeit not in great detail, the limitations of the MUD database described in Section 4.4.3. Several comparisons were made between the total quantities of Electric Arc Furnace Slag (EAFS) and Ladle Furnace Slag (LFS), as well as between slags classified as "*waste*" and "*by-product*" and between slags destined for recovery and slags destined for disposal. The time period taken into consideration was from 2017 to 2020.

Table 4-1 shows the summary of the abovementioned data for EAFS and LFS. Out of the total slag produced in the Province of Brescia, about 80% is EAFS and the remaining 20% is LFS. This ratio remains almost constant for all years, due to the percentage of slag production per tonne of steel produced or refined (see Sections 2.3.1.1 and 2.4.1.1 for more details).

Table 4-1: EAFS and LFS production in the Province of Brescia and subdivision into "by-product", "waste for recovery" and "waste for disposal". Values in thousand tonnes (x10^3) [4].

Year	**EAFS**				**LFS**			
	Total prod.	***By-product***	***Waste – recovery***	***Waste – disposal***	***Total prod.***	***By-product***	***Waste – recovery***	***Waste – disposal***
2017	831.3	179.7	241.2	464.2	275.7	0.2	2.7	279.8
2018	824.9	92.0	317.2	415.7	280.6	0.0	3.2	277.4
2019	823.5	142.2	330.7	350.6	284.8	0.0	2.4	282.4
2020	674.6	121.9	369.2	183.6	229.1	0.0	1.2	233.9

Figure 4-9 shows a comparison between the amount of EAFS classified with the status of "*by-product*" and that classified with the status of "*waste*", expressed in thousand tonnes. For the latter category, a further subdivision was made according to whether the slag was destined for recovery or disposal. The same processing was carried out for LFS slag and the results are shown in Figure 4-10. Comparing the two graphs, a huge difference can be seen with regard to the classification, and consequently the management, of the two types of slags: EAFS was classified as a "*by-product*" in percentages ranging from 10 to 20% of the total, depending on the year, while the percentages of LFS classified as a "*by-product*" were 0. With regard to the classification as "*waste*" destined for recovery, the percentages of EAFS ranged from 30 to 55% of the total, depending on the year, while those of LFS never exceeded 1% of the total. Finally, a considerable difference can be noted with regard to the part of slags classified as "*waste*" and destined for disposal: while the percentages of EAFS classified in this way have ranged from 27 to 52% of the total, depending on the year, those of LFS have always reached 99% of the total, denoting a reduced, if not null, demand for the material on the market and further highlighting the difficulties of the management, treatment and reuse of this type of slag.

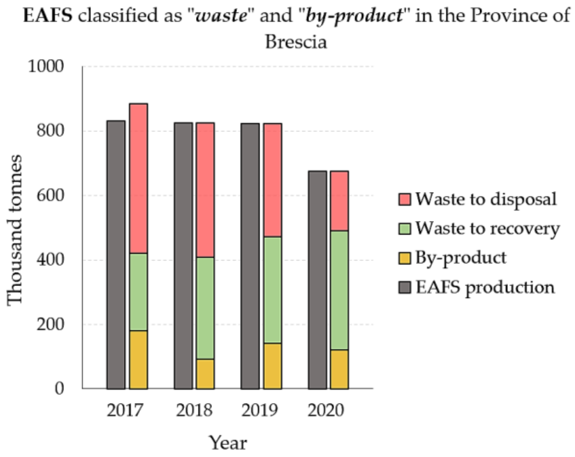


Figure 4-9: EAFS production in the Province of Brescia and subdivision into "by-product", "waste to recovery" and "waste to disposal". Values in thousand tonnes (x10^3) [4].

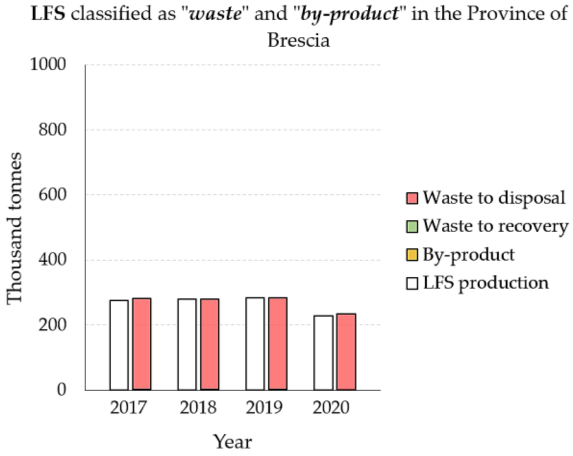
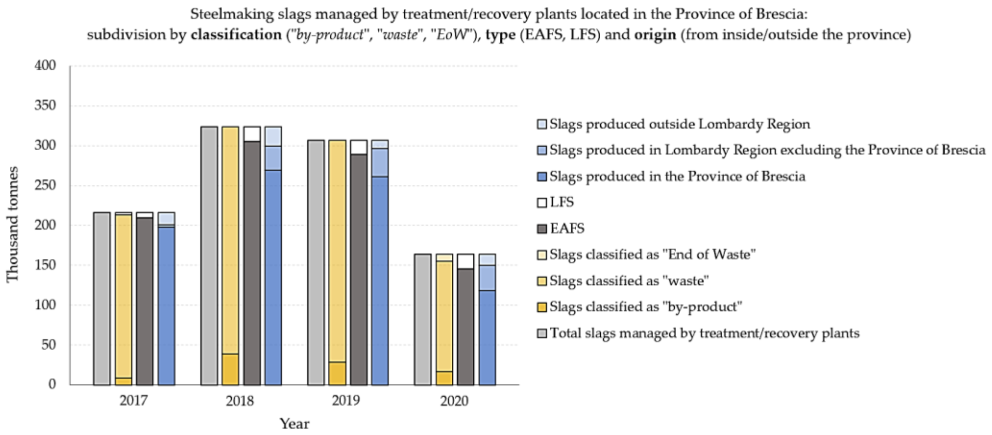


Figure 4-10: LFS production in the Province of Brescia and subdivision into "by-product", "waste to recovery" and "waste to disposal". Values in thousand tonnes (x10^3) [4].

Figure 4-9 and Figure 4-10 show, for the year 2017, a difference between the production of slags and their classification as a “*by-product*”, “*waste to recovery*” or “*waste to disposal*”. This is probably due to the presence of stocks at the steel mills or at the treatment/recovery plants, which accumulated in the years prior to 2017 and were recovered/disposed in 2017. According to data available from sector consortia, from 2018 to 2020, the slags produced were all destined to recovery/disposal, with no stocks at the end of each year. Even if EAFS are recovered in a higher percentage than LFS (50 to 80% of total production) and the recovery options are wide (see Section 2.3.1.2 for more details), the classification as “*by-product*” still appears low, highlighting the critical aspects still present in Italy that hinder producers in managing these residues as by-products. As a result, producers prefer to divert their residues to dedicated treatment plants. The bottleneck is the difficulty of proving the condition for by-products concerning certainty of use (condition (a), art. 5 of the Directive 2008/98/EC [16]). In this context, industrial symbiosis initiatives at regional or national level, supported by planning actions using MFA, will enable the creation of an industrial symbiosis network among the various companies in the sector in order to achieve sustainable commercial opportunities for its members and to use resources efficiently.

4.5.3 Results from questionnaires data: slags managed by treatment/recovery plants

Through the analysis of the MUD database and the processing of data obtained from the steel sector consortia in the Province of Brescia, a general picture of the production and management of steel slags in the province was obtained. The next step was to involve companies directly by sending out data request questionnaires, in order to go into detail especially regarding treatments, recovery and reuse activities. In particular, steel mills and treatment/recovery plants were involved and the processed data obtained from questionnaires are shown below. Figure 4-11 shows the total amount of steelmaking slags managed by treatment/recovery plants that participated in the survey (out of 6 recovery plants in the Province of Brescia, 4 actively participated in the data collection, representing about 80% of the total slags treated and recovered in the province), for the period 2017–2020. For each year, the total amount of slags is divided according to classification (“*by-product*”, “*waste*”, “*End of Waste*”), type (EAFS, LFS) and origin (produced in the province, produced in the Lombardy Region excluding the Province of Brescia or produced outside the Lombardy Region). For a better understanding, the figure is accompanied by a table showing numerical values (in thousand tonnes) and percentages of the total, for each subdivision made. It is clear that most of the slag treated by treatment/recovery plants are classified as “*waste*” and comes from electric arc furnace steel production (EAF) within the Province of Brescia.

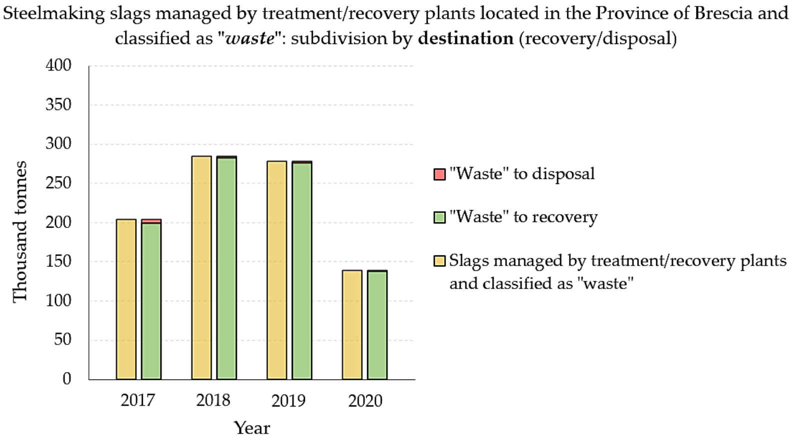


	2017	2018	2019	2020
Total slag managed	216.16	323.35	306.86	163.77
Subdivision by classification				
Slags classified as "*by-product*"	8.81 *(4.1%)*	38.84 *(12.0%)*	28.57 *(9.3%)*	16.40 *(10.0%)*
Slags classified as "*waste*"	204.25 *(94.5%)*	284.51 *(88.0%)*	278.29 *(90.7%))*	138.55 *(84.6%)*
End of Waste	3.10 *(1.4%)*	0.00 *(0.0%)*	0.00 *(0.0%)*	8.82 *(5.4%)*
Subdivision by type				
EAFS (or "*black slag*")	209.63 *(97.0%)*	305.27 *(94.4%)*	288.72 *(94.1%)*	145.21 *(88.7%)*
LFS (or "*white slag*")	6.53 *(3.0%)*	18.08 *(5.6%)*	18.14 *(5.9%)*	18.56 *(11.3%)*
Subdivision by origin				
Slags produced in the Province of Brescia	197.61 *(91.4%)*	269.47 *(83.3%)*	260.80 *(85.0%)*	118.42 *(72.3%)*
Slags produced in Lombardy Region excluding the Province of Brescia	3.24 *(1.5%)*	29.64 *(9.2%)*	35.62 *(11.6%)*	31.61 *(19.3%)*
Slags produced outside Lombardy Region	15.31 *(7.1%)*	24.24 *(7.5%)*	10.44 *(3.4%)*	13.74 *(8.4%)*

Figure 4-11: Steelmaking slags managed by treatment/recovery plants located in the Province of Brescia: subdivision by classification, type and origin. Period 2017–2020. For a better comprehension, the figure is accompanied by a table showing numerical values and percentages of the total, for each subdivision made. Values in thousand tonnes (x10^3) [4].

4.5.3.1 *Recovered slags classified as “waste”*

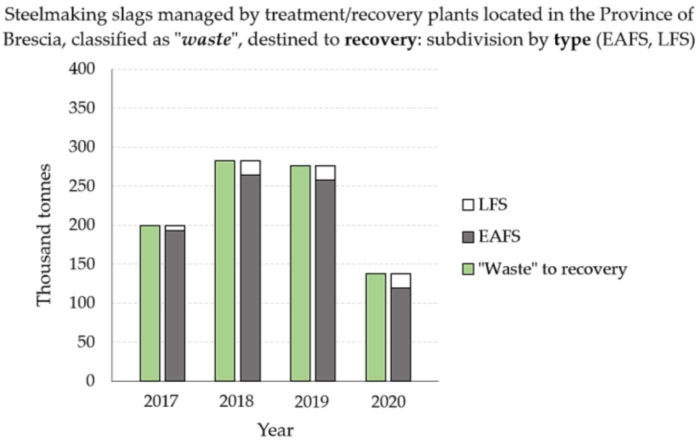
In the following, the subdivision by classification will be analysed in detail. Going into detail about the slags classified as “*waste*”, Figure 4-12 shows their subdivision according to whether they are destined for recovery or disposal. Since these data are related to that obtained by treatment/recovery plants, the percentage of slags destined for disposal in landfills is obviously more than negligible.



	2017	**2018**	**2019**	**2020**
Slags classified as “*waste*”	204.25	284.51	278.29	138.55
Subdivision by destination				
“*Waste*” to recovery	199.80 *(97.8%)*	282.64 *(99.3%)*	276.26 *(99.3%)*	137.86 *(99.5%)*
“*Waste*” to disposal	4.45 *(2.2%)*	1.87 *(0.7%)*	2.03 *(0.7%)*	0.69 *(0.5%)*

Figure 4-12: Steelmaking slags managed by treatment/recovery plants located in the Province of Brescia and classified as “waste”: subdivision by destination. Period 2017–2020. For a better comprehension, the figure is accompanied by a table showing numerical values and percentages of the total, for each subdivision made. Values in thousand tonnes (x10^3) [4].

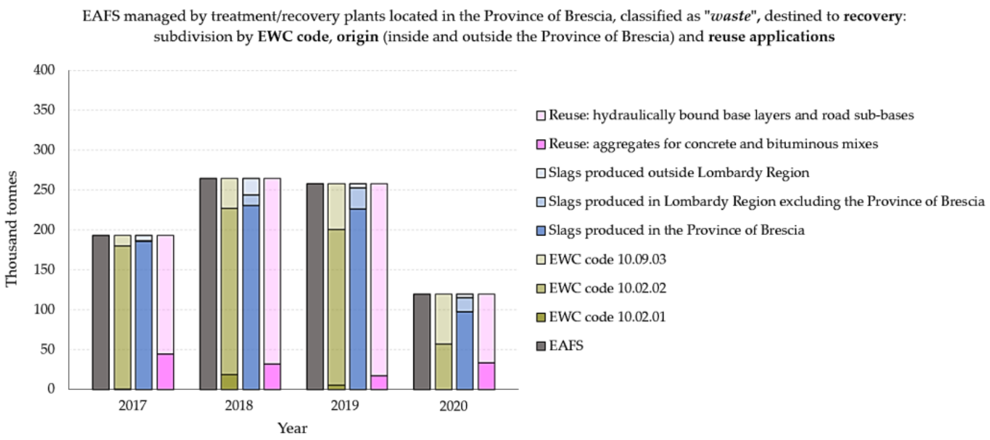
Slags classified as “*waste*” and destined for recovery were then further subdivided according to type, EAFS and LFS (Figure 4-13) and further processing were carried out for each type. Figure 4-13 confirms, once again, that slags from steel production in the electric arc furnace (EAFS) represents the vast majority of the slags destined for recovery (see Section 2.3.1.2 for their possible reuse applications). The recovery of LFS is less widespread.



	2017	2018	2019	2020
Slags as "*waste*" to recovery	199.80	282.64	276.26	137.86
Subdivision by type				
EAFS (or "*black slag*")	193.27 *(96.7%)*	264.56 *(93.6%)*	258.12 *(93.4%)*	119.30 *(86.5%)*
LFS (or "*white slag*")	6.53 *(3.3%)*	18.08 *(6.4%)*	18.14 *(6.6%)*	18.56 *(13.5%)*

Figure 4-13: Steelmaking slags managed by treatment/recovery plants located in the Province of Brescia, classified as "waste", destined to recovery: subdivision by type. Period 2017–2020. For a better comprehension, the figure is accompanied by a table showing numerical values and percentages of the total, for each subdivision made. Values in thousand tonnes (x10^3) [4].

Figure 4-14 shows the data processing carried out with regard to EAFS (or "*black slag*") destined for recovery. They were subdivided by EWC classification codes, origin and reuse fields. While the quantities classified with EWC code 10.02.01 can be considered negligible, it can be seen that most of them are classified with EWC code 10.02.02. The percentage of EAFS classified with EWC code 10.09.03 shows an increasing trend from 2017 to 2020. As expected, most of the EAFS destined for recovery in the Province of Brescia comes from production within the province, with negligible quantities imported from outside the province and the region. Figure 4-14 also shows that most of the EAFS treated and recovered in the Province of Brescia are reused for hydraulically bound base layers and road sub-bases.



	2017	2018	2019	2020
EAFS destined for recovery	193.27	264.56	258.12	119.30
Subdivision by EWC code				
EWC 10.02.021	0.26 *(0.1%)*	18.79 *(7.1%)*	5.49 *(2.1%)*	0.00 *(0.0%)*
EWC 10.02.02	179.81 *(93.0%)*	208.14 *(78.7%)*	194.64 *(75.4%)*	56.66 *(47.5%)*
EWC 10.09.03	13.20 *(6.8%)*	37.63 *(14.2%)*	57.99 *(22.5%)*	62.64 *(52.5%)*
Subdivision by origin				
Slags produced in the Province of Brescia	185.63 *(96.0%)*	230.89 *(87.3%)*	226.47 *(87.7%)*	97.53 *(81.8%)*
Slags produced in Lombardy Region excluding the Province of Brescia	0.51 *(0.3%)*	13.24 *(5.0%)*	26.00 *(10.1%)*	17.30 *(14.5%)*
Slags produced outside Lombardy Region	7.13 *(3.7%)*	20.43 *(7.7%)*	5.65 *(2.2%)*	4.47 *(3.7%)*
Subdivision by reuse applications				
Aggregates for concrete and bituminous mixes	44.49 *(23.0%)*	32.02 *(12.1%)*	17.17 *(6.7%)*	33.02 *(27.7%)*
Hydraulically bound base layers / road sub-bases	148.78 *(77.0%)*	232.54 *(87.9%)*	240.95 *(93.3%)*	86.28 *(72.3%)*

Figure 4-14: EAFS managed by treatment/recovery plants located in the Province of Brescia, classified as “waste”, destined to recovery: subdivision by EWC code, origin and reuse applications. Period 2017–2020. For a better comprehension, the figure is accompanied by a table showing numerical values and percentages of the total, for each subdivision made. Values in thousand tonnes (x10^3) [4].

The plants authorized for the recovery of EAFS-C slag typically operate on the material crushing, grinding and screening operations to obtain grain size curves requests, deferrization possibly in several phases and, in some cases, stabilization/maturation, wetting and washing. It would be possible to use other operations, including innovative ones, which in any case must be provided and described in the individual authorizations.

Table 4-2 shows the main characteristics of the treatment plants directly involved in the present work: the accepted EWC codes for EAFS, the different areas for storage/treatment of waste and storage of final products and a brief description of the treatment processes performed at each plant.

Table 4-2: Main characteristics of treatment plants directly involved in this research: EWC codes treated, areas, facilities and treatments [4].

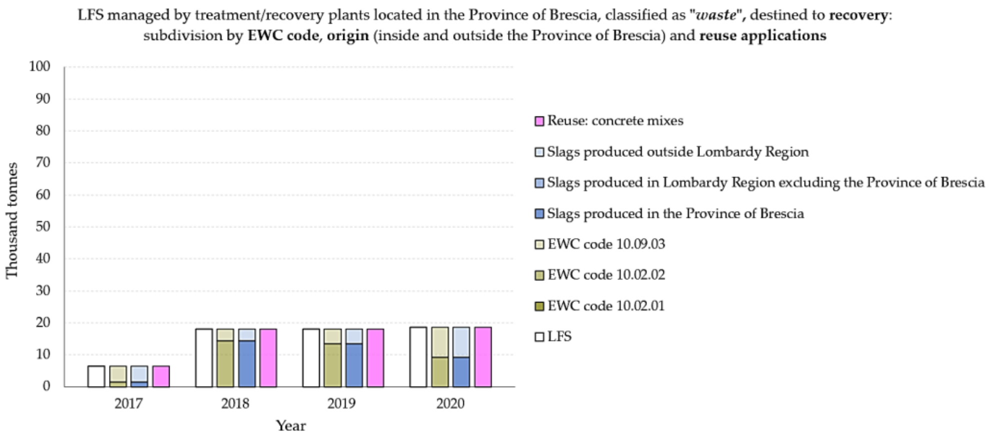
Plant	EWC codes	Areas	Facilities and treatments
#1	10.02.01, 10.02.02, 10.09.03	• Storage/processing areas for incoming and intermediate waste • Storage areas for final products	• Crushing/deferrization/screening/selection plant, to obtain CE 2+ certified unbound aggregates, in different sizes and in accordance with the UNI EN technical standards • Mixing plant for the production of cement and/or bituminous mixes and concretes with predefined strengths
#2	10.02.02, 10.09.03	• Storage/processing areas for incoming and intermediate waste; • Storage areas for final products.	• Initial manual selection to remove fractions unsuitable for subsequent treatments • Crushing/deferrization/screening plant (all aggregates are marked CE 2+, in accordance with the UNI EN technical standards)
#3	10.02.01, 10.02.02, 10.09.03	• Storage/processing areas for different incoming waste (C&D, steelmaking slags, asphalt, etc) • Storage areas for final products	• Crushing/deferrization/screening/selection plant, to obtain CE and CE 2+ certified unbound aggregates in different sizes and in accordance with the UNI EN technical standards • Bituminous mix production plant • Small plant for the production of concrete with natural and artificial aggregates

Table 4-2: Cont..

Plant	EWC codes	Areas	Facilities and treatments
#4	10.02.01, 10.02.02, 10.09.03	• n.d.	• Crushing/screening/particle-size selection/deferrization plant • Plants for mixing aggregates with hydraulic binders (cement mixes), complying with the UNI EN technical standards • Treatments on materials received from third parties and qualified as by-products/EoW: grinding/screening /granulometric selection, in order to obtain aggregates fractions having selected particle size

The same data processing and elaborations were carried out for LFS (or "*white slag*") from steel refinements in ladle furnaces (Figure 4-15). As for EAFS, the majority of LFS is classified with EWC code 10.02.02, with increasing percentages of slag classified with EWC code 10.09.03 from 2017 to 2020 and mostly coming from production within the Province of Brescia.

The small quantities recovered of this type of slag can be justified by their poor physical, chemical and mechanical characteristics (high volumetric instability, tendency to self-pulverize during the cooling process, low hydraulic properties, etc.), which make them unsuitable for the most of reuses for which EAFS are suitable (see Section 2.4.1.2 for critical issues and possible reuses of LFS). From the data obtained and processed, all the LFS recovered in the Province of Brescia are reused in concrete mixes.



	2017	2018	2019	2020
LFS destined for recovery	6.53	18.08	18.14	18.56
Subdivision by EWC code				
EWC 10.02.021	0.00 *(0.0%)*	0.00 *(0.0%)*	0.00 *(0.0%)*	0.00 *(0.0%)*
EWC 10.02.02	1.50 *(23.0%)*	14.43 *(79.8%)*	13.40 *(73.9%)*	9.31 *(50.2%)*
EWC 10.09.03	5.03 *(77.0%)*	3.65 *(20.2%)*	4.74 *(26.1%)*	9.25 *(49.8%)*
Subdivision by origin				
Slags produced in the Province of Brescia	1.50 *(23.0%)*	14.43 *(79.8%)*	13.40 *(73.9%)*	9.31 *(50.2%)*
Slags produced in Lombardy Region excluding the Province of Brescia	0.00 *(0.0%)*	0.00 *(0.0%)*	0.00 *(0.0%)*	0.00 *(0.0%)*
Slags produced outside Lombardy Region	5.03 *(77.0%)*	3.65 *(20.2%)*	4.74 *(26.1%)*	9.25 *(49.8%)*
Subdivision by reuse applications				
Concrete mixes	6.53 *(100%)*	18.08 *(100%)*	18.14 *(100%)*	18.56 *(100%)*

Figure 4-15: LFS managed by treatment/recovery plants located in the Province of Brescia, classified as "waste", destined to recovery: subdivision by EWC code, origin and reuse applications. Period 2017–2020. For a better comprehension, the figure is accompanied by a table showing numerical values and percentages of the total, for each subdivision made. Values in thousand tonnes (x10^3) [4].

4.5.3.2 *Recovered slags classified as "by-product"*

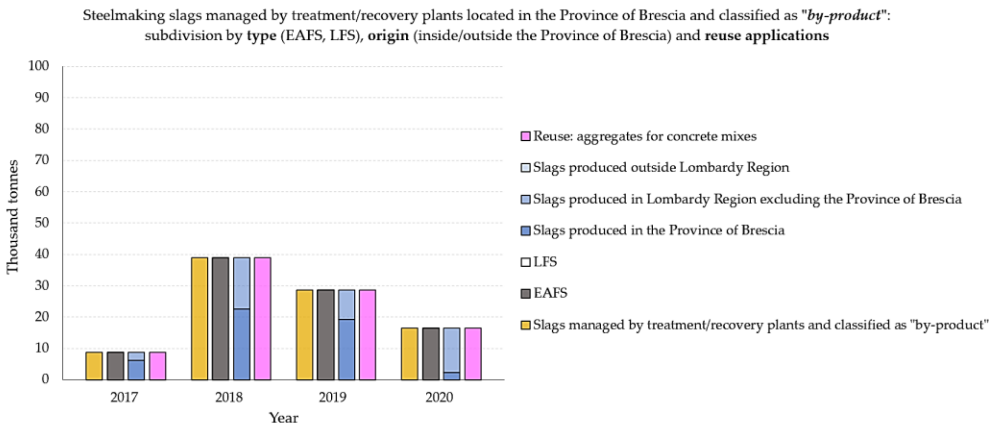
As far as the part of steelmaking slags classified as "*by-product*" is concerned, Figure 4-16 shows their subdivision according to type (EAFS, LFS), origin (produced in the Province of Brescia, produced in the Lombardy Region excluding the Province of Brescia or produced outside the Lombardy Region) and reuse applications.

In contrast to slags classified as "*waste*", slags classified as "*by product*" are mainly treated directly by the producer, most often without the need to involve third parties. The slags classified as "*by-product*", after the common post-slagging treatments (characterization of the chemical composition, cooling, solidification, crushing/grinding, deferrization), undergo further crushing/grinding and screening operation, and division into heaps, directly at steel mills, thus following a different procedure compared to that for slags classified as "*waste*" (for more details see Section 3.4). Once registered with ECHA and CE marked, the by-products can be directly placed on the market, without passing through a treatment/recovery plant.

This explains the small quantities shown in Figure 4-16, as the treatment/recovery plants are the subject of this analysis. Of the few quantities of by-products shown in Figure 4-16, all are EAFS, mostly produced in the Province of Brescia and reused as aggregates for the concrete production (after having undergone, in the recovery plant, simple treatments such as grinding, screening and granulometric selection to obtain aggregate fractions with a suitable and selected granulometry).

As mentioned before, not all the companies in the steel sector contacted for the survey participated actively. In addition to the treatment/recovery plants, some steel mills also took part in the questionnaires. Their contributions unfortunately do not represent percentages that would allow a detailed analysis like the one carried out for the treatment/recovery plants. However, the processing of these data also showed that the slags classified as "*by-products*" are almost exclusively EAFS and that are reused not only for the production of certified products (e.g. aggregates for concrete production), but also for backfilling, yards, embankments and draining layers for landfill cover.

Analysis of data from one of the four treatment/recovery plants considered revealed small quantities of incoming EAFS classified as "*End of Waste*" (Figure 4-11). These slags have already undergone appropriate recovery treatments at the steel mills or by third parties (depending on the waste treatment and recovery policy adopted by the producer), in order to cease being classified as "*waste*". This small percentage of slag entering the treatment plant and already classified as "*End of Waste*", undergoes simple grinding, screening and granulometric selection treatments to obtain inert fractions of a suitable and selected granulometry. After these treatments, they were marketed as industrial aggregates for concrete mixes, in accordance with the sector technical standards.



	2017	**2018**	**2019**	**2020**
Slags classified as "*by-product*"	8.81	38.84	28.57	16.40
Subdivision by type				
EAFS (or "*black slag*")	8.81 *(100%)*	38.84 *(100%)*	28.57 *(100%)*	16.40 *(100%)*
LFS (or "*white slag*")	0.00 *(0.0%)*	0.00 *(0.0%)*	0.00 *(0.0%)*	0.00 *(0.0%)*
Subdivision by origin				
Slags produced in the Province of Brescia	6.09 *(69.1%)*	22.55 *(58.1%)*	19.16 *(67.1%)*	2.23 *(13.6%)*
Slags produced in Lombardy Region excluding the Province of Brescia	2.72 *(30.9%)*	16.29 *(41.9%)*	9.41 *(32.9%)*	14.17 *(86.4%)*
Slags produced outside Lombardy Region	0.00 *(0.0%)*	0.00 *(0.0%)*	0.00 *(0.0%)*	0.00 *(0.0%)*
Subdivision by reuse applications				
Aggregates for concrete mixes	8.81 *(100%)*	38.84 *(100%)*	28.57 *(100%)*	16.40 *(100%)*

Figure 4-16: Steelmaking slags managed by treatment/recovery plants located in the Province of Brescia and classified as "by-product": subdivision by type, origin and reuse applications. Period 2017–2020. For a better comprehension, the figure is accompanied by a table showing numerical values and percentages of the total, for each subdivision made. Values in thousand tonnes (x10^3) [4].

4.6 Concluding remarks

The problem of proper production, management, recovery, disposal and reuse of steelmaking slags is certainly highly topical, especially in areas with high production, such as the Province of Brescia, Italy. Analysis, processing and integration of big data from different sources (regional and provincial databases, sector consortia and questionnaires directly submitted to companies) are therefore essential in order to identify and subdivide the different quantities according to classification, type, origin and final applications. This allows to obtain useful information to identify any critical issues that hinder recovery and reuse and to individuate paths of industrial symbiosis that can be established among local companies. With specific reference to the analysis conducted in the Province of Brescia, results of the big data processing showed the following:

- According to the MUD database, a small percentage of the total amount of slags managed as "*waste*" in the Province of Brescia (from both internal and external production) was destined for recovery operations in authorized plants (18% in 2017 and 25% in 2018), while the remaining part was destined for disposal in landfills. In order to reduce this amount, research should focus on use higher percentages of slags for applications for which they are already known to be suitable and, at the same time, studying their possible reuse in innovative fields that are already being tested or are still being studied;
- The amount of slags classified as "*by-product*" still appears low, highlighting critical issues still present in Italy that hinder producers in managing these residues. As consequence, producers prefer divert their residues to dedicated treatment plants;
- According to the data obtained from questionnaires, the total amount of steelmaking slags to be managed at the treatment/recovery plants located in the Province of Brescia is almost entirely EAFS (above 90%) and comes mainly from production within the province (between 80 and 90%);
- Of the slags classified as "*waste*" and destined for recovery, almost all of them are EAFS (more than 90%). There are also small percentages of LFS destined for recovery, although their physico-chemical, mineralogical and performance characteristics make their reuse very difficult;
- EAFS destined for recovery comes almost entirely from production within the province (above 80%) and are mainly reused for hydraulically bound base layers and road foundations (over 70% of the total) and as aggregates in the production of bituminous and cement mixes. On the other hand, the origin of LFS destined for recovery is more uneven, with rather significant percentages also from production outside the Lombardy Region and are

instead reused as partial replacement of the binder in the concrete production;

- The processing of data obtained directly from few steel mills located in the Province of Brescia showed that the slags classified as "*by-products*" and managed directly in the steelmaking plants are almost exclusively EAFS. Once placed on the market, they were reused not only for the production of certified products (e.g. aggregate from slags for concrete production), but also for backfilling, yards, embankments and draining layers to cover landfills;
- In addition to slags classified as "*waste*" and "*by-products*", small quantities of EAFS classified as "*End of Waste*" have been identified as entering treatment/recovery plants. After simple treatments, they have been reused as industrial aggregates for concrete mixes, in accordance with the sector technical standards.

In order to ensure a complete and adequate monitoring of steelmaking slags flows, it is therefore appropriate to integrate existing systems (e.g. the MUD database) or to set up special registers (e.g. similar to the MUD database). The combination of information from both regional databases and specific surveys on all actors of the recovery chain allows to overcome the possible limitations of local and national databases, to draw a rather detailed picture of the state of implementation of recovery/reuse and industrial symbiosis at different levels, which is useful for planning and implementing policies, strategies and industrial symbiosis at local, regional or national scale.

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5. EXPERIMENTAL PROGRAM

5.1 Introduction

Section 2 of this document details the physical, chemical, mineralogical and mechanical characteristics of the different types of slag typically produced during the production and refining processes of pig iron and steel. In addition, the various possibilities of reuse have been investigated, highlighting their advantages and critical aspects, with particular focus on their reuse for concrete production.

On the other hand, the Material Flow Analysis of steelmaking slags at the local (regional and provincial) level presented in Section 4 provided a rather detailed picture of the production, management, treatment and reuse of these types of materials. The elaborations and analyses previously shown have also helped to identify the type of slag predominant at local level and for which an increase in recovery rates is necessary, especially in anticipation of its use in the experimental campaign under consideration in this research.

Therefore, combining the analyses carried out in Section 4 with the different types and properties of slags in Section 2, the choice for the present experimental campaign fell on **E**lectric **A**rc **F**urnace **S**lag from **C**arbon steel production ("***EAFS-C***"), added to structural concrete as a partial replacement of fine and coarse natural aggregates.

The reuse of EAFS-C in partial substitution of natural aggregates for concrete production is certainly a well-established and investigated application. The literature reports numerous researches on the subject, highlighting the advantages of concrete with EAFS-C compared to the reference concrete, especially in terms of strength and depending on the replacement percentage between natural aggregates and slag. However, as previously highlighted, this type of reuse is not free from critical aspects and problems, which have also been analysed and studied and with more or less valid solutions available in the literature (see Section 2.3.1.3 for more details).

Knowing the characteristics of EAFS-C and its behaviour once added into "*standard*" structural concrete (after careful mix design), the literature has also focused on the production of the so-called "*non-ordinary*" concretes (pervious, self-compacting, fibre-reinforced, high-performance, etc.) and on the study of full-scale elements (beams, columns, beam-column joints, etc.), in order to assess whether the addition of EAFS-C in the mix can affect the behaviour of these structural elements.

On the other hand, a limited number of researches are available in the literature regarding the topic of the durability of concrete with the addition of EAFS-C in different percentages, thus representing a gap to be filled with special analyses and evaluations.

The topic of this experimental campaign is therefore the reuse of **E**lectric **A**rc **F**urnace **S**lag from **C**arbon steel production (*"EAFS-C"*) **as a partial replacement of fine and coarse aggregates (in three different percentages) for the production of structural concrete**. Tests were carried out on the designed mix to assess their rheological and performance properties, which were then compared with those of a reference structural concrete and with provision of current standards. In addition to the mere characterisation of the material, tests were also conducted to investigate certain aspects relating to the durability of the mixes under examination.

The results obtained highlight and confirm the suitability of EAFS-C for this application and are mostly in line with those found in the literature. In addition to providing a further contribution to the world of steelmaking slags in concrete, they contribute to laying the foundations for the continuation of the experimental campaign already planned and, in particular, for further in-depth studies on durability, a topic that is still poorly studied but of fundamental importance for the correct production of this type of concrete.

5.2 Materials

For the present experimental campaign, 4 different concrete mixes were designed, which will be identified with the following acronyms:

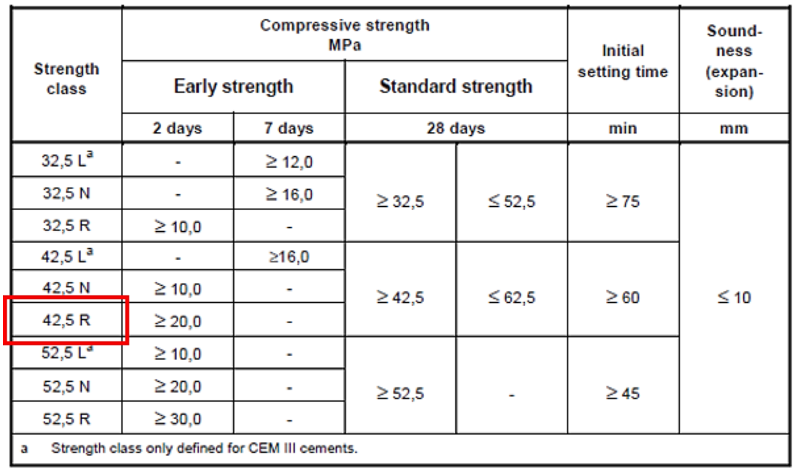
- **NAT**: reference concrete, without the addition of EAFS-C (the acronyms "*NAT*" is the Italian abbreviation of "*Naturale*", i.e. "*Natural*" in English);
- **10%**: concrete with a replacement percentage between natural aggregates and EAFS-C of 10% (by weight);
- **25%**: concrete with a replacement percentage between natural aggregates and EAFS-C of 25% (by weight);
- **50%**: concrete with a replacement percentage between natural aggregates and EAFS-C of 50% (by weight).

The materials used in the mix design will be described in detail below.

5.2.1 Cement

The cement used is a Portland cement composite type II/A-LL 42.5 R, which is part of the type II cement and contains percentages of clinker and limestone (LL) between 80 and 94% and between 6 and 20%, respectively (with percentages of secondary constituents ranging between 0 and 5%), as indicated in Table 1 of the EN 197-1 [1].

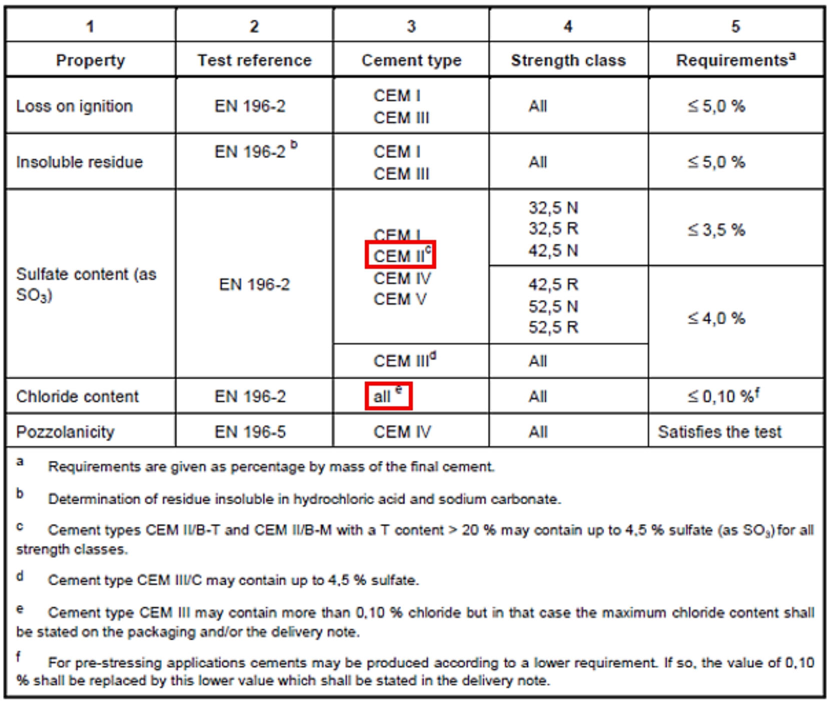
Figure 5-1 and Figure *5-2* show extracts from Tables 3 and 4 of the EN 197-1 concerning the physical/mechanical and chemical requirements of cement, respectively, highlighting the type of interest in the present research.



Strength class	Compressive strength MPa				Initial setting time	Soundness (expansion)
	Early strength		Standard strength			
	2 days	7 days	28 days		min	mm
32,5 L[a]	-	≥ 12,0	≥ 32,5	≤ 52,5	≥ 75	≤ 10
32,5 N	-	≥ 16,0				
32,5 R	≥ 10,0	-				
42,5 L[a]	-	≥16,0	≥ 42,5	≤ 62,5	≥ 60	
42,5 N	≥ 10,0	-				
42,5 R	≥ 20,0	-				
52,5 L[a]	≥ 10,0	-	≥ 52,5	-	≥ 45	
52,5 N	≥ 20,0	-				
52,5 R	≥ 30,0	-				

a Strength class only defined for CEM III cements.

Figure 5-1: Extract from Table 3 of EN 197-1 concerning the mechanical and physical requirements of the different types of cement, given as characteristic values [1].



1	2	3	4	5
Property	Test reference	Cement type	Strength class	Requirements[a]
Loss on ignition	EN 196-2	CEM I CEM III	All	≤ 5,0 %
Insoluble residue	EN 196-2 [b]	CEM I CEM III	All	≤ 5,0 %
Sulfate content (as SO_3)	EN 196-2	CEM I CEM II[c] CEM IV CEM V	32,5 N 32,5 R 42,5 N	≤ 3,5 %
			42,5 R 52,5 N 52,5 R	≤ 4,0 %
		CEM III[d]	All	
Chloride content	EN 196-2	all [e]	All	≤ 0,10 %[f]
Pozzolanicity	EN 196-5	CEM IV	All	Satisfies the test

a Requirements are given as percentage by mass of the final cement.

b Determination of residue insoluble in hydrochloric acid and sodium carbonate.

c Cement types CEM II/B-T and CEM II/B-M with a T content > 20 % may contain up to 4,5 % sulfate (as SO_3) for all strength classes.

d Cement type CEM III/C may contain up to 4,5 % sulfate.

e Cement type CEM III may contain more than 0,10 % chloride but in that case the maximum chloride content shall be stated on the packaging and/or the delivery note.

f For pre-stressing applications cements may be produced according to a lower requirement. If so, the value of 0,10 % shall be replaced by this lower value which shall be stated in the delivery note.

Figure 5-2: Extract from Table 4 of EN 197-1 concerning the chemical requirements of the different types of cement, given as characteristic values [1].

5.2.2 Natural aggregates

For the production of concrete, natural aggregates in 3 different sizes were used, sourced from 2 local producers: fine sand 0/2 mm, medium sand 0/5 mm and gravel 6/20 mm. Their main characteristics are shown in Table 5-1 and were taken from the individual aggregate **D**eclaration of **P**erformance (“***DoP***”) sheets and in relation to the harmonised technical specification EN 12620 (“*Aggregates for concrete*”) [2].

Table 5-1: Main properties of natural aggregates used, taken from the DoP sheets and according to EN 12620 [2].

Property		U.M.	Fine sand	Medium sand	Gravel
Size		[mm]	0/2	0/5	6/20
Density		[kg/m^3]	2650	-	-
Density	(s.s.d.)	[kg/m^3]	-	2730	2720
	(dry)	[kg/m^3]	-	2710	2700
	(apparent)	[kg/m^3]	-	2770	2770
Water absorption		[%]	1	0.8	0.9
Los Angeles (LA)		[%]	-	-	≤25 (LA$_{25}$)

Note: all 3 sizes showed values below the legal limits for radioactivity emissions, release of heavy metals, polyaromatic hydrocarbons and other hazardous substances


(a) (b) (c)

Figure 5-3: Fine sand 0/2 mm (a); medium sand 0/5 mm (b) and gravel 6/20 mm (c). Photos taken by Alan Piemonti.

5.2.3 Artificial aggregate: Electric Arc Furnace Slag from Carbon steel production ("EAFS-C")

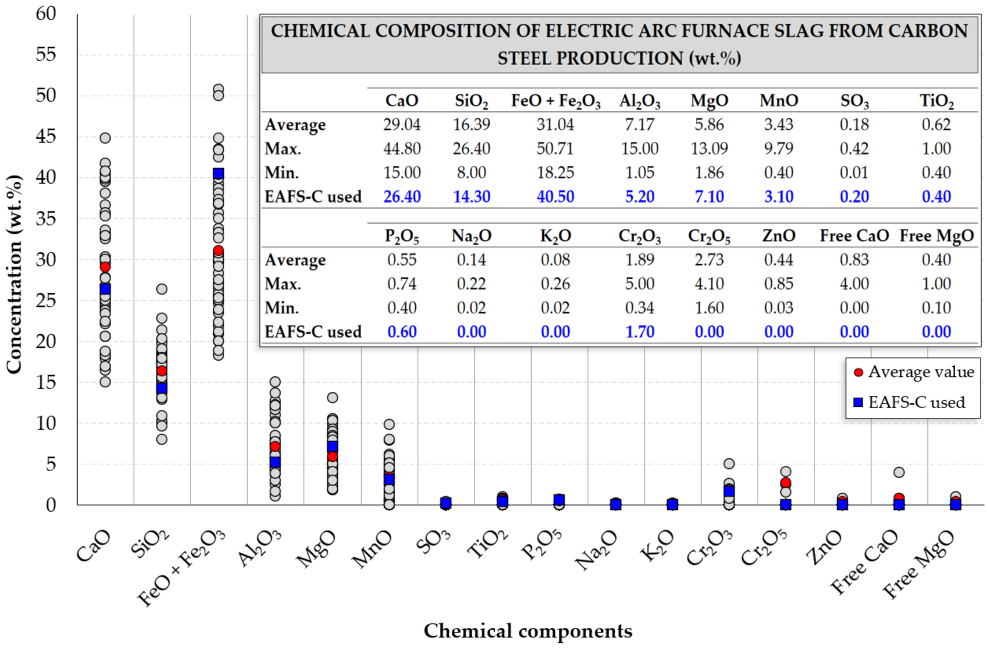
As previously explained, natural aggregates were partially replaced by artificial aggregate (in 3 different percentages) in concrete mixes under investigation. The artificial aggregate consists of Electric Arc Furnace Slag from Carbon steel production ("EAFS-C"), sourced from a local steel mill.

Table 5-2 shows the main physical properties of EAFS-C used and a comparison with typical values available in the literature (already illustrated in Table 2-29).

Table 5-2: Physical properties of the artificial aggregate (EAFS-C) used and comparison with typical values available in the literature (already present in Table 2-29 and shown here for better understanding).

Property	**Standard**	**EAFS-C used**	***Typical values***
Size [mm]	-	0/16	*(0/32)*
Specific gravity [kg/m^3]	UNI EN 1097-6 [3]	3700–3800	*(2900–3970)*
Water absorption [%]	UNI EN 1097-6 [3]	0.9–1.2	*(0.18–10.5)*
Los Angeles (LA) [%]	UNI EN 1097-2 [4]	14–16	*(11.6–29)*
Shape index [%]	UNI EN 933-4 [5]	13	*(1–10)*
Resistance to polishing (PSV) [%]	UNI EN 1097-8 [6]	53–54	*(44; 47)*
Micro Deval abrasion resistance (MDE) [%]	UNI EN 1097-1 [7]	5–7	*(6.5–9.5)*
Mass loss after freeze/thaw cycles [%]	UNI EN 1367-1 [8]	0.5	*(0–2.1)*
Thermal shock resistance [%]	UNI EN 1367-5 [9]	1	*(1; 2)*
Shape	-	Sub-angular	*(Cubical, sharp pointed)*
Colour	-	Dark grey	*(Black/grey)*

Figure 5-4 shows the chemical composition of EAFS-C used (for a better comparison with typical values available in the literature, the chemical properties have been plotted on the graph already shown in Section 2.3.1.2 (Figure 2-22)). Chemical composition analysis was performed using the X-ray fluorescence ("*XRF*") methodology (UNI EN 15309 [10]).



CHEMICAL COMPOSITION OF ELECTRIC ARC FURNACE SLAG FROM CARBON STEEL PRODUCTION (wt.%)

	CaO	SiO_2	$FeO + Fe_2O_3$	Al_2O_3	MgO	MnO	SO_3	TiO_2
Average	29.04	16.39	31.04	7.17	5.86	3.43	0.18	0.62
Max.	44.80	26.40	50.71	15.00	13.09	9.79	0.42	1.00
Min.	15.00	8.00	18.25	1.05	1.86	0.40	0.01	0.40
EAFS-C used	**26.40**	**14.30**	**40.50**	**5.20**	**7.10**	**3.10**	**0.20**	**0.40**

	P_2O_5	Na_2O	K_2O	Cr_2O_3	Cr_2O_5	ZnO	Free CaO	Free MgO
Average	0.55	0.14	0.08	1.89	2.73	0.44	0.83	0.40
Max.	0.74	0.22	0.26	5.00	4.10	0.85	4.00	1.00
Min.	0.40	0.02	0.02	0.34	1.60	0.03	0.00	0.10
EAFS-C used	**0.60**	**0.00**	**0.00**	**1.70**	**0.00**	**0.00**	**0.00**	**0.00**

Figure 5-4: Chemical composition of the artificial aggregate (EAFS-C) used, shown on the average composition graph already illustrated in Figure 2-22 for better comprehension and comparison.

Table 5-3 shows the main mineralogical constituents of the EAFS-C used, identified using the X-ray diffraction (“*XRD*”) methodology (UNI EN 13925-2 [11]).

Table 5-3: Mineral constituents of the artificial aggregate (EAFS-C) used.

Constituent	Formula	Values [wt.%]
Wustite	FeO	36
Belite (dicalcium silicate)	C_2S (or Ca_2SiO_4)	35
Mayenite	$Ca_{12}Al_{14}O_{33}$	11
Brownmillerite	C_4AF (or $Ca_2(Al,Fe)_2O_5$)	8
Magnetite	Fe_3O_4	5
Gehlenite	$Ca_2Al_2SiO_7$	5

Table 5-4 shows the results of the leaching behaviour of EAFS-C used, compared with the regulatory limit values. The electric arc furnace slag used in this experimental campaign was classified as a “*by-product*” in accordance with Art. 184-bis of Legislative Decree 152/2006 [12]. Based on that shown in Table 3-11 and the Lombardy Region Council Resolution n. XI/5224 of 13 September 2021 [13], the leaching test was carried out according to the methodology of EN 1744-3 [14], and not according to EN 12457-2 [15], a methodology that applies instead to slag classified as waste (for more details on the methodology see Section 3.6). The results show that the EAFS-C used complies with the limits for black slag as indicated by the Lombardy Region Council Resolution n. XI/5224 of 13 September 2021 [13].

Table 5-4: Results of the leaching test of the artificial aggregate (EAFS-C) used (carried out according to EN 1744-3 [14]) and comparison with the limit values, as indicated by the Lombardy Region Council Resolution n. XI/5224 [13].

Parameters	U.M.	Values	Limit values
Fluorides	mg/l	0.48	1.5
Barium	mg/l	0.068	1
Copper	mg/l	<0.002	0.05
Zinc	mg/l	0.004	3
Beryllium	µg/l	<2	10
Cobalt	µg/l	<2	250
Nickel	µg/l	<2	10
Vanadium	µg/l	28	250
Arsenic	µg/l	<2	50
Cadmium	µg/l	<0.5	5
Total chromium	µg/l	6	50
Lead	µg/l	<2	50
Molybdenum	mg/l	0.014	0.15
Selenium	µg/l	<2	10
Mercury	µg/l	<0.1	1
COD(*)	mg/l	12	30
pH	-	10.25	9–13

(*) *COD: Chemical Oxygen Demand.*

Figure 5-5: EAFS-C used in this experimental campaign. Photo taken by Alan Piemonti.

5.2.4 Additive

Additives are products which, when added in small quantities to concrete, change some of its properties chemical or physical action. They are chemical substances generally used in liquid form and added in percentages (with respect to the mass of the cement or pozzolanic additions) varying between 0.1 and 3%. The UNI EN 934-2 standard [16], in addition to defining the minimum requirements based on the function performed once added to the mix, also defines an admixture for concrete as a "*material added during the mixing process of concrete in a quantity not more than 5% by mass of the cement content of the concrete, to modify the properties of the ix in the fresh and/or hardened state*". According to Table 1 of UNI EN 934-2, the different types of concrete admixtures are [16]:

- Water reducing/plasticizing admixtures;
- High range water reducing/superplasticizing admixtures;
- Water retaining admixtures;
- Air entraining admixtures;
- Set accelerating admixtures;
- Hardening accelerating admixtures;
- Set retarding admixtures;
- Water resisting admixtures;
- Set retarding/water reducing/plasticizing admixtures;
- Set retarding/high range water reducing/superplasticizing admixtures;
- Set accelerating/water reducing/plasticizing admixtures;
- Viscosity modifying admixture.

The additive used in this experimental campaign is an acrylic polymer-based superplasticiser, which is particularly suitable for concretes made with aggregates characterised by higher water absorption than natural aggregates, such as artificial aggregates (e.g. EAFS-C) or recycled aggregates (e.g. C&D waste). The amount of additive used are shown below (Table 5-6).

5.3 Mix design and tests performed

For the production of good concrete, it is necessary that the different aggregate sizes respect certain weight proportions. By means of a vibrating screen (Figure 5-6(a)), an initial sieving was carried out for the 3 types of natural aggregates as well as for the slag, with the aim of determining the particle size distribution and building the particle size curve for each type of aggregate. The sieving is carried out by passing the aggregates through sieves (Figure 5-6(b)), arranged one on top of the other in a vertical direction, with meshes of decreasing width from top to bottom (provisions on the number of sieves and the size of the meshes are provided in

Section 4 "*Geometrical requirements*" of EN 12620 [2]). The aim of this phase is to obtain, for each aggregate considered, a particle size curve, which can be represented graphically by showing on the x-axis the sieve openings (on a logarithmic scale) and on the y-axis the passing percentage by weight for each sieve. Figure 5-7 shows the particle size curves of the aggregates considered.

(a) (b)

Figure 5-6: Vibrating screen (a) and some of the sieves (b) used for the granulometric analysis. Photos taken by Alan Piemonti.

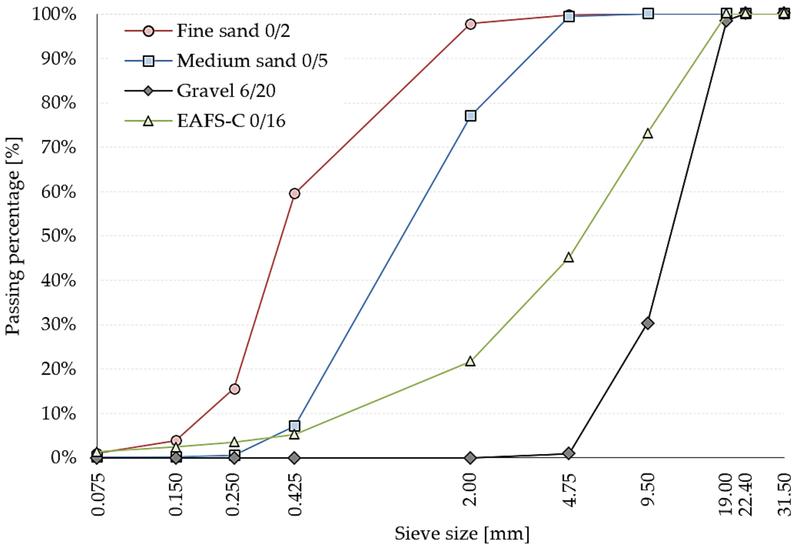


Figure 5-7: Grain size curves of natural and artificial aggregates used in this experimental campaign.

The curves of each aggregate are then combined according to the percentage of presence of each aggregate in the mix design to obtain the so-called "*optimal*" or "*resulting*" particle size curve.

The second phase in a proper particle size analysis is the selection of a so-called "*reference*" or "*comparison*" curve (derived from a graphical approximation of the "*reference spindle*"), with which the "*resulting*" curve can be compared. Given the high degree of difficulty (or near-impossibility) of obtaining a resulting curve that precisely follows the comparison one, it is therefore sufficient for the standard that the resulting curve is as contained as possible within the reference spindle [17]. There are two spindles usually considered in practice: the Fuller-Thompson spindle and the Bolomey spindle, whose difference lies in the criteria considered for their construction and the equations that represent them. To summarise, the Fuller curve (derived from the graphical approximation of the Fuller-Thompson spindle) is based on the criterion of "*greatest possible compactness*". A mix based on this criterion will be characterised by maximum compactness of the aggregate and minimum paste volume, making it possible to produce concretes with good mechanical strength (due to excellent compaction) and reduced production costs, but with reduced workability [17]. The Fuller curve is built by means of the following equation, known as the "*Fuller equation*":

$$P\,(\%) = 100 \cdot \sqrt{\frac{d}{D_{max}}} \tag{5-1}$$

Where P is the passing percentage through the sieve with opening d and D_{max} is the maximum diameter of the aggregate considered.

The problem related to the workability of concrete obtained with a mix based on Fuller criterion led other researchers to formulate new criteria or refine existing ones. To date, one of the most widely used criteria is certainly that of Bolomey, who proposed to modify the optimal curve by including a constant "A" which would take into account the shape of the aggregate and the consistency of the concrete. Compared to Fuller criterion, a concrete mix that follows the curve of Bolomey will be characterised by a higher percentage of voids, which will then be filled by cement paste, resulting in greater flow and workability [17]. The Bolomey curve is built using the following equation, known as the "*Bolomey equation*":

$$P\,(\%) = A + (100 - A) \cdot \sqrt{\frac{d}{D_{max}}} \tag{5-2}$$

Where P is the passing percentage through the sieve with opening d, D_{max} is the maximum diameter of the aggregate considered and "A" is the constant of

Bolomey, i.e. a parameter that takes into account the required workability and the type of aggregate available (Table 5-5).

Table 5-5: Bolomey coefficient "A" according to aggregate type and concrete consistency.

Aggregate type	**Value of "*A*" for concretes with consistency class:**		
	S1	***S2–S3***	***S4–S5***
Alluvial origin	8	10	12
Crushed	10	12	14

In the present experimental campaign, the Bolomey criterion (with constant "*A*" value of 14, thus corresponding to crushed aggregates and fluid/superfluid concrete consistency) was adopted for the composition of the resulting particle size curve, for each of the 4 mixes considered. The resulting particle size curves for each mix are shown below, compared with the reference curve and reference spindles of the Bolomey criterion.

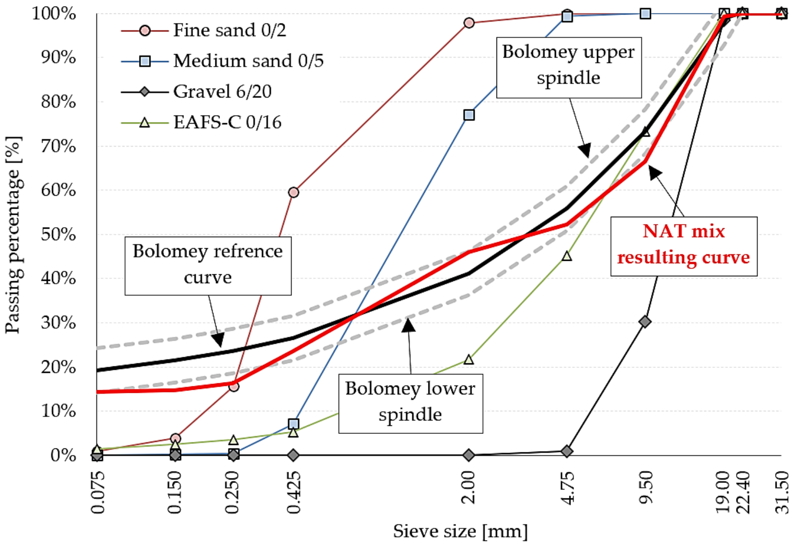


Figure 5-8: Resulting particle size curve for the NAT mix and comparison with the reference curve and reference spindles of the Bolomey criterion.

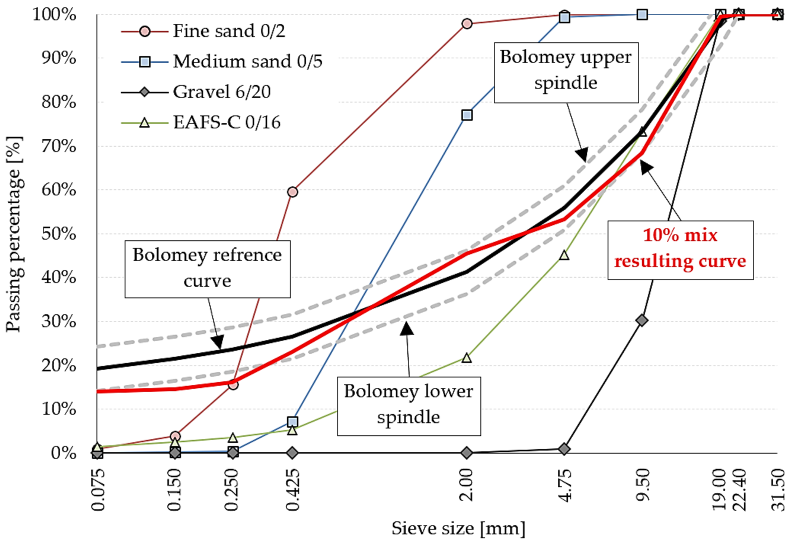


Figure 5-9: Resulting particle size curve for the 10% mix and comparison with the reference curve and reference spindles of the Bolomey criterion.

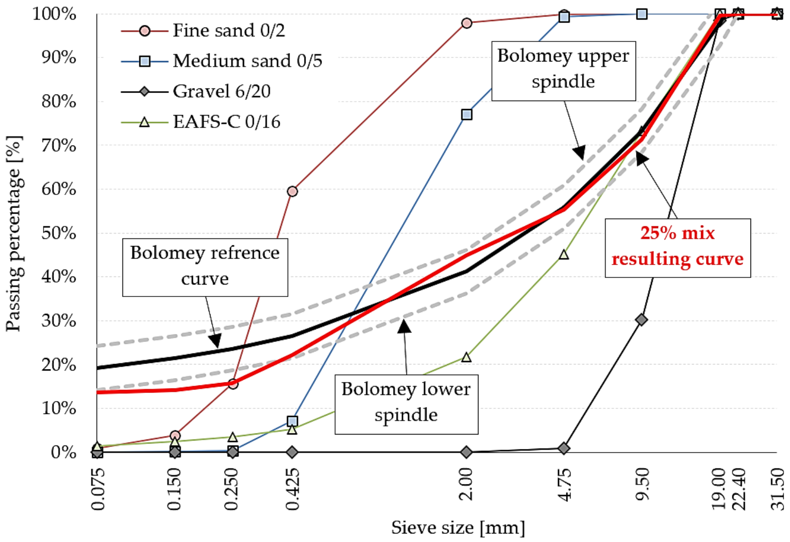


Figure 5-10: Resulting particle size curve for the 25% mix and comparison with the reference curve and reference spindles of the Bolomey criterion.

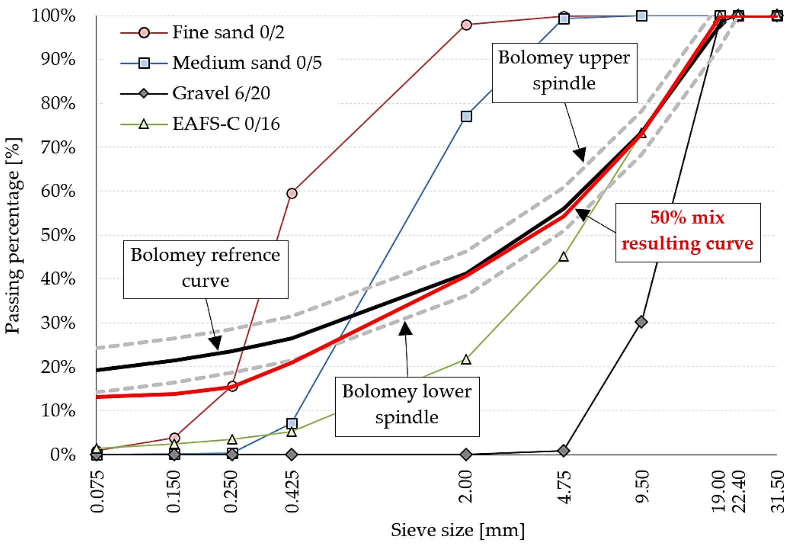


Figure 5-11: Resulting particle size curve for the 50% mix and comparison with the reference curve and reference spindles of the Bolomey criterion.

Table 5-6 shows the 4 different mix design compositions used in the present experimental campaign. The water/cement ratio (w/c) was kept at 0.5 for all mixes in order to allow an adequate comparison of the results of the different tests performed. Prior to the so-called "*final*" castings for the evaluation of the different concrete properties, simple preliminary castings ("*trial batches*") with different amount of admixture were carried out for all the four mixes in order to assess its influence on the workability of the concretes considered. It can be seen that it was only necessary to add small amounts of admixture to each mix to keep the workability under control.

Table 5-6: Mix design compositions.

Component	**Natural aggregate/EAFS-C replacement %**			
	NAT	***10%***	***25%***	***50%***
Portland cement type II/A-LL 42.5 R [kg/m^3]	320	320	320	320
Water [l/m^3]	160	160	160	160
Fine sand (0/2 mm) [kg/m^3]	283	264	226	188
Medium aggregate (0/5 mm) [kg/m^3]	565	526	487	292
Gravel (6/20 mm) [kg/m^3]	1084	948	735	483
EAFS-C (0/16 mm) [kg/m^3]	-	256	640	1279
Superplasticiser admixture [l/m^3]	0.25	0.50	0.50	1.00
Water/cement ratio (w/c) [-]	0.5	0.5	0.5	0.5

Once the 4 different mix design were defined and the amount of admixture was calibrated appropriately, concrete castings were carried out and their properties assessed. The moisture content of both natural aggregates and EAFS-C was measured 24h before each casting in order to consider any corrections to be made to the amount of water in the mixes. An aggregate with a moisture content lower than its water absorption value tends to absorb water once it is added to the mix, resulting in reductions in the mix design water content, water/cement ratio and workability (strengths will be slightly higher (and in any case different) than those expected). On the other hand, an aggregate with a moisture content higher than its absorption value tends to release water to the mix during the casting phase, thus causing an increase in the water in the mix (and therefore in the water/cement ratio), a reduction in the strength (which is in any case different from that expected) and an increase in concrete shrinkage compared to that expected during the mix design.

The water absorption of the slag is in fact determined both by the presence of open capillaries and by the chemically bound water, i.e. the water required for the transformation of the oxides into hydroxides (the latter is in fact different from the "*free*" water or the water absorbed through the capillaries (which can be easily assessed) and affects workability).

Special attention was therefore given to the "*treatment*" of the EAFS.C before its addition to the mixture. In addition to assessing its moisture content, EAFS-C was in fact pre-saturated 24h before its reuse. If a slag is not pre-saturated, there is a water absorption during the "*dormant*" phase. When the setting reaction occurs, this part of the previously absorbed water will no longer be available to the cement and the above reaction will therefore be compromised (the cement granule will in fact remain anhydrous). The transition zone (i.e. the interface between the slag and matrix) will therefore be non-optimal and strongly penalized.

On the other hand, if the slag used is saturated, it tends to release water to the mix, which will help to better hydrate the cement surrounding it and promote hydration reactions.

The use of pre-saturated slag therefore brings benefits both from both a rheological and strength perspective. In fact, it contributes to internal curing, promoting good hydration of the cement around the aggregate and thus improving the transition zone between slag and cement paste.

The pre-saturation of the slag in the present experimental campaign took place 24h before each casting, by soaking the slag in the 75% of water foreseen in the mix design phase (already appropriately corrected in relation to the moisture content of the different types of aggregates used, in order to avoid affecting the water/cement ratio).

It should also be noted that the almost or total absence of free-CaO and free-MgO in the chemical composition of the slag used (Figure 5-4) makes it possible to avoid expansive phenomena due to high concentrations of these two elements (for more details on these expansive phenomena, see Section 2.2.2.3 of this document). Before its use, EAFS-C was in any case left in the open air for 2–3 months.

Table 5-7 shows the tests performed to evaluate the properties of the 4 mixes considered and the reference standards.

Table 5-7: Tests performed in the experimental campaign and reference standards.

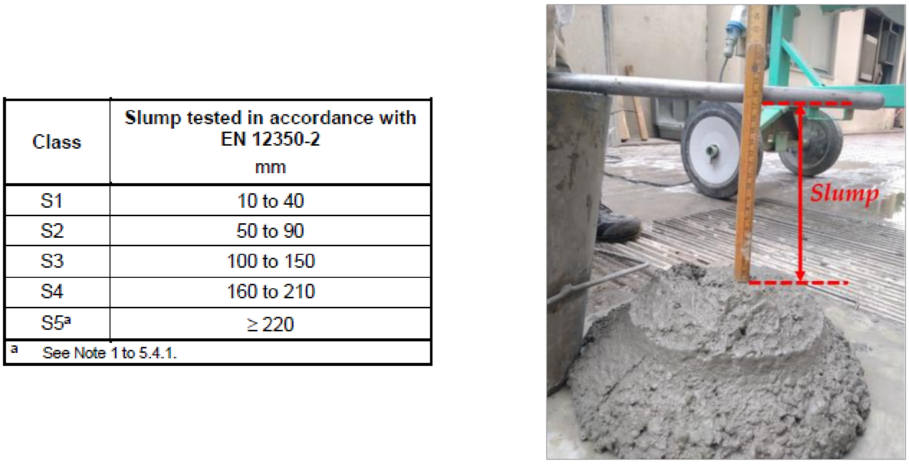
Tests and evaluated properties	Standard	Ref.
Fresh concrete		
Workability	EN 12350-2	[18]
Air content	EN 12350-7	[19]
Density	EN 12350-6	[20]
Hardened concrete		
Compressive strength	EN 12390-3	[21]
Flexural tensile strength	EN 14651	[22]
Elastic modulus	EN 12390-13	[23]
Shrinkage	ASTM C490/C490M	[24]
Beam test	UNI EN 10080 (Appendix C)	[25]
Tension ties	-	-
Durability		
Capillarity absorption	EN 13057	[26]

5.4 Results and discussion

5.4.1 Fresh concrete

5.4.1.1 Workability

The consistency of concrete is determined by means of the "*Slump test*", according to EN 12350-2 [18]. The equipment consists of a truncated cone-shaped container made of sheet metal, smooth inside and open at both ends, 30 cm high, 1.5 mm thick, with a diameter of 20 cm at the base and 10 cm at the top. For a correct execution of the test, the cone must first be held in place (by placing the feet on the base clamps), after which it is filled with concrete to a heigh of approximately 1/3 of the total height of the cone. The same procedure is then repeated twice, filling to a height of approximately 2/3 until the cone is completely filled. At each height reached (1/3, 2/3 and 3/3 of the total height of the cone), the concrete inside the cone is compacted with 25 pestle strokes (the pestle is a piece of smooth steel with a diameter of 16 mm and a length of 60 cm). Once completely filled, the top of the cone is levelled off and the cone is raised. The "*slump*" of the concrete, measured in relation to the 30 cm height of the metal cone (Figure 5-12(b)) provides an indication of its consistency. The consistency of concrete is a parameter closely related to its workability and therefore influences its properties in both the fresh and hardened state.



Class	Slump tested in accordance with EN 12350-2 mm
S1	10 to 40
S2	50 to 90
S3	100 to 150
S4	160 to 210
S5^a	≥ 220

[a] See Note 1 to 5.4.1.

(a) (b)

Figure 5-12: Table 3 of EN 206 [27] concerning concrete consistency classes in relation to slump (a) and example of slump measurement. Photo taken by Alan Piemonti.

Table 5-8 shows the measured slump for each of the 4 mixes. All the mixes showed very similar workability, being classified with consistency class S4 (slump between 160 and 210 mm according to EN 206 [27], Figure 5-12(a)). The addition of small percentages of superplasticiser additive (Section 5.2.4) allowed the workability to be kept under control, as also demonstrated in other studies in the literature [28,29].

Table 5-8: Slump value and consistency class of the 4 mixes considered.

Mix	Slump [mm]	Class
NAT	176	S4
10%	198	S4
25%	190	S4
50%	185	S4

5.4.1.2 Air content

The air content is very important for concrete. It depends on many factors (maximum aggregate diameter, particle size distribution, mix design, method and duration of vibration during casting, possible addition of admixtures, etc.) and can influence several properties (strength, porosity, durability, etc.). For example, concretes with high air content will be characterised by higher porosity and lower compressive strength [30].

The evaluation of the air content in concrete is carried out with the aim of determining the volume of air present in fresh concrete, according to EN 12350-7 [19]. Figure 5-13 shows the passages for a correct measurement of the air content in the mix by means of a porosimeter, which are listed more exhaustively below (the letters in the following list correspond to those shown in Figure 5-13):

(a) Filling the cylindrical lower part (of known volume and tare), with the concrete considered (its mass is also measured in order to easily calculate its density in the fresh state). Filling must be done "*in layers*", whereby each layer must be well compacted using a pestle;
(b) Application of a watertight lid;
(c) Saturation of the voids in the concrete with water injected by means of a bulb from one hole and air bubbles escaping from a second hole (located on the opposite side);
(d) The saturation of the voids is complete when no more air bubbles come out of the second hole but water mixed with concrete (indicated with a red box). The operation is then repeated with inverted holes;
(e) Closing of the vent hole;
(f) Closing the water injection hole;
(g) Manual pressurisation of the porosimeter. The pointer of the pressure gauge thus begins to move (visible from point (f) to point (g) in the figure);
(h) Pressure correction until 0% is reached and then manual "*release*" of air by venting the porosimeter. Wait a few seconds for the pointer of the pressure gauge to stabilise;
(i) Air content reading on the pressure gauge.

Table 5-9 shows the air content of the 4 mixes considered.

Table 5-9: Air content of the 4 mixes considered.

Mix	**Air content [%]**
NAT	2.70
10%	3.00
25%	2.60
50%	2.00

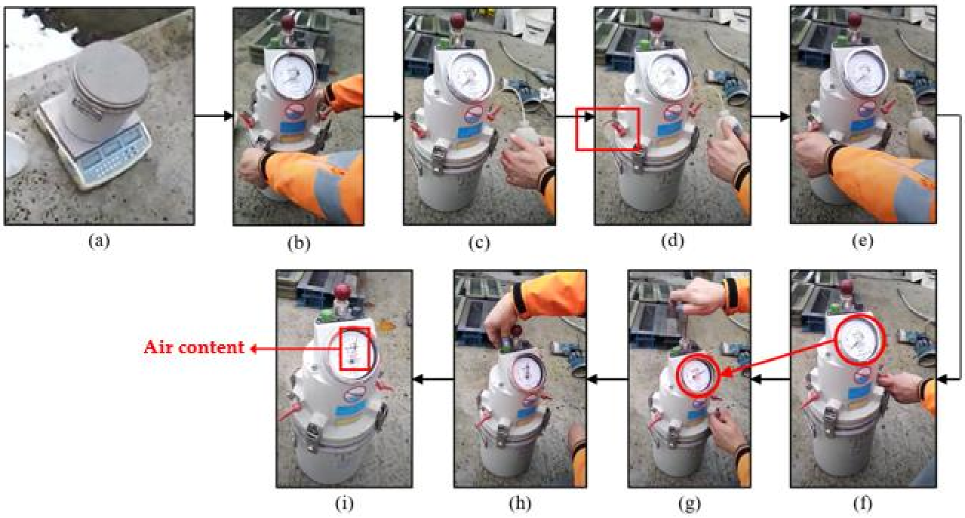


Figure 5-13: Procedure for measuring the air content in fresh concrete using a porosimeter (EN 12350-7 [19]). Photos taken by Alan Piemonti.

As shown in Table 5-9, all the mixes showed a very similar air content (as shown by some studies in the literature [28]), with the exception of the 50% mix which showed an air content 26% lower than the NAT reference mix.

5.4.1.3 *Density (fresh concrete)*

The density of the fresh concrete was measured according to EN 12350-6 [20]. For its evaluation, the cylindrical container forming the base of the porosimeter used for measuring the air content (described in the previous paragraph) was used. The density was obviously measured after point (a) in the list in the previous paragraph, i.e. after filling and compacting the concrete but prior to the application of the cover and the introduction of water for the subsequent air content evaluation. The mass (m_1, 3.60 kg) and volume (V, 7 litres) of the empty cylindrical container were first measured, followed by filling with concrete and subsequent compaction (filling in “successive layers” and compaction of each layer by means of a pestle). Finally, the mass of the container full of concrete was measured (m_2). From the ratio of the difference between the two masses (m_2-m_1) and the volume (V) of the container, the density of the fresh concrete was determined. Table 5-10 shows the density of the 4 fresh concretes considered and the difference (in percentages and italics) between the density of the mixes with the addition of EAFS-C compared to that of the reference NAT mix.

Table 5-10: Density of the 4 fresh concretes considered and difference between the density of the EAFS-C mixes compared to that of reference NAT mix.

Mix	Density [kg/m³]	Diff.
NAT	2385	-
10%	2480	*+4.0%*
25%	2570	*+7.8%*
50%	2730	*+14.5%*

The mixes showed a higher density as the substitution percentage of natural aggregate-EAFS-C increased, due to the higher density of EAFS-C compared to that of natural aggregate (~35% higher). This is in line with results available in the literature (e.g., [30,31,32]).

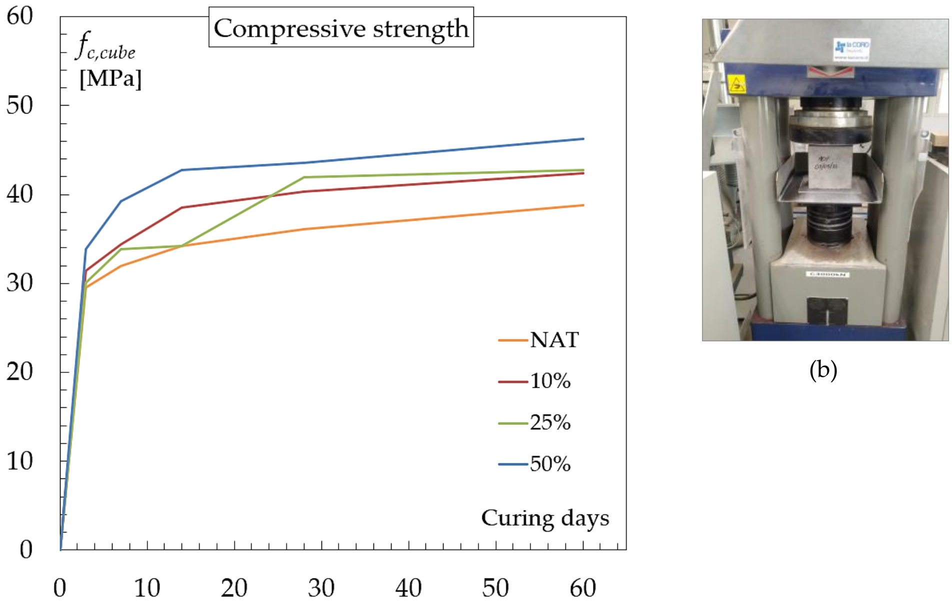
5.4.2 Hardened concrete

5.4.2.1 Compressive strength

Compressive strength is one of the main properties for the mechanical characterisation of concrete and is influenced by several factors (type of cement and aggregate, class of concrete, water/cement ratio, air content, etc.). In a concrete mix, the compressive strength provided by the matrix increases with the concrete curing, with an initial development usually faster, a slight growth in later periods and reaching the asymptote after a few years. On the other hand, the contribution of aggregates to compressive strength depends on their nature (type, texture, chemical composition in the case of recycled or artificial aggregates, etc.) and they usually have higher compressive strength and elastic modulus than the cement paste. One of the key factors for the development of good mechanical resistance of concrete is the interfacial transition zone between aggregate and cement paste (this is generally one of the weakest point, where the bond strength between aggregate and cement paste along the contact surface may fail and local fractures may be generated, thus affecting the mechanical resistance of the element).

In this experimental campaign, the compressive strength was evaluated on cubic concrete specimens of 150 mm side, according to EN 12390-3 [21]. The test was conducted after 3, 7, 14, 28 and 60 days of curing in order to assess the development of compressive strength over time. Three cubes were tested at each deadline for each of the 4 mixes considered and the average values of the results were determined. The curing of the cubes took place in a chamber with relative humidity ≥95% and temperature (20±2)°C.

Figure 5-14 shows a specimen during the execution of the test and the development of the compressive strength of the mixes considered over time, respectively. For a better comprehension, Table 5-11 shows the average compressive strength values and the Coefficient of Variation "*CV*" (in brackets) of each mix considered.



(a)

(b)

Figure 5-14: Development of the compressive strength of the 4 mixes considered (a) and specimen during the test (b). Photo taken by Alan Piemonti.

Table 5-11: Average compressive strength of the 4 concretes considered. Coefficient of Variation "CV" (in brackets) and difference between the values of the EAFS-C mixes compared to those of reference NAT mix (in percentages and italics).

Curing days	**Compressive strength [GPa]**						
	NAT	***10%***	***Diff.***	***25%***	***Diff.***	***50%***	***Diff.***
3	29.50	31.41	*+6.5%*	30.10	*+2.0%*	33.88	*+14.9%*
	(0.046)	*(0.051)*		*(0.107)*		*(0.053)*	
7	31.96	34.40	*+7.6%*	33.82	*+5.8%*	39.21	*+22.7%*
	(0.051)	*(0.056)*		*(0.051)*		*(0.015)*	
14	34.21	38.48	*+12.5%*	34.23	*+0.1%*	42.78	*+25.0%*
	(0.025)	*(0.012)*		*(0.057)*		*(0.025)*	
28	36.09	40.29	*+11.6%*	41.97	*+16.3%*	43.58	*+20.8%*
	(0.057)	*(0.035)*		*(0.045)*		*(0.016)*	
60	38.80	42.37	*+9.2%*	42.77	*+10.2%*	46.22	*+19.1%*
	(0.045)	*(0.035)*		*(0.042)*		*(0.037)*	

The tests for the evaluation of compressive strength showed a faster strength development of the mixes with EAFS-C compared to the reference NAT mix. With the exception of the 25% mix (which showed a rather "*swinging*" development at 7 and 14 days of curing, most likely due to "*defective*" and underperforming cubes tested all at the same deadline), an increase in compressive strength was recorded for the others as the replacement percentage between natural aggregates and EAFS-C increased. As described above, Table 5-11 shows the increase and decrease in compressive strength of the slag mixes compared to NAT mix. The greatest difference was recorded between the 50% mix and the NAT mix, where, at 28 days, the strength of the former was almost 21% higher than that of the latter. These results are in line with some studies available in the literature. In particular, the higher compressive strength of concretes with EAFS-C could be related to two main factors: the higher Los Angeles class of the slag compared to natural aggregate [31] and an improvement of the Interfacial Transition Zone ("*ITZ*") between the slag and the cement matrix [29,31,33].

For completeness and for comparison with the density in the fresh state (Table 5-10), the average density values of the 4 hardened concretes (28 days of curing), obtained by accurately recording the mass and volume of each cube before the test, are shown in Table 5-12. The Coefficient of Variation "*CV*" (in brackets) and the difference (in percentages and italics) between the density of the mixes with the addition of EAFS-C compared to that of the reference NAT mix are also shown.

Table 5-12: Density of the 4 hardened concretes considered (28 days of curing), Coefficient of Variation "CV" (in brackets) and difference between the density of the EAFS-C mixes compared to that of reference NAT mix (in percentages and italics).

Mix	**Density [kg/m³]**		**Diff.**
NAT	2396	*(0.001)*	-
10%	2407	*(0.010)*	*+0.5%*
25%	2523	*(0.007)*	*+5.3%*
50%	2733	*(0.016)*	*+14.1%*

As for the strength of concrete in the fresh state the mixtures showed a higher density in the hardened state as the replacement percentage of natural aggregate-EAFS-C increased, due to the higher density of EAFS-C compared to natural aggregate (~35% higher).

5.4.2.2 *Flexural tensile strength*

In addition to compressive strength, the evaluation of tensile strength is also of fundamental importance for a correct characterisation of the material. It is well known that the value of the tensile strength of a standard structural concrete is approximately one order of magnitude lower than the compressive strength, with different standards (e.g. Eurocode 2 [34]) suggesting empirical formulae for its calculation in case it is not possible to perform the appropriate test. In literature and in standards there are several tests for the evaluation of tensile strength and the most commonly used are the "*direct tensile test*", the "*indirect tensile test*" (or "*Brazilian test*") and the "*flexural tensile test*". In this experimental campaign it was decided to use the latter, since the set-up and size of the specimens guarantee greater stability of the specimen itself during the test. The "*direct tensile test*" has in fact fell out of use due to the need to apply special resins to the ends of the cylindrical or prismatic specimens to allow the machine to grip the specimen. However, these resins very often did not provide sufficient strength and were subject to fracture before the specimen failed. The "*indirect tensile test*" (or "*Brazilian test*") is certainly the most suitable for assessing the tensile strength of the material, but it was not applied in the present experimental campaign due to the limited stability of the cylindrical specimen during the execution of the test (it is in fact arranged horizontally and loaded along its lateral surface, orthogonally to its axis).

It was therefore decided to perform the "*flexural tensile test*", i.e. a **3**-**P**oint **B**ending **T**est ("***3PBT***"), according to EN 14651 [22], carried out on 150x150x600 mm^3 beams, notched for a height of approximately 25 mm in the middle (on the opposite face to that of load application).

EN 14561 is a standard specifically designed to calculate the flexural tensile strength of concrete with metallic fibres. It allows the evaluation of its post-peak ductile behaviour due to the presence of a certain fibre content in the cement matrix and the calculation of the residual post-peak flexural tensile strength corresponding to different values of Crack Mouth Opening Displacement ("*CMOD*"). The procedure is also adaptable to concretes without fibres (useful for comparison when studying fibre-reinforced concrete) and the parameters required for the calculation of the flexural tensile strength are [22,35]:

- f_L, evaluated on the "*Nominal stress–CMOD*" diagram and can be defined as peak strength in case of large strength losses after reaching the peak or strength at CMOD equal to 0.05 in case of post-peak hardening. Parameter of interest for both plain and fibre-reinforced concrete:

$$f_L = \frac{3 \cdot F_L \cdot l}{2 \cdot b \cdot h_{sp}^2} \tag{5-3}$$

- $f_{R,j}$: residual flexural tensile strength corresponding to a j value of CMOD. In particular, there are 4 $f_{R,j}$ to be considered and they are $f_{R,1}$, $f_{R,2}$, $f_{R,3}$ and $f_{R,4}$ (corresponding to the residual flexural tensile strength for 0.5, 1.5, 2.5 and 3.5 mm crack openings, respectively). These are parameters of interest only for fibre-reinforced concretes since concretes without fibres do not exhibit post-peak ductile behaviour (as an example, see Figure 5-16):

$$f_{R,j} = \frac{3 \cdot F_j \cdot l}{2 \cdot b \cdot h_{sp}^2} \tag{5-4}$$

Where F_L is the load corresponding to the peak in the "*Nominal stress–CMOD*" diagram [N]; F_j is the load corresponding to CMOD = CMOD$_j$ [N]; b and l are the width and the length of the specimen on which the test is carried out [mm], respectively; h_{sp} is the difference between the specimen heigh and the notch size.

Figure 5-15 shows the load scheme of the 3 Point Bending Test and a specimen during the execution of the test while Figure 5-16 shows an example of a "*Nominal stress–CMOD*" diagram comparing the behaviour of plain concrete specimens and fibre-reinforced concrete specimens (extract from [36]). It can be seen the difference between the different types of specimens, with the fibre-reinforced ones showing ductile post-peak behaviour.

(a) (b)

Figure 5-15: Load scheme of the 3 Point Bending Test (a) [36] and a specimen during the execution of the test (b). Photo taken by Alan Piemonti.

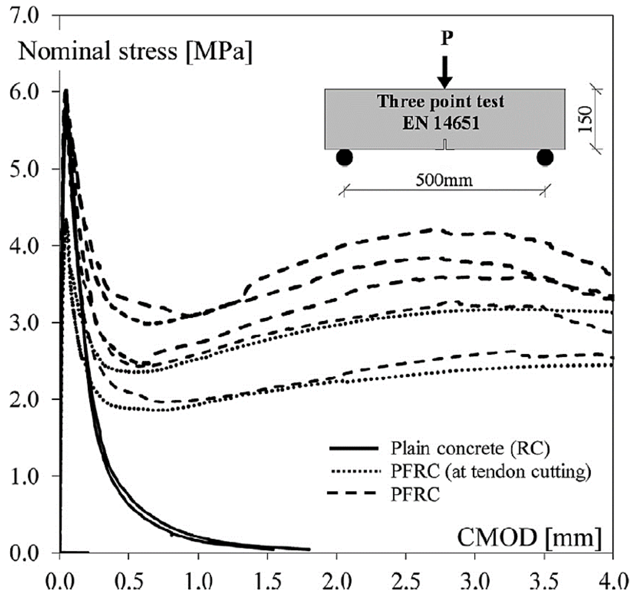


Figure 5-16: Example of a "Nominal stress–CMOD" diagram comparing the behaviour of plain concrete specimens (RC) and fibre-reinforced concrete specimens (in this case PFRC or Polypropylene Fibre-Reinforced Concrete), extract from [36].

Finally, the Figure 5-17 shows the *"Nominal stress–CMOD"* diagram for the specimens analysed in the present experimental campaign (curves derived from the average of 3 specimens for each type of concrete).

As previously mentioned, the tests were carried out on 150x150x600 mm^3 beams, notched for a height of approximately 25 mm in the middle (on the opposite face to that of load application). The tests were conducted after 28 days of curing in a chamber with relative humidity ≥95% and temperature (20±2)°C. Table 5-13 contains the average values of the flexural tensile strength obtained for the 4 mixes considered, the Coefficient of Variation *"CV"* in brackets and the comparison between the density of the EAFS-C mixes compared to that of reference NAT mix (in percentages and italics).

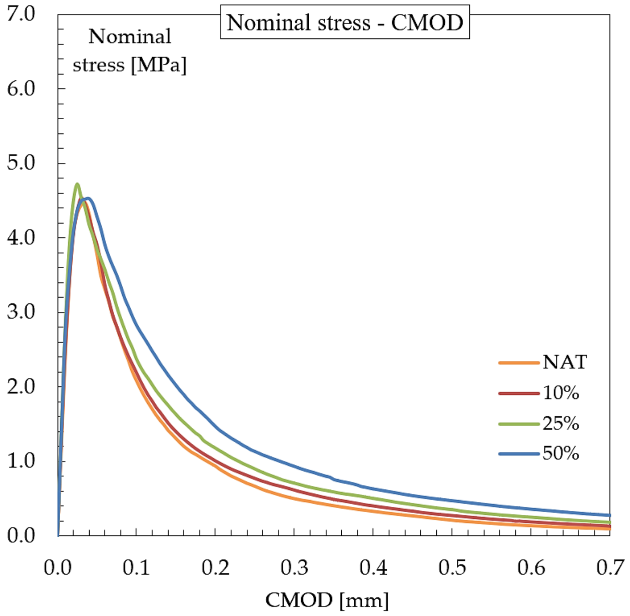


Figure 5-17: "Nominal stress–CMOD" diagram for the specimens analysed in the present experimental campaign (curves derived from the average of 3 specimens for each type of concrete).

Table 5-13: Average tensile strength values of the 4 concretes considered (28 days of curing), Coefficient of Variation "CV" (in brackets) and difference between the values of the EAFS-C mixes compared to that of reference NAT mix (in percentages and italics).

Mix	Tensile strength [MPa]	Diff.
NAT	4.72 *(0.079)*	-
10%	4.55 *(0.143)*	*-3.6%*
25%	4.76 *(0.051)*	*+0.9%*
50%	4.56 *(0.030)*	*-3.3%*

The results from the 28-day tests showed no significant improvements in the tensile strength of the mixes with EAFS-C compared to the reference NAT mix. The 10% and 50% mixes showed a slight decrease, while a slight increase was achieved by the 25% mix. However, the values are very similar to each other, with differences not exceeding the order of 3.5%. These results are in line with those obtained by other researchers and available in the literature, where the tensile strengths of the slag mixes have been found to be slightly lower [32], comparable or slightly higher [37] than those of ordinary reference concrete. The ratio between the tensile and compressive strengths of the mixes was found to be between 10 and 13%.

5.4.2.3 Elastic modulus

When concrete is subjected to a stress (σ), whether compressive or tensile, it undergoes a dimensional change (ε). The modulus of elasticity therefore represents the ratio between the stress σ and the strain ε, the latter measured in the direction of load application. For relatively small values of stress, the Hooke equation, which express the linear proportionality between these two variables, applies:

$$\sigma = E \cdot \varepsilon \tag{5-5}$$

Where σ, E and ε represent the stress [MPa], the elastic modulus [MPa] and the strain [-].

The factors that mainly influence the elastic modulus are the strength class of concrete (a higher class corresponds to a higher elastic modulus, but with an increase in the brittleness of the material), the mix composition (type of aggregate, grain size curve, water/cement ratio, etc.) and the curing conditions.

In the present experimental campaign, the evolution of the elastic modulus over time was investigated, evaluating it at different deadlines (3, 7, 28 and 60 days) by performing a compression test on 150 mm diameter and 300 mm height cylindrical specimens. For each deadline and for each of the 4 mixes considered, 4 cylinders were tested and the final result represents the average of the values obtained. The curing of the cylinders took place in a chamber with relative humidity ≥95% and temperature (20±2)°C. Prior to testing, the base surfaces of each cylinder were smoothed in order to obtain a perfectly flat surface for optimal test execution. Two specially drilled metal "*crowns*" were placed on each cylinder at a predetermined distance to allow the insertion of the measuring instruments (Linear Variable Displacement Transducers or "*LVDTs*") along 3 measurement lines, equally spaced along the side surface of the cylinder (Figure 5-18).

Starting from the mean cubic compressive strength ($f_{c,cube}$, calculated at each deadline and for each of the 4 mixes, as specified in Section 5.4.2.1), the mean cylindrical compressive strength was calculated ($f_{c,cyl} = f_{c,cube} \cdot 0.83$). The latter was then divided by a coefficient equal to 3 in order to obtain the maximum stress value applicable to the cylinder during the test (well below $f_{c,cyl}$, in order to be sure to be within the elastic range). The test was then carried out by means of 3 load/unload cycles with a maximum applied stress of $f_{c,cyl}/3$, according to EN 12390-13 [23]. As an example, for the 28-day reference NAT mix:

- $f_{c,cube,NAT}^{28days} = 36.09\ MPa$ (from Table 5-11 of this document);
- $f_{c,cyl,NAT}^{28days} = f_{c,cube,NAT}^{28days} \cdot 0.83 = 29.95\ MPa;$
- $f_{c,cyl,NAT}^{28days}/3 = 9.98\ MPa$ (and this is the maximum stress applied during the load/unload cycles, for the NAT mix at 28-day deadline).

The same calculation is also performed for the other mixes, for each deadline.
As already mentioned, the test consists of the application of 3 load/unload cycles and the elastic modulus is given by the linearisation of the unloading part of the last cycle (shown by a red line in Figure 5-19). This Figure also shows the equation of this line, the angular coefficient of which corresponds to the value of the elastic modulus (the graph shows an example of the test performed at 28 days in cylinder no. 1 of the mix 50%). Analytically, the calculation of the elastic modulus according to EN 12390-13 is performed using the following formula [23]:

$$E_S = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \tag{5-6}$$

Where (according to Figure 5-19), E_S is the secant elastic modulus, σ_1 and ε_1 are the preload stress and associated strain and σ_2 and ε_2 are the peak stress at the last load cycle and associated strain.
Figure 5-20 shows a comparison of the elastic moduli of the 4 mixes considered (for each deadline (for a better comprehension, Table 5-14 shows the same values accompanied by the Coefficient of Variation (“*CV*”, in brackets) and a comparison (in terms of increase/decrease) of the elastic modulus of the EAFS-C mixes compared to the reference NAT mix (in percentages and italics).

(a) (b)

Figure 5-18: Example of instrument application on the cylinder (a) and cylinder during the test (b). Photos taken by Alan Piemonti.

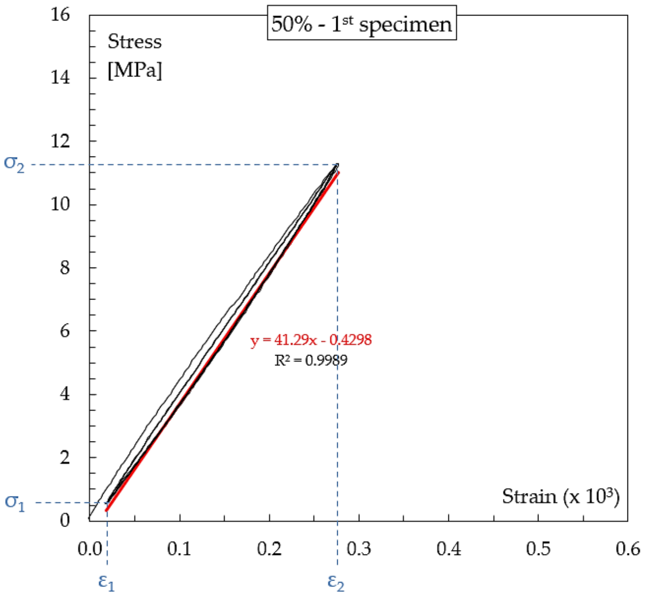


Figure 5-19: Example of a graph from one of the tests performed in which the elastic modulus is given by the linearisation of the unloading part of the last cycle (in red). The angular coefficient of the equation represents the elastic modulus.

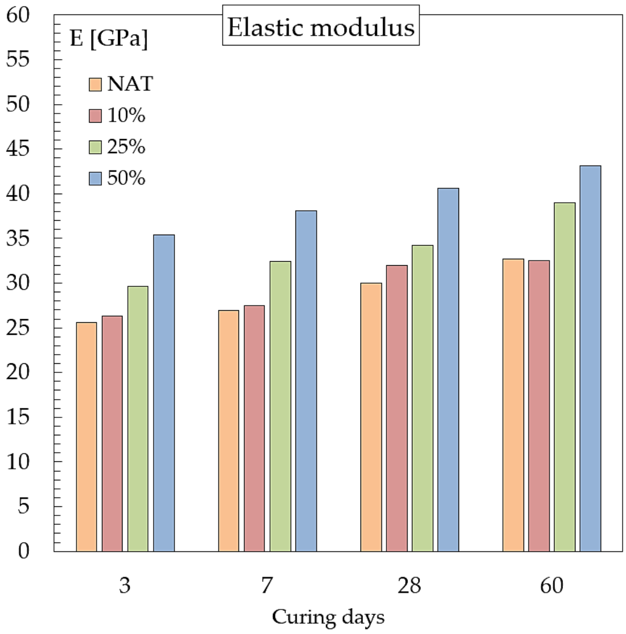


Figure 5-20: Elastic moduli of the 4 mixes considered at different deadlines.

Table 5-14: Average elastic modulus of the 4 concretes considered. Coefficient of Variation "CV" (in brackets) and difference between the values of the EAFS-C mixes compared to those of reference NAT mix (in percentages and italics).

Curing days	**Elastic modulus [GPa]**						
	NAT	***10%***	***Diff.***	***25%***	***Diff.***	***50%***	***Diff.***
3	25.56 *(0.019)*	26.28 *(0.055)*	*+2.8%*	29.67 *(0.045)*	*+16.1%*	35.38 *(0.022)*	*+38.4%*
7	26.95 *(0.041)*	27.47 *(0.098)*	*+1.9%*	32.46 *(0.025)*	*+20.4%*	38.13 *(0.018)*	*+41.5%*
28	30.02 *(0.029)*	32.02 *(0.024)*	*+6.7%*	34.22 *(0.016)*	*+14.0%*	40.57 *(0.032)*	*+35.2%*
60	32.72 *(0.027)*	32.56 *(0.046)*	*-0.5%*	38.97 *(0.027)*	*+19.1%*	43.13 *(0.039)*	*+31.8%*

Depending on the mix considered, the results of the test at different deadlines showed a general increase in the elastic modulus of the slag mixes compared to the reference NAT mix (higher at higher natural aggregate-EAFS-C substitution percentage). With the exception of the elastic modulus of the mix 10% at 60 days of curing, which recorded a slightly lower value compared to the NAT mix (-0.5%), all the others increased, even recording increases in the order of +35–45% (50% mix).

The results are in line with those obtained in other studies available in the literature [30,31,38], in which some researchers highlighted how the elastic modulus depends greatly on the characteristics and mechanical properties (compression, porosity, hardness, etc.) of the aggregate used [30,38].

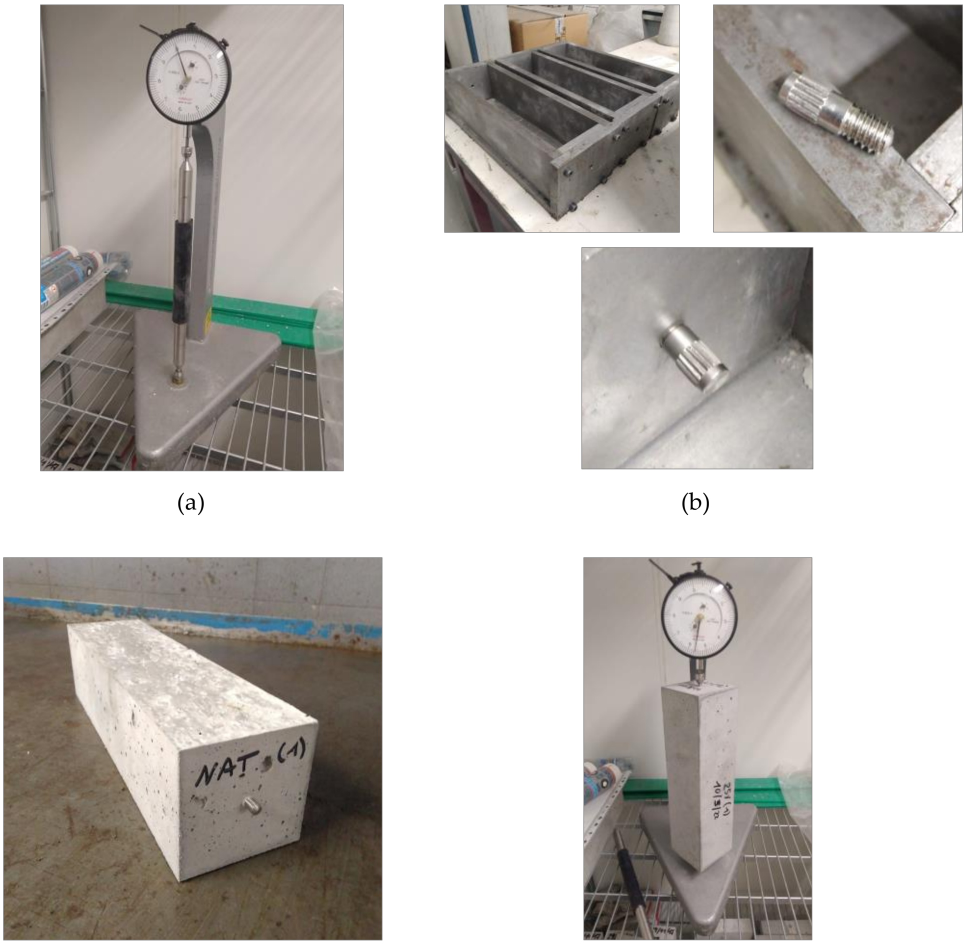
5.4.2.4 Shrinkage

The gradual removal of water (through evaporation or migration) during the setting and hardening phases of concrete causes a volumetric change in the concrete itself, referred to as "*shrinkage*" in case of contraction. Depending on several factors (e.g. external environment, materials, etc.), the shrinkage can be classified as "*plastic shrinkage*" (short term, usually a few hours after casting, caused by the evaporation of water from the surface), "*drying shrinkage*" or "*hygrometric shrinkage*" (characterises the entire life of the element but most develops in the few months, caused by the evaporation of the water contained in the conglomerate) and "*autogenous shrinkage*" (caused by the hydration of the cement and little dependent on the hygrometric conditions of the environment).

The part of the concrete affected by the shrinkage phenomenon is therefore the cement matrix, the contraction of which may cause the formation of cracks (which, in case of reinforced concrete, lead to an increased exposure of the steel rebars and consequent problems related to the durability of the element). As far as the aggregates in the mix are concerned, they do not contribute to the shrinkage phenomenon, since they do not present any dimensional variations related to the relative humidity of the environment. On the other hand, they also play a "*counter*" function against the shrinkage of the cement matrix, due to their mechanical properties and elastic modulus. It is therefore of fundamental importance to understand how the addition of alternative materials (such as steelmaking slags) in different percentages in place of the natural aggregate can affect the shrinkage behaviour of concrete.

In the present experimental campaign, the evolution of the "*drying shrinkage*" of concrete was assessed by means of measurements taken on 75x75x285 mm^3 small beams at different deadlines (2, 3, 5, 7, 14, 28, 60, 75 and 90 days after casting). The curing of these small beams took place in a chamber with relative humidity (50±5)% and temperature (20±2)°C. The measuring instrument was also placed in the same chamber to ensure correct measurements and avoid variations due to different environmental conditions.

The ASTM C490/C490-M [39] standard was used for the shrinkage measurements, which provides for the use of the instrument shown in Figure 5-21(a). The small beams were cast in special metal forms with threated holes at the ends, which allow the insertion of small pegs (also threated and specially shaped) so they can then be embedded in the concrete during casting (Figure 5-21(b)). Due to the shaping, the peg will be able to "*grip*" the cement paste and follow its contraction, allowing the measurement of the shrinkage of the test specimen once positioned on the instrument (positioning and measurement shown in Figure 5-21(d)).



(a) (b)

(c) (d)

Figure 5-21: Instrument used for measuring shrinkage (a); metal formwork, peg shaped and inserted at the ends of the metal forms (b); specimen for shrinkage measurement (c); specimen placed on the measuring instrument (d). Photos taken by Alan Piemonti.

Figure 5-24 shows the shrinkage trend for the 4 mixes considered and is the result of the average of the measurements in 3 specimens for each mix (3 measurements were therefore taken for each beam and the average of the individual beam was calculated, a further average of the average measurements of the 3 beams was then taken for each mix, in order to find the shrinkage value for the mix considered at the deadline considered, a procedure then repeated for each deadline).

The measured shrinkage was also compared with 2 different standard predictions: NTC 2018 [40] and Eurocode 2 [34]. The formulae and procedures adopted according to the aforementioned standards are illustrated below.

NTC 2018 [40]

The total shrinkage deformation is given by:

$$\varepsilon_{cs} = \varepsilon_{cd} + \varepsilon_{ca} \tag{5-7}$$

Where:

- ε_{cs} is the "*total shrinkage*" deformation;
- ε_{cd} is the "*drying shrinkage*" deformation;
- ε_{ca} is the "*autogenous shrinkage*" deformation.

In the present experimental campaign, only the "*drying shrinkage*" was considered and not the "*autogenous shrinkage*", which represents only a small percentage of the "*total shrinkage*". The development of the "*drying shrinkage*" over time is given by:

$$\varepsilon_{cd}(t) = \beta_{ds}(t - t_s) \cdot \varepsilon_{cd,\infty} \tag{5-8}$$

Where $\beta_{ds}(t - t_s)$ represents the time development function and $\varepsilon_{cd,\infty}$ represents the infinite-time average value of the "*drying shrinkage*" deformation.
In particular, the time development function is given by:

$$\beta_{ds}(t - t_s) = \frac{(t - t_s)}{\left[(t - t_s) + 0.04 \cdot \sqrt{h_0^3}\right]} \tag{5-9}$$

Where:

- t is the age of the concrete at the time considered [days];
- t_s is the age of the concrete from which the effect of "*drying shrinkage*" is considered (normally the end of curing, [days]);
- h_0 is the fictitious dimension [mm] equal to the ratio:

$$h_0 = \frac{2 \cdot A_c}{u} \tag{5-10}$$

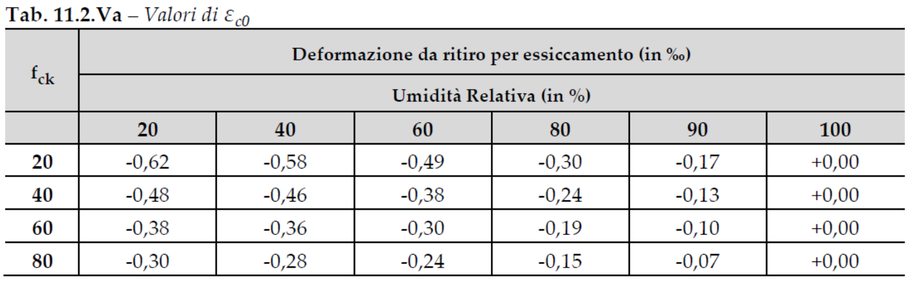
- A_c is the area of the concrete section;
- u is the perimeter of the concrete section exposed to air.

The infinite-time average value of the "*drying shrinkage*" deformation is given by the following formula:

$$\varepsilon_{cd,\infty} = k_h \cdot \varepsilon_{c0} \tag{5-11}$$

Where:

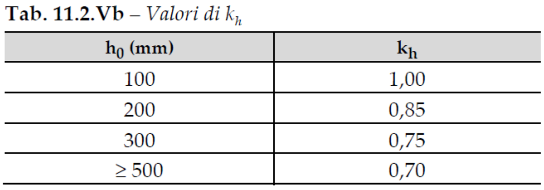
- ε_{c0} is given by Table 11.2.Va of NTC 2018 (Figure 5-22 of this document), as a function of the characteristic cylindrical compressive strength of concrete and relative humidity (in %);
- k_h is provided by Table 11.2.Vb of NTC 2018 (Figure 5-23 of the present document), as a function of the fictitious dimension h_0.



Tab. 11.2.Va – *Valori di* ε_{c0}

f_{ck}	Deformazione da ritiro per essiccamento (in ‰)					
	Umidità Relativa (in %)					
	20	**40**	**60**	**80**	**90**	**100**
20	-0,62	-0,58	-0,49	-0,30	-0,17	+0,00
40	-0,48	-0,46	-0,38	-0,24	-0,13	+0,00
60	-0,38	-0,36	-0,30	-0,19	-0,10	+0,00
80	-0,30	-0,28	-0,24	-0,15	-0,07	+0,00

Figure 5-22: Values of ε_{c0} (Table 11.2.Va of NTC 2018 [40]).



Tab. 11.2.Vb – *Valori di* k_h

h_0 (mm)	k_h
100	1,00
200	0,85
300	0,75
≥ 500	0,70

Figure 5-23: Values of k_h (Table 11.2.Vb of NTC 2018 [40]).

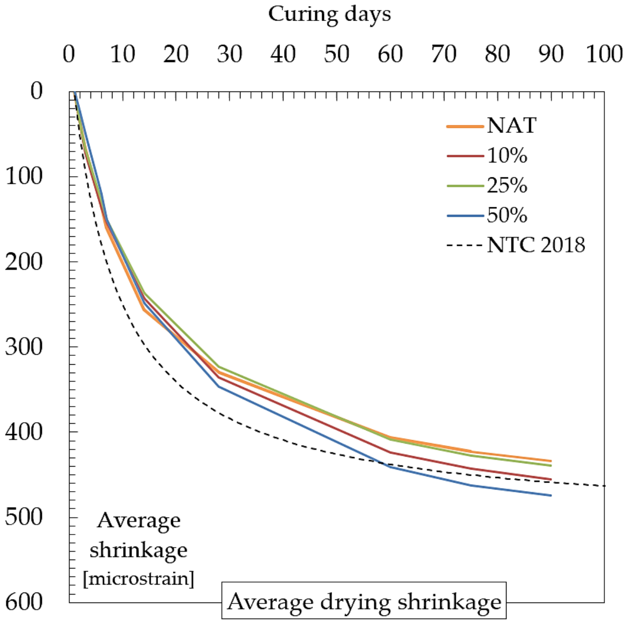


Figure 5-24: Average drying shrinkage trend for the 4 mixes considered and comparison with NTC 2018 prediction [40].

Figure 5-24 shows how the addition of EAFS-C in percentages up to 50% does not seem to lead to substantial changes in the drying shrinkage of the 4 mixes considered. A slight increase can be seen for the 10% and 50% mixes, from day 28 onward, compared to the reference NAT mix, but the differences are nevertheless minimal and the trend is in line with that predicted by NTC 2018 [40]. The results obtained are in line with those found in the literature, where similar drying shrinkage trends between EAFS-C concretes and reference concretes have also been recorded [29,38], highlighting how the shrinkage phenomenon is essentially related to the behaviour of the cement matrix and only minimally dependent on the aggregate [38]. It should be noted that Coppola *et al* [31] obtained higher shrinkage for the EAFS-C mixes compared to the reference mix. According to the Authors, the higher water absorption of the slag compared to natural aggregate led to higher shrinkage; a solution could be to soak the slag in water before casting, in order to guarantee its saturation and reduce the risk of water absorption from the mix once introduced into it, with consequent control and reduction of the shrinkage phenomenon (proceed performed in this experimental campaign and described in detail in Section 5.3).

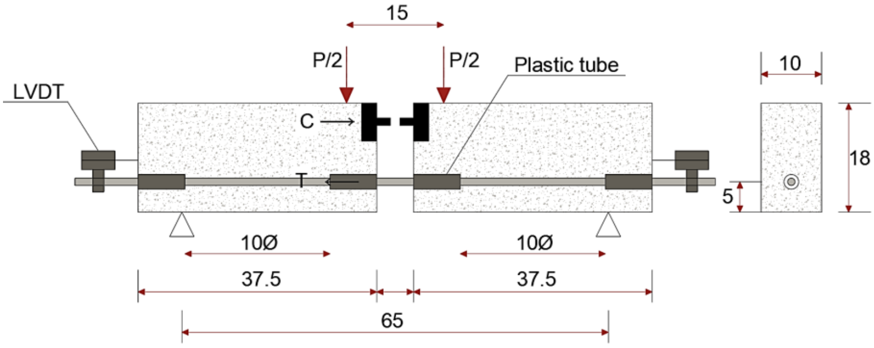
5.4.2.5 Beam test

Once the rheological properties in the fresh state and the strength properties in the hardened state have been analysed, a key factor for the correct use of structural concrete certainly lies in how the bond between the concrete and the steel bar embedded in it develops. The addition of different materials other than those typically used leads to a change in the mix composition, which may also affect the bond behaviour. It is therefore extremely important to investigate whether the addition of different percentages of EAFS-C in partial substitution of natural aggregates may affect the bond. In summary, the bond between concrete and steel bar depends on several factors: available bond length, bar diameter and rib geometry, possible presence of transverse reinforcement, resistance to splitting crack development provided by the concrete cover, method of casting execution, etc. [41].

There are several types of tests for the evaluation of the bond between steel bar and concrete present in the literature and calibrated on so-called "*conventional*" or "*ordinary*" concretes. The execution of these tests also on "*non-ordinary*" concretes, such as for example those with the addition of steelmaking slags, is therefore of fundamental importance in order to understand whether their behaviour can be represented by the empirical formulations proposed in the literature and compared with that of reference "*ordinary*" concrete [41].

Among the tests for the evaluation of the bond between steel bar and concrete, the most widely used is the "*pull-out test*" [42]. In a very brief summary, in this test a steel bar is placed in the centre of a cubic concrete specimen. During the test, the bar is pulled out and the pulling force is measured at one end while the displacement is measured at the other end [43]. However, the application and actual representativeness of the phenomenon given by the pull-out test finds conflicting opinions among researchers. In fact, some praise its simple and easy execution [44], others the accuracy of the results [45] and the fact that it takes into account all the variables for an appropriate study of the phenomenon [46]. On the other hand, other researchers have highlighted how the set-up of the pull-out test is not entirely representative of any real situation, in several aspects: reduced embedded length, large concrete cover, presence of friction between the bottom support plate and the specimen, optimal casting conditions compared to those normally found in real practice (good compaction, reduced voids around the bar, different ratio between the strength of the bar near the top and near the bottom surface of the casting, etc.) [41].

In addition to the pull-out test, another test available in the literature for evaluating the steel–concrete bond is the "*beam test*" (proposed by RILEM RC5 [47] and adopted by EN 10080 [25]). It essentially consists of a 4-point load test performed on the type of specimen shown in Figure 5-25.

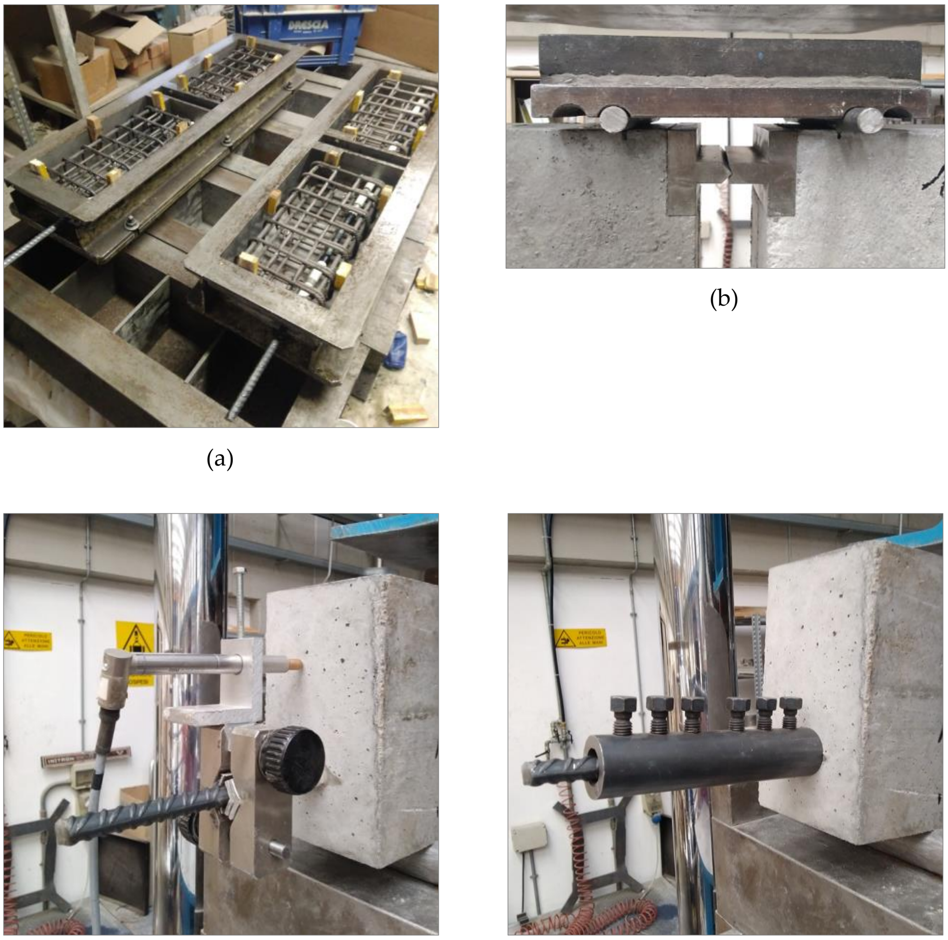


(a)

(b)

Figure 5-25: Details on the measurements (in cm) of the beam test specimen ((a), adapted from [43]); example of a test specimen (NAT mix) cast and used for the test in the present experimental campaign (b), for steel bar $\phi < 16mm$. Photo taken by Alan Piemonti.

The test specimen consists of two separate concrete blocks cast in special metal formwork (Figure 5-26(a)), into which a steel bar is embedded, connecting them. The bar sections at the end are "*insulated*" by means of plastic sleeves in order to avoid contact between the bar and concrete and to ensure a well-defined bond length (equal to 10ϕ, with ϕ diameter of the bar). Before the test, two metal hinges are placed in the appropriate mouldings in the upper part of the blocks (Figure 5-26(b)) due to the special shape of the formwork. After applying the appropriate instrumentation to the ends of the two blocks (Figure 5-26(c)), a force F is applied (continuously) at two points symmetrical to the centre of the specimen. The entire specimen bends and, using the aforementioned instrumentation, the slip of the bar towards the inside of the block is measured. However, the bar does not move in the same way in the two blocks and, once a certain load value is reached, the slip of the bar in one of the two blocks stops while the slip in the other block continues up to a predetermined value (imposed by EN 10080 [25] and shown below). Once this slip has been reached in one of the two block, the test is temporarily stopped, the slip measuring instrument is removed and a "*locking*" instrument is applied, which adheres to the end of the block and which "*hooks*" onto the bar by means of appropriate shaped screws (Figure 5-26(d)), so as to prevent further sliding of the bar in the block considered. The test is then restarted and, after a small drop and a resumption of load *F*, the bar also begins to move in the second block until the same slip value is reached as previously obtained for the first block, after which the test is interrupted.



(a)

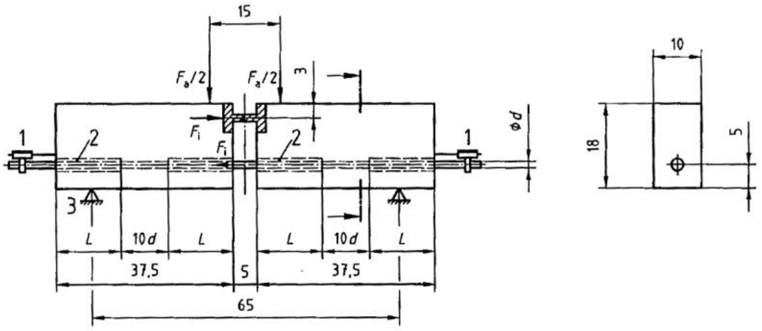
(b)

(c)

(d)

Figure 5-26: Metal formwork for casting specimens (a); metal hinges and support for load application (b); slip measuring instrument (LVDT) (c); “locking” instrument (d). Photos taken by Alan Piemonti.

Depending on the bar diameter, the standard provides two different sizes for the specimens (Figure 5-27), as well as providing construction details for the internal transverse reinforcement and metal hinge [25].

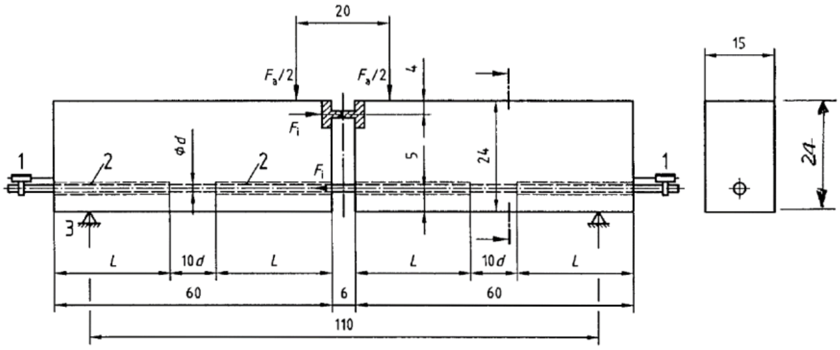


Key

1 slip measuring device
2 plastic sleeves
3 movable support

Figure C.3 — Beam test type A (d < 16 mm)

(a)



Key

1 slip measuring device
2 plastic sleeves
3 movable support

Figure C.4 — Beam test type B ($d \geq$ 16 mm)

(b)

Figure 5-27: Details on the measurements (in cm) of the beam test specimen for steel bar $\phi < 16mm$ (a) and for steel bar $\phi \geq 16mm$ [25].

As for the pull-out test, there are conflicting opinions in the literature on the actual representativeness of the steel–concrete bond. In particular, with regard to the positive aspects, in the "*beam test*" the anchorage zone of the bar is in good condition and the bond length is 10ϕ (double that of the pull-out test). On the other hand, there are also some critical aspects such as the very high transverse reinforcement density, the almost constant concrete cover (regardless of the diameter of the bar), the impossibility of measuring the bar slip at final load and the difficult handling due to the size and shape of the specimen [41].

In light of this and having clearly understood that a complete study on the bond phenomenon is not possible by means of beam tests alone, in the present experimental campaign it was decided to implement this type of test in order to preliminarily investigate the bond behaviour, considering the better conditions offered and the greater bond length with respect to the pull-out test. However, a possible in-depth study can be conducted by means of tests on other more complete and complex types of specimens (e.g., the "*beam end test*" proposed in [41]).

Two specimens were produced and tested (after being cured for 28 days in a chamber with relative humidity ≥95% and temperature (20±2)°C) for each of the 4 mixes considered, with a steel bar diameter ϕ of 12 mm (the dimensions of the specimens are therefore as shown in Figure 5-25 or Figure 5-27(a)). During the test, the force F was applied continuously and the following parameters were calculated for each slip value required by the standard [25]:

- Stress in the steel bar (for $\phi < 16\ mm$):

  $$\sigma_s = \frac{1.25 \cdot F_a}{A_n} \tag{5-12}$$

  (where F_a is the total force applied to the test specimen and A_n is the nominal cross-sectional area of the reinforcing steel)

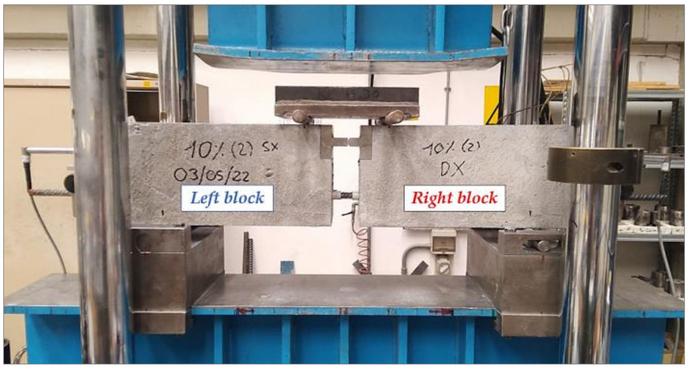
- Bond stress:

  $$\tau_b = \frac{\sigma_s}{40} \tag{5-13}$$

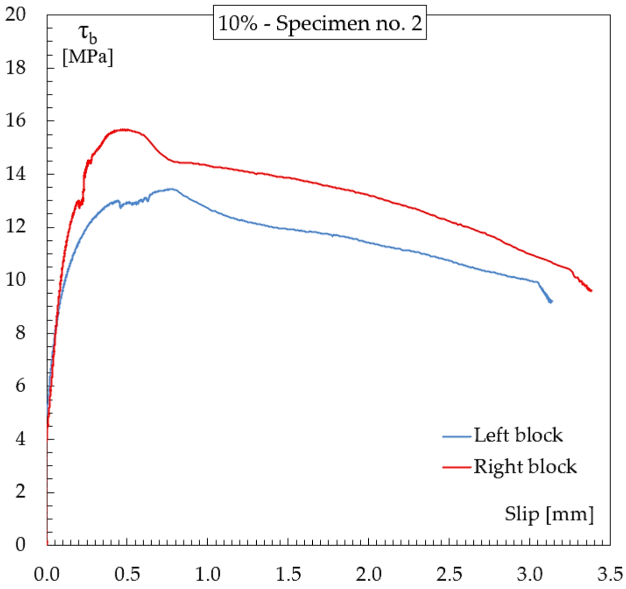
According to the standard, the bond stress must be calculated at imposed and predefined slip values:

- $\tau_{b,0.01}$: bond stress at 0.01 mm slip;
- $\tau_{b,0.1}$: bond stress at 0.1 mm slip;
- $\tau_{b,1}$: bond stress at 1 mm slip;
- $\tau_{b,3}$: bond stress at 3 mm slip (not required by the standard but added in this experimental campaign);
- τ_{bu}: bond stress at maximum force F_a.

Figure 5-28(a) shows an example of a specimen ready for the test and Figure 5-28(b) shows the corresponding bond stress–slip graph obtained by processing the test data and comparing the trend of the left and right block of the specimen.



(a)



(b)

Figure 5-28: Example of a specimen ready for the test (a) and corresponding bond stress–slip graph obtained by processing the test data and comparing the trend of the left and right block of the specimen (b). Photo taken by Alan Piemonti.

Table 5-15 shows the results in terms of average values of the bond stresses obtained from the 2 specimens tested for each of the 4 mixes considered. The Coefficient of Variation *"CV"* (in brackets) and the difference in terms of increase/decrease of the bond stress of the mixes with EAFS-C compared to the reference NAT mix (in percentages and italics) are also shown.

Table 5-15: Average values of the bond stress of the 4 concretes considered. Coefficient of Variation "CV" (in brackets) and difference between the values of the EAFS-C mixes compared to those of reference NAT mix (in percentages and italics).

Bond stress	***NAT***	***10%***	***Diff.***	***25%***	***Diff.***	***50%***	***Diff.***
$\tau_{b,0.01}$ [MPa]	6.05	4.51	*-25.4%*	3.90	*-35.5%*	6.02	*-0.5%*
	(0.187)	*(0.167)*		*(0.193)*		*(0.219)*	
$\tau_{b,0.1}$ [MPa]	12.09	10.16	*-16.0%*	10.41	*-13.9%*	10.67	*-11.8%*
	(0.171)	*(0.035)*		*(0.037)*		*(0.139)*	
$\tau_{b,1}$ [MPa]	14.29	13.87	*-2.9%*	14.85	*+3.9%*	13.75	*-3.7%*
	(0.054)	*(0.049)*		*(0.021)*		*(0.061)*	
$\tau_{b,3}$ [MPa]	11.82	11.21	*-5.1%*	12.19	*+3.1%*	11.30	*-4.4%*
	(0.083)	*(0.074)*		*(0.038)*		*(0.079)*	
τ_{bu} [MPa]	15.56	14.70	*-5.5%*	15.51	*-0.3%*	14.14	*-9.2%*
	(0.046)	*(0.056)*		*(0.033)*		*(0.078)*	

The great difference in the values of the bond stresses (τ) calculated for very low slips (0.01 and 0.1 mm), even in relation to rather high coefficients of variation, can be explained by the difficulty of controlling the specimen in the initial phases of the test and by the difference in terms of strength of the mixes considered. The shape and dimensions of the specimen, together with the difficulty and the great care that must be observed during its handling and positioning phases, cause inevitable movements of the steel bar inside it. These relative movements, although apparently imperceptible, could affect the behaviour of the specimen in the initial phases of the test, especially for such small slips (hundredths and tenths of a millimetre). Once the initial phase and the relative critical aspects had been overcome, the mixes then exhibited very similar behaviour, with differences in bond stresses (τ) never exceeding 6% (with the exception of the τ_{bu} of the 50% mix) and reduced coefficients of variation.

5.4.2.6 Tension ties

After having preliminarily investigated the behaviour of the mixes with the addition of EAFS-C with regard to the bond between steel and concrete, this part of the experimental campaign aims to study the development of the crack pattern in the same concretes. In fact, cracking is a phenomenon that characterises concrete structures in service conditions, generating more or less preferential pathways for the penetration of external agents (water, CO_2, chlorides, etc.), able to affect the normal life cycle of the structure and any steel reinforcement present in it. In light of this, several international standards have begun to specify admissible crack widths depending on service life and exposure conditions [48].

In order to investigate whether concrete with the addition of different percentages of EAFS-C has similar or different behaviour compared to natural concrete in terms of crack formation, opening and spacing, a particular type of prismatic specimen, hereafter referred to as "*tension ties*" was produced and tested (following the example of those studied by Leporace-Guimil *et al* [48] for corrosion tests on fibre-reinforced concrete).

Details and geometric characteristics of tension ties are shown in Figure 5-29. They thus represent the lower part of a bent beam, where the reinforcement embedded in it is subjected to tension (these specimens are often used for the study and comparison of the crack patterns of ordinary and fibre-reinforced concretes [48]).

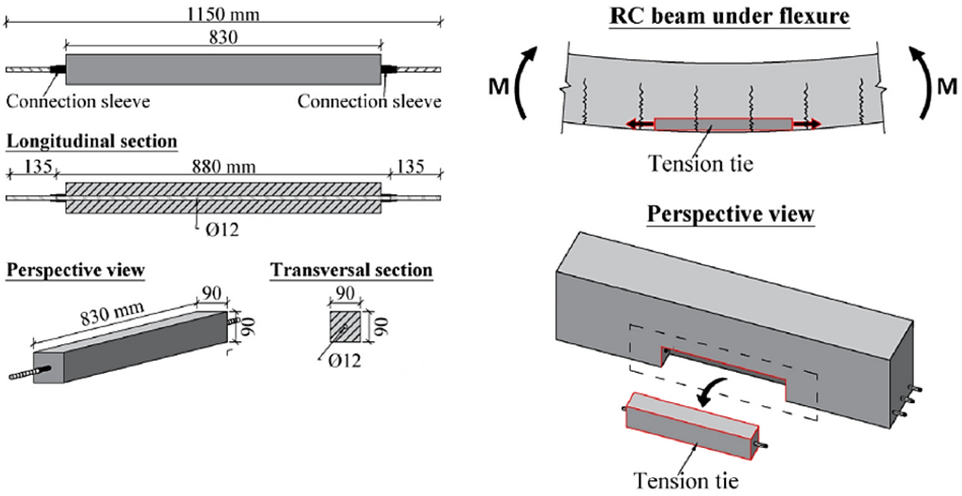


Figure 5-29: Details and geometric characteristics of tension ties (adapted from [48]).

As previously mentioned, the tension ties are prisms with a length of 830 mm (so that at least 4–5 cracks can develop, according to *fib* Model Code 2010 [35]) and a 90x90 mm^2 cross-section. For each specimen, a steel bar (ϕ12, derived from the same batch as those used for the beam tests (Section 5.4.2.5 of this document) and used as received from the producer) is placed along the axis of the specimen, resulting in concrete cover of 39 mm and an effective reinforcement ratio $\rho_{s,eff} = A_s/A_{c,eff} = 1.40\%$. In order to be able to make a comparison with the results of the tensile tests performed on the tension ties, further tensile test were also performed on "*bare*" steel bar sections with a length of approximately 550–600 mm, obtaining the load-strain curve, the yielding stress ($f_y = \sim 550\ MPa$) and the failure stress ($f_u = \sim 660\ MPa$).

Once cast, the specimens were cured in a chamber with relative humidity ≥95% and temperature (20±2)°C for 28 days and then tested.

3 tension ties were cast and tested for each of the 4 mixes considered, for a total of 12 specimens. The test consisted of tensile stressing the element (by means of a monotonically applied load), by placing it on the machine using the two pieces of bar protruding from the ends of the specimen. A Linear Variable Displacement Transducers ("*LVDT*") was placed on each side of the specimen in order to measure the elongation on each side and then take an average (Figure 5-30).

Each test on each specimen was temporarily stopped at load steps of 40 and 50 kN (corresponding to stresses in the bar of 350 and 450 MPa, respectively). At these 2 steps, photographs of the cracks were taken using a digital microscope. Then, from each photo, 3 measurements were taken for each crack on each side of the specimen. Next, the average crack width was calculated for each crack on each side, then the average of the 4 sides and finally the average crack width for each specimen.

The test results in terms of load-strain curves are shown in Figure 5-31. The strain was calculated by taking an average of the elongation obtained from the 4 LVDTs placed one on each side of the specimen. The average load-strain curves of each mix were also compared with the average curve obtained from the tensile tests on the "*bare*" rebar sections (3 sections for each mix, as previously mentioned, visible in red in Figure 5-31). As can be seen from the graph, the response of all 4 mixes considered was characterised by 3 phases [48]:

(1) Initial uncracked stage, which extends up to the cracking load of the specimen (P_{cr});
(2) Cracked stage, which in turn is divided into two sub-stages: crack formation stage and stabilized crack stage;
(3) Steel yielding stage.

The average values of the different parameters recorded during the tests or processed subsequently are shown in Table 5-16, in which the Coefficient of variation "*CV*" (in brackets) and the difference in terms of increase/decrease (in

percentages and italics) of the values of the mixes with EAFS-C compared to those of the reference NAT mix are also highlighted.
In particular, the parameters included in Table 5-16 are:

- P_{cr}: first crack load of the specimen;
- ε_{40}: strain at a load value of 40 kN;
- ε_{50}: strain at a load value of 50 kN;
- w_{40}: average crack width at a load value of 40 kN;
- w_{50}: average crack width at a load value of 50 kN;
- s_r: mean measured crack spacing (average value considering the 4 sides of the specimen);
- $s_{r,MC2010}$: predicted crack spacing, calculated according to *fib* Model Code 2010 [35];
- $s_r/s_{r,MC2010}$: ratio between measured and predicted crack spacing.

The *fib* Model Code 2010 [35] proposes a relationship for the prediction of the crack spacing. The formula considered in the present experimental campaign is the one derived by Tiberti *et al* [49] for RC members, starting from the models for evaluating the expected crack width and mean crack spacing of *fib* Model Code 1978 [50] and *fib* Model Code 2010 [35]:

$$s_{r,MC2010} = 1.17 \cdot l_{s,max} = 1.17 \cdot \left[k \cdot c + \frac{1}{4} \cdot \frac{\phi}{\rho_{s,eff}} \cdot \frac{f_{ctm}}{\tau_{bm}}\right] \tag{5-14}$$

Where:

- $l_{s,max}$: length over which slip between concrete and steel occurs (the steel and concrete strains, which occur within this length, contribute to the width of the crack);
- k: empirical parameter to take into account the influence of the concrete cover, assumed to be 1 for simplification;
- c: concrete cover (39 mm in the present study);
- ϕ: bar diameter (12 mm in the present study);
- $\rho_{s,eff} = A_s/A_{c,eff}$: effective reinforcement ratio (1.40% in the present study). A_s is the cross-section area of the steel bar and $A_{c,eff}$ is the effective area of concrete in tension;
- f_{ctm}: mean concrete tensile strength (calculated with the eq. 5.1-3a of *fib* Model Code 2010 [35]);
- τ_{bm}: mean bond strength between steel and concrete (assumed as $1.8 \cdot f_{ctm}$, Table 7.6-2 of *fib* Model Code 2010 [35]).

Figure 5-30: Example of a tension tie during the test. Photo taken by Alan Piemonti.

Table 5-16: Average values of the different parameters recorded during the tests or processed subsequently, for the 4 concretes considered. Coefficient of Variation "CV" (in brackets) and difference between the values of the EAFS-C mixes compared to those of reference NAT mix (in percentages and italics).

Parameter	***NAT***	***10%***	***Diff.***	***25%***	***Diff.***	***50%***	***Diff.***
P_{cr} [kN]	28.2	22.0	*-22.1%*	28.6	*+1.4%*	22.9	*-18.8%*
	(0.089)	*(0.059)*		*(0.038)*		*(0.068)*	
ε_{40} [‰]	1.060	1.083	*+2.2%*	1.016	*-4.2%*	1.005	*-5.2%*
	(0.088)	*(0.097)*		*(0.129)*		*(0.059)*	
ε_{50} [‰]	1.612	1.588	*-1.5%*	1.582	*+1.8%*	1.477	*-8.4%*
	(0.031)	*(0.009)*		*(0.028)*		*(0.057)*	
w_{40} [mm]	0.185	0.156	*-15.5%*	0.169	*-8.6%*	0.165	*-11.0%*
	(0.097)	*(0.025)*		*(0.035)*		*(0.050)*	
w_{50} [mm]	0.272	0.243	*-10.4%*	0.257	*-5.5%*	0.244	*-10.3%*
	(0.059)	*(0.116)*		*(0.054)*		*(0.023)*	
s_r [mm]	164.2	140.2	*-14.6%*	171.5	*+4.5%*	150.8	*-8.1%*
	(0.075)	*(0.104)*		*(0.066)*		*(0.085)*	
$s_{r,MC2010}$ [mm]	183.3	183.3		183.3		183.3	
$s_r/s_{r,MC2010}$ [-]	0.90	0.76		0.94		0.82	

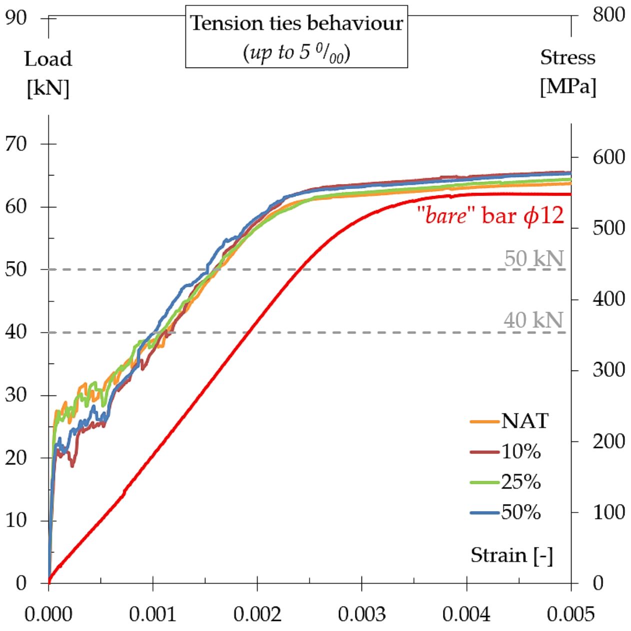


Figure 5-31: Results of the test on tension ties of each of the 4 mixes considered in terms of load-stress-strain curves and comparison with the average curve obtained from the tensile tests on the "bare" rebar sections.

From Table 5-16 it can be seen that the strains recorded at loads of 40 and 50 kN (ε_{40} and ε_{50}) for EAFS-C specimens are comparable or slightly lower than those of the reference concrete specimens (NAT). The same considerations can be made regarding the average crack widths at the same load steps (w_{40} and w_{50}), with lower values than the average crack widths of the reference concrete. Depending on the substitution percentage, the average crack spacings (s_r) of the EAFS-C tension ties are also comparable to or lower than those of the reference concrete. In spite of comparable or lower P_{cr}, the behaviour in terms of post-crack stiffness and crack pattern is quite similar among the different mixes. Considering also the results obtained in the tests for the evaluation of the tensile strength and the steel-concrete bond (comparable values among the different mixes), the models present in the standard for the prediction of the behaviour in terms of crack width and spacing and the tension stiffening of traditional concrete can also be adopted for EAFS-C concretes. Finally, all tension ties tested recorded the formation of 4 cracks, with the exception of the specimen no. 2 of the 10% mix, which recorded 5 cracks.

5.4.2.7 Resistance of capillary absorption

The characteristics, size and connection between the pores in concrete depend on several factors, the main ones being the water/cement ratio, the air content in the fresh state and the hydration degree. The evaporation of the residual water in concrete (i.e. the water that has not participated in hydration processes), together with the air bubbles already present in the fresh state, results in what is known as "*total porosity*". The capillary action, i.e. the penetration of water into the concrete through the aforementioned pores, also depends on several factors; in addition to the internal structure of the concrete, the phenomenon is in fact strongly influenced by temperature and humidity, and any water pressure other than atmospheric pressure. Depending on the entity of the phenomenon, degradation may occur in the concrete (corrosion due to carbonation) or in the steel reinforcement if the water transports aggressive substances (chlorides, sulphates, etc.), thus affecting the durability of the considered element.

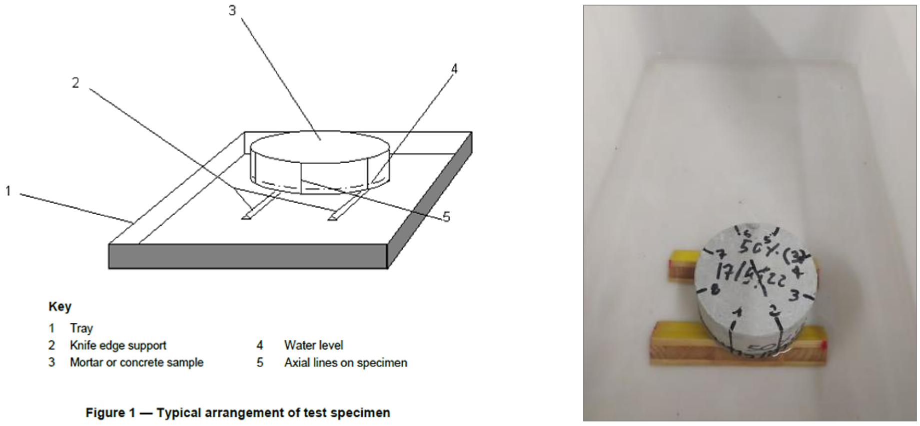
The characteristics of the pores in a concretes made with materials (such as EAFS-C) different from those commonly used may be more or less different to those of a standard concrete. An assessment of the resistance to water penetration by capillary absorption is therefore of fundamental importance for evaluating the behaviour of these types of concrete, and a comparison with the behaviour of the reference concrete then helps highlight any possible advantages or critical aspects.

According to the specifications of EN 13057 [26], a test was performed to assess the resistance of water penetration by capillary absorption on the 4 mixes considered in this experimental campaign, evaluating 3 different parameters: the water uptake per unit area (i), the sorption coefficient (S) and the time to completion of capillary saturation (t_c).

For each of the 4 mixes considered, the tests were carried out on 3 cylinders with a diameter of 100 mm and a height of 60 mm (the standard requires the height of the cylinder to be at least 20 mm or three times the maximum size of the aggregate used), for a total of 12 cylinders tested. As no moulds with a diameter of 100 mm and a height of 60 mm were available, cylindrical moulds with a diameter of 100 mm and a height of 200 mm were used. The test specimens thus obtained were then cut perpendicular to the axis at a height of 60 mm, taking care during the test to place the cylinder surface subject to the cut in contact with water (as prescribed by the standard).

The test specimens were cured as follow: 27 days in a chamber with relative humidity ≥95% and temperature (20±2)°C, 7 days in the laboratory at room temperature (21±2)°C and humidity (60±10)% plus 7 days in an oven at (40±2)°C, in order to obtain specimen of constant mass.

Still according to the standard, each test specimen was weighted and its dimension were recorded with a calibre before the test. With an indelible marker, eight equally spaced axial lines were then marked on the lateral surface along the entire height of the specimen. Each specimen was then placed on specially cut wooden triangular supports, with the cut surface facing downwards and in contact with water. In addition to the base surface, the lateral surface of the cylinder was also partially submerged to a maximum of (2±1) mm. Figure 5-32 shows a comparison between the requirements of the standard and the specimens during the test.



(a) (b)

Figure 5-32: Comparison between the requirements of the EN 13057 [26] (a) and the specimens during the test (b). Photo taken by Alan Piemonti.

12 measurement intervals of the capillary rising front were considered. In the initial phase, the standard time intervals (12 min, 30 min, 1h, 2hrs, 4hrs and 24hrs, required for the evaluation of the sorption coefficient (S)) were considered, while 6 further measurements at time intervals subsequent to 24hrs were carried out for the evaluation of the time to completion of capillary saturation (t_c, i.e. the time at which the rising front reaches the top surface of the specimen).

During each measurement, the specimen was removed from the water and carefully dried with paper towels to remove excess water, it was weighted (balance with an accuracy of 0.01g) and the level of the rising front was marked by means of dashes on the 8 axial lines first drawn on the lateral surface of the cylinder (all these operations took 2 minutes).

The following parameters were obtained from the test results:

- *Water uptake per unit area* (i) [kg/m^2], calculated for each time interval by dividing the weight of water absorbed [kg] by the base surface area of the specimen [m^2]. For each time interval, the weight of the absorbed water was calculated by subtracting the initial weight of the cylinder from the weight of the cylinder at the time interval considered;

- *Sorption Coefficient* (*S*) [kg/(m^2·h$^{0.5}$)], obtained by plotting on a graph the water uptake per unit area (*i*) against the square root of the "*immersion*" time (h$^{0.5}$, where h stands for hours).

The standard distinguishes 3 different possibilities for the calculation of the sorption coefficient (*S*):

(1) Linear behaviour (Figure 5-33). The sorption coefficient (*S*) is given by the slope of the resulting line;

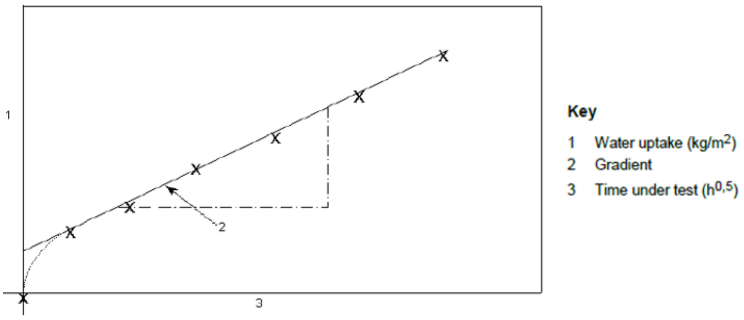


Figure 2 — Linear graph

Figure 5-33: Water uptake per unit area (i) vs. square root of "immersion" time (h$^{0.5}$) – Linear behaviour [26].

(2) Linear behaviour with a flat end portion (Figure 5-34). This occurs when the specimen has reached its complete saturation before the end of the test period (i.e. the rising front reaches the top of the specimen before 24hrs). The sorption coefficient (*S*) is given by the slope of the initial linear portion of the graph;

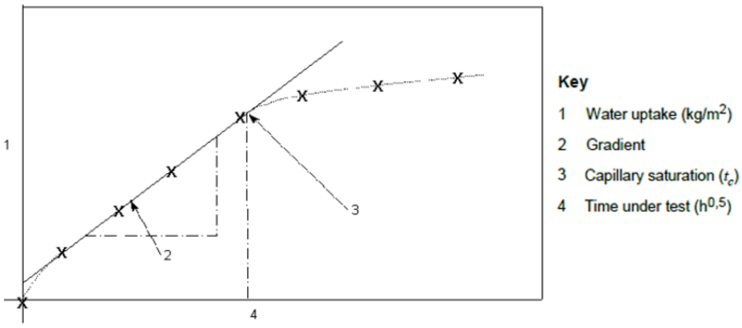


Figure 3 — Specimen fully saturated

Figure 5-34: Water uptake per unit area (i) vs. square root of "immersion" time (h$^{0.5}$) – Linear behaviour with a flat end portion [26].

(3) Non-linear behaviour (Figure 5-35). This occurs when the material properties change with depth or when the system changes over time. The sorption coefficient (*S*) is given by the slope of the intercept at the last measurement (24hrs).

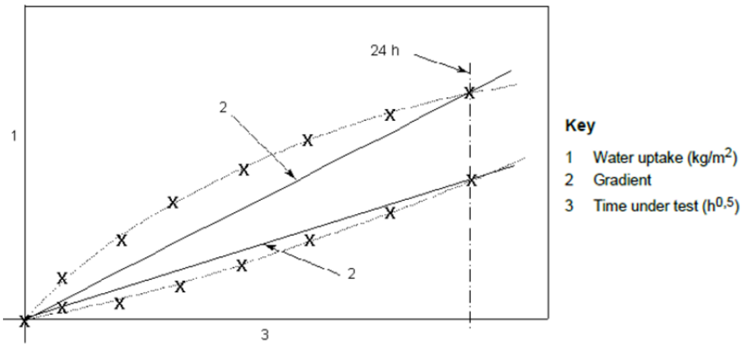
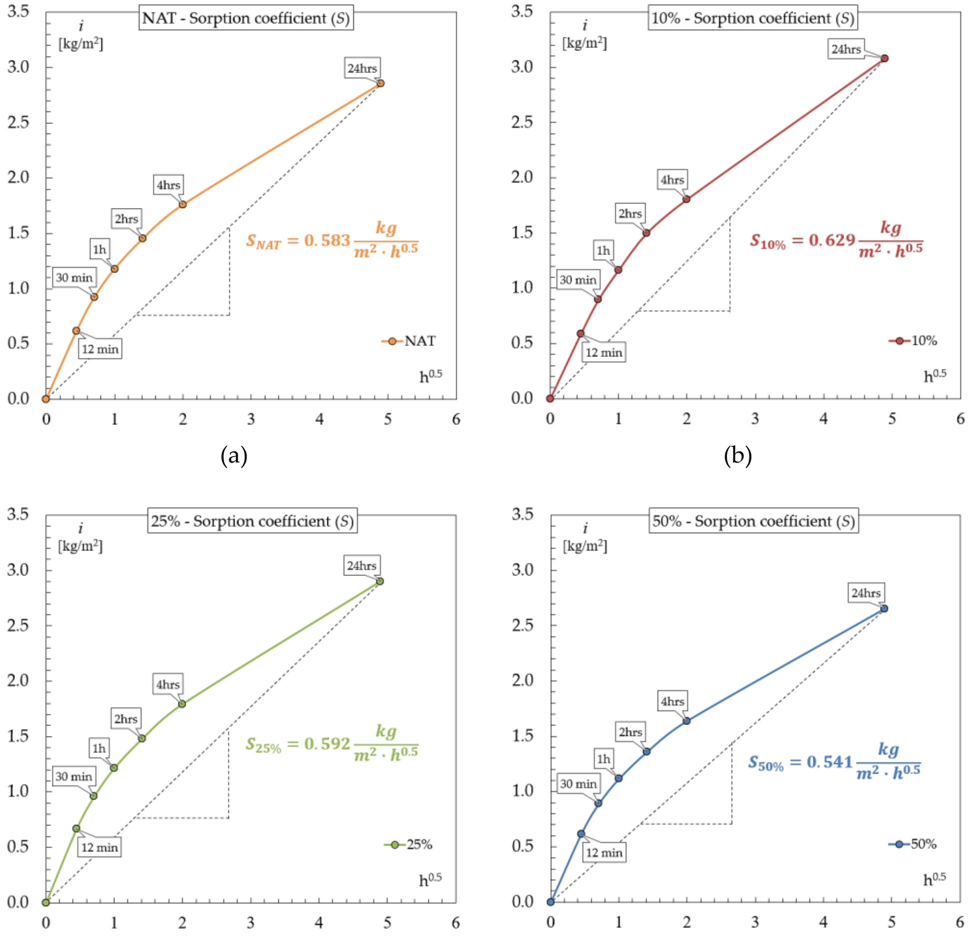


Figure 4 — Non-linear graph

Figure 5-35: Water uptake per unit area (i) vs. square root of “immersion” time ($h^{0.5}$) – Non-linear behaviour [26].

Figure 5-36 shows the mean results of the test performed on 3 cylinders for each of the 4 mixes analysed. All 4 graphs obtained correspond to the possibility no. (3) of the standard (Figure 5-35) and therefore the sorption coefficients (*S*) were given by the slope of the intercept at the 24hrs measurement.

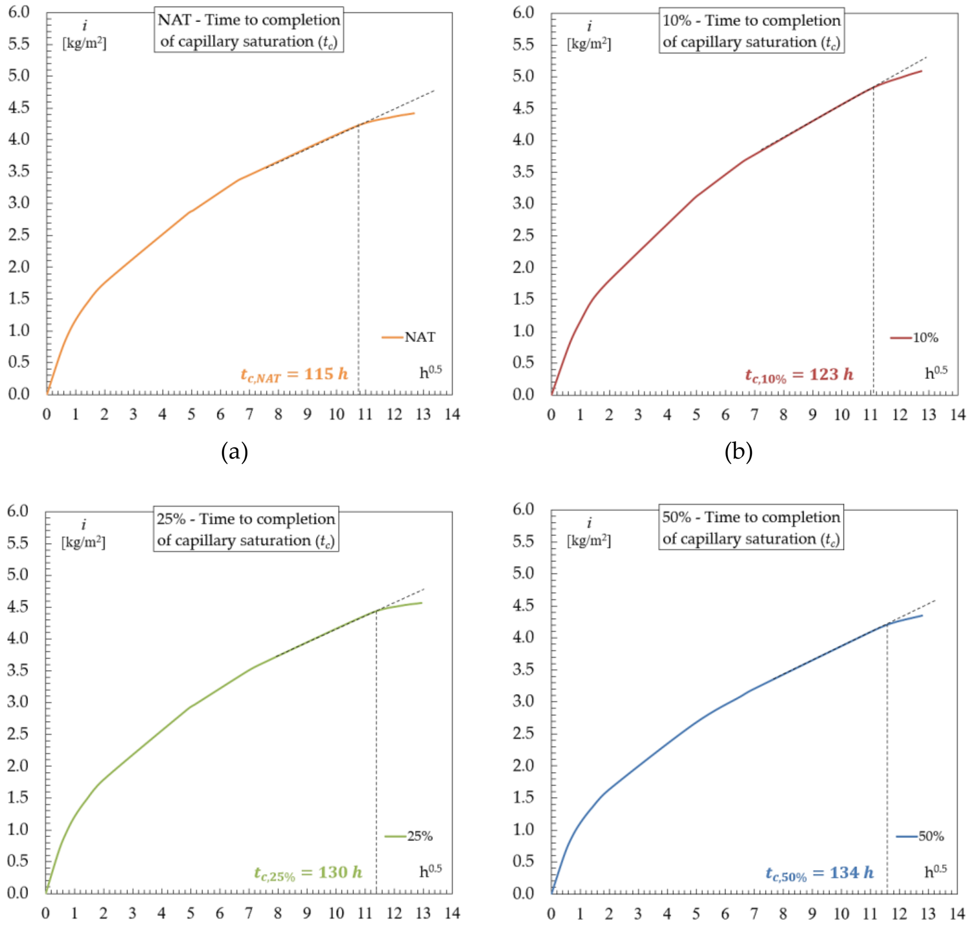


(a) (b)

(c) (d)

Figure 5-36: Mean results of the test performed on 3 cylinders for each of the 4 mixes analysed. Sorption coefficients (S) for NAT (a), 10% (b), 25% (c) and 50% (d) mixes.

As previously described, the time to completion of capillary saturation (t_c) was instead calculated by means of measurements after 24hrs, again plotting the water uptake per unit area (*i*) against the square root of the "*immersion*" time ($h^{0.5}$, where h stands for hours), as shown in Figure 5-37 (average of the measurements on 3 cylinders for each of the 4 mixes analysed).



(a) (b)

(c) (d)

Figure 5-37: Mean results of the test performed on 3 cylinders for each of the 4 mixes analysed. Time to completion of capillary saturation (t_c) for NAT (a), 10% (b), 25% (c) and 50% (d) mixes.

For a better understanding, Figure 5-38 shows a comparison of the average results of the 4 mixes. Finally, Table 5-17 summarises the results for the sorption coefficient (*S*) and the time to completion of capillary saturation (t_c). The Coefficient of Variation "*CV*" (in brackets) and the difference in terms of increase/decrease of the results of the mixes with EAFS-C compared to those of the reference NAT mix are also shown (in percentages and italics).

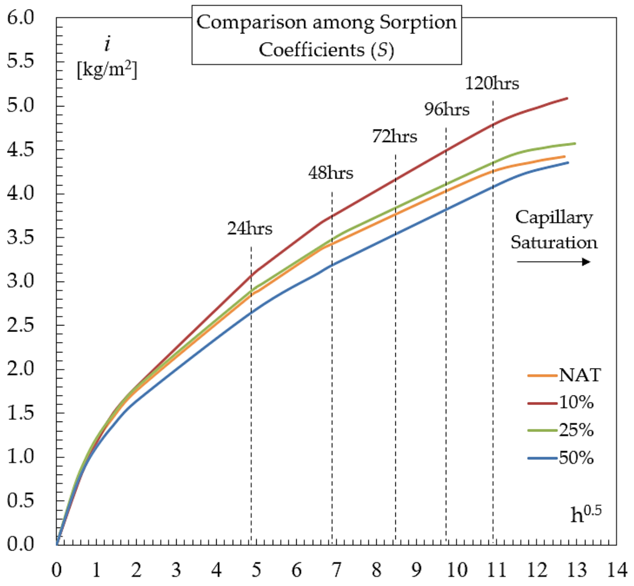


Figure 5-38: Mean results of the test performed on 3 cylinders for each of the 4 mixes analysed (NAT (a), 10% (b), 25% (c) and 50% (d) mixes).

Table 5-17: Mean values of the sorption coefficient (S) and the time to completion of capillary saturation (t_c). Coefficient of Variation "CV" (in brackets) and difference between the values of the EAFS-C mixes compared to those of reference NAT mix (in percentages and italics).

Parameter	***NAT***	**10%**	***Diff.***	**25%**	***Diff.***	**50%**	***Diff.***
S [kg/(m²·h$^{0.5}$)]	0.583	0.629	*+7.9%*	0.592	*+1.6%*	0.541	*-7.1%*
	(0.051)	*(0.008)*		*(0.033)*		*(0.013)*	
t_c [h]	115	123	*+6.8%*	130	*+12.9%*	134	*+16.2%*
	(0.011)	*(0.012)*		*(0.006)*		*(0.028)*	

The test results show that the addition of EAFS-C as partial replacement of the natural aggregate does not lead to substantial differences in the capillary water absorption of the concrete. With regard to the sorption coefficient (*S*), a slight increase compared to the NAT mix was recorded in the 10% and 25% mixes (i.e. for the same area and time, the phenomenon of absorption by capillarity was slightly more intense, with water uptake per unit area (*i*) being more or less higher). On the other hand, the 50% mix showed a reduction in the sorption coefficient (*S*) of around 7% (i.e. for the same area and time, the phenomenon of absorption by capillarity was less intense, with lower water uptake per unit area (*i*) when compared to other mixes). However, these values are very close to each other, with differences of no more than 8%. These results are also in line with those present in other studies in the literature where, depending on the mix analysed and the standard used (and therefore also on the possible different shape and size of the specimens), the addition of EAFS-C did not lead to substantial differences in the resistance to water absorption by capillarity of concrete [28].

As the percentage of natural aggregate-EAFS-C substitution increased, the time to completion of capillary saturation (t_c) also increased (i.e. the rising front of the EAFS-C mixes took longer to reach the top of the specimen compared to the NAT mix), with t_c increases up to 16% (50% mix compared to NAT mix). This depends on the internal structure and the organisation and distribution of the pores in the concrete considered.

5.5 Concluding remarks

In this experimental campaign, 4 structural concrete mixes with the addition of different percentages of EAFS-C (0, 10, 25 and 50%) in partial replacement of natural fine and coarse aggregates were studied and analysed. The behaviour (in terms of rheological properties, strength and durability) of the mixtures with the addition of slag was compared to that of a reference structural concrete mix. Due to the addition of low doses of superplasticiser admixture, it was possible to control the workability of the different mixes, all of which were classified with consistency class S4. The air content values are also comparable with each other, with the exception of the 50% mix, which exhibited a value 26% lower than that of the reference mix. The concrete density increased as the replacement percentage increased, due to the higher slag density compared to natural aggregate. Increases in compressive strength and elastic modulus were recorded as the substitution percentage increased, while comparable results between the different mixes were obtained with regard to tensile strength. The addition of slag did not seem to substantially influence the drying shrinkage of the mixes. The bond stresses between steel and concrete, evaluated by means of beam tests, recorded very similar values between the mixes, apart from the critical aspects found in the initial part of the test with regard to the evaluation of the bond stresses at small slips (0.01 and 0.1 mm). Comparable behaviour between the different mixes was also recorded regarding the development, opening and spacing between cracks (assessed by means of tensile tests on tension ties). The calculation models found in the standards and calibrated for ordinary structural concretes can thus be used to study and analyse the behaviour of concrete mixes with the addition of EAFS-C in terms of crack opening and spacing, as well as tension stiffening. Finally, the sorption coefficients (S) of the 4 mixes were found to be very similar to each other and a slight improvement in terms of time to completion of capillary saturation (t_c) was noted as the replacement percentage increased.

The results obtained are in line with those found in the literature and once again confirm the possibility of using EAFS-C as a partial replacement of fine and coarse natural aggregates for the production of structural concrete, with replacement rates of up to 50%. However, further studies and in-depth investigations should be carried out concerning the durability aspect, which is of fundamental importance in view of concrete production for real applications. The knowledge of the physical, chemical, mineralogical and performance properties of EAFS-C, combined with a good and careful mix design and an understanding of the behaviour of the slag once introduced into the mix, is therefore a necessary and essential factor for the correct reuse of this material and for obtaining structural concretes with performance that is comparable if not better than that of traditional concrete and capable of good behaviour even in the long term.

5.6 Future developments

The good results obtained from the 4 mixes designed and tested in this experimental campaign allow to consider the possibility of carrying out further in-depth analysis of structural concretes with EAFS-C and a comparison with reference mix. The mixes studied provided results in line with those found in the literature and thus lend themselves very well to the performance of further tests for the evaluation of several aspects that go beyond the mere and simple characterisation of the material. As illustrated in Section 2, the reuse of steelmaking slag from the production of carbon steel in electric arc furnace has been extensively studied in the literature, obtaining sometimes conflicting results but confirming the complete possibility of including this material as a partial or total replacement of binder and/or fine and/or coarse aggregate for the production of concrete, even "*non-ordinary*" concretes. In some cases, in addition to the characterisation of the material, several researchers also investigated some aspects related to the durability of concrete with the addition of EAFS-C and also tested full-scale elements (e.g. beams, columns, beam-column joints, etc.) to fully understand their behaviour (bending, shear, etc.). In the light of the good results achieved by the mixes analysed in this research and the lacunae present in the literature, especially with regard to the durability aspect, the possibilities of further investigations would primarily include more tests to evaluate the durability of the concretes produced with these mixes (e.g. evaluation of the carbonation depth, chloride penetration, behaviour after freeze-thaw cycles, etc.). At the same time, full-scale elements (e.g. beams) would also be produced and tested to investigate certain aspects such as flexural and shear behaviour, which would be compared with the results obtained from reference structural concrete.

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6. CONCLUSIONS

This PhD Thesis investigated several aspects of the "*life cycle*" of steelmaking slags from production to final reuse. The literature review showed how the slags currently produced in the world iron and steelmaking industry differs considerably, depending on the production process considered, the raw materials used, the furnace management processes and any additions to obtain steels with the desired compositions and characteristics.

In particular, steel production takes place through two distinct production cycles: the "*integral cycle*" and the "*electric cycle*", which are followed by refining of the steel in the ladle furnace. Each of the aforementioned production processes result in the formation of slags: Blast Furnace Slags ("*BFS*"), Basic Oxygen Furnace Slag ("*BOFS*"), Electric Arc Furnace Slags ("*EAFS*") and Ladle Furnace Slag ("*LFS*"). Blast furnace slags can be subdivided into four further subcategories, depending on the cooling process they undergo: Granulated Blast Furnace Slag ("*GBFS*"), Air-cooled Blast Furnace Slag ("*ABFS*"), Pelletised Blast Furnace Slag ("*PBFS*") and Expanded Blast Furnace Slag, while electric arc furnace slags are also divided into two subcategories, depending on whether Carbon steel ("*EAFS-C*") or Stainless/high alloy steel ("*EAFS-S*") is produced. Each of them differs greatly from the others in terms of physical, chemical, mineralogical and performance properties and lends itself to different reuses.

The literature review focused on the reuse of steelmaking slags for concrete production showed good rheological properties and rather conflicting results in terms of strength development when Ground Granulated Blast Furnace Slag ("*GGBFS*") were used in partial substitution of the cement. On the other hand, good results were obtained with regard to durability aspects. Despite this, few results are still available in the literature and more tests should be performed to better study and understand the long-term behaviour of this material. Concrete made with ABFS added as partial or total replacement of the natural fine and coarse aggregate showed rheological and strength properties comparable to those of the reference concrete, despite a slower strength development at early age. As for GGBFS, few results are available in the literature regarding long-term tests to study the durability of this particular mix. The continuous development of research has made it possible to investigate the possibility of including blast furnace slags in the production of "*non-ordinary*" concretes (self-compacting, high-strength and fibre-reinforced concretes), obtaining discordant results in terms of rheological and performance properties, but nevertheless encouraging for further research in this direction.

The reuse of BOFS in mortars and concretes is difficult due to the volumetric expansion phenomena to which they are subjected (however, the literature offers several solutions to allow a reduction of the responsible components and to ensure a proper reuse of slag in this sector). Nevertheless, the use of BOFS in partial or total replacement of aggregates for concrete production has led to conflicting results. This type of slag must be properly treated before being added to the mix. On the other hand, slag stabilisation treatments are rather "*complicated*" and "*cumbersome*" from a technical, economic and time-consuming point of view. Consequently, reuse in concrete is therefore not the best option for this type of slag, which is mostly reused for unbound applications, such as in road construction, for which the problems related to volumetric instability are not as relevant as they are for bound applications.

In addition to their reuse in road construction, EAFS-C can also be reused for the production of cement and concrete (as partial or total replacement of the binder and/or fine and/or coarse aggregate), resulting in materials with comparable if not better performance than the reference concrete. On the other hand, with regard to the durability aspect, there are rather conflicting results in the literature. Further tests and researches must therefore be carried out on this latter aspect, as it is of fundamental importance for the correct reuse of the material in this application and for obtaining products with good performance not only at early age but also in the long period. Good results have also been obtained in the literature regarding the reuse of EAFS-C for the production of "*non-ordinary*" concretes and for the evaluation of the behaviour of full-scale structural elements (beams, columns, beam-column nodes, etc.).

The volumetric instability of LFS, together with its tendency to self-pulverise during the cooling process and its poor hydraulic properties, greatly complicates its recovery possibilities. In particular, its reuse as a partial replacement of cement for the production of concrete is rather difficult and the few studies in the literature offer very conflicting results. An analysis of the literature suggests that reuse in ordinary concrete is possible but not the best recovery application for this type of slag. Some applications of LFS as an alternative to reuse in concrete are the reintroduction into the steel production cycle as a source of lime, reuse in road construction, for soil stabilisation and for the production of Portland cement and cement-based mortars.

The analysis, processing and integration of big data from different sources (regional and provincial databases, sector consortia and questionnaires submitted directly to the companies) proved to be of fundamental importance to identify and subdivide the different quantities of slags produced at local level according to classification, type, origin and final reuse. However, during the database analysis processes, some critical aspects were found, especially concerning the classification and reuse of slags. To ensure a complete and appropriate monitoring of steelmaking slags flows, existing systems should therefore be integrated. It was also shown how the integration of information from regional databases with specific questionnaires sent directly to the operators in the supply chain allows for a rather detailed picture of steelmaking slags management at different levels, highlighting the supply chains and making it possible to plan and implement industrial symbiosis policies and strategies on a local, regional or national scale. The following conclusions can be deduced from the analysis of big data for the province of Brescia:

- According to the MUD database, a small percentage of the total amount of slags managed as "*waste*" in the Province of Brescia (from both internal and external production) was destined for recovery operations in authorized plants (18% in 2017 and 25% in 2018), while the remaining part was destined for disposal in landfills;
- The amount of slags classified as "*by-product*" still appears low, highlighting critical issues still present in Italy that hinder producers in managing these residues;
- According to the data obtained from questionnaires, the total amount of steelmaking slags to be managed at the treatment/recovery plants located in the Province of Brescia is almost entirely EAFS (above 90%) and comes mainly from production within the province (between 80 and 90%). There are also small percentages of LFS destined for recovery, although their physico-chemical, mineralogical and performance characteristics make their reuse very difficult;
- EAFS destined for recovery comes almost entirely from production within the province (above 80%) and are mainly reused for hydraulically bound base layers and road foundations (over 70% of the total) and as aggregates in the production of bituminous and cement mixes. On the other hand, the origin of LFS destined for recovery is more uneven, with rather significant percentages also from production outside the Lombardy Region and are instead reused as partial replacement of the binder in the concrete production;
- The processing of data obtained directly from few steel mills located in the Province of Brescia showed that the slags classified as "*by-products*" and managed directly in the steelmaking plants are almost exclusively EAFS. They were reused not only for the production of certified products (e.g. aggregate from slags for concrete production), but also for backfilling, yards, embankments and draining layers to cover landfills.

Finally, from the results of the experimental campaign on the reuse of EAFS-C as a partial replacement of fine and coarse aggregate in 4 different percentages (0, 10, 25 and 50%) for the production of 4 structural concrete mixes, the following conclusions can be deduced:

- Good rheological properties of the slag mixes compared to the reference mix (in terms of workability, air content and density in the fresh state);
- Increases in compressive strength and elastic modulus were found as the replacement percentage increased, while comparable results were obtained between the different mixes with regard to tensile strength;
- The addition of slag did not seem to substantially influence the drying shrinkage of the different mixes;
- Very similar values were obtained for the bond stresses between steel and concrete of the 4 mixes analysed;
- Comparable behaviour between the different mixes with regard to crack development, opening and spacing;
- The calculation models in the standards (calibrated for ordinary structural concrete) can be used to study and analyse the behaviour of concrete mixes with the addition of EAFS-C in terms of crack opening and spacing and tension stiffening;
- Similar values were found for the Sorption coefficient (S) of the 4 mixes and slight improvement in terms of time to completion of capillary saturation (t_c) were obtained as the replacement percentage increases;
- The results obtained are in line with those found in the literature and confirm the possibility of using EAFS-C slag as a partial replacement of fine and coarse natural aggregate for the production of concrete, with replacement percentages of up to 50%;

In the light of the good results achieved by the mixes analysed in this research and the lacunae present in the literature, especially with regard to the durability aspect, the possibilities of further investigations would primarily include more tests to evaluate the durability of the concretes produced with these mixes (e.g. evaluation of the carbonation depth, chloride penetration, behaviour after freeze-thaw cycles, etc.). At the same time, full-scale elements (e.g. beams) would also be produced and tested to investigate certain aspects such as flexural and shear behaviour, which would be compared with the results obtained from reference structural concrete.