25 Years Working with Green Steel Slag Concrete

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Abstract. Industrial production of iron and steel within Spain has historically been situated in the north area of Spain. Although a major economic activity for the region, the industry also generates large volumes of waste that have hitherto been dumped in unsightly landfill sites. Over 25 years ago, a group of engineers and researchers from the same area set themselves the challenge of regenerating this waste. In this study, the advances developed in the technology of green slag concrete are reviewed, focusing on the expertise that the research group has accumulated over the past 25 years. Electric arc furnace slag is a stony material that is now often used as aggregate in hydraulic and bituminous mixes. Its use in hydraulic cement-based materials and the important properties of slag aggregates for mix workability are analyzed. Likewise, the mechanical behavior and the durability of slag concrete specimens is presented, paying special attention to expansive compounds and to the performance of electric arc furnace concrete in marine environments. In addition, real scale elements manufactured with slag concrete and their behavior are analyzed, as well as the advantages of applying current standards to their design. Finally, new lines of research are discussed for the use of electric arc furnace slag in cement-based materials.

Keywords: Electric arc furnace slag · green concrete · mechanical behavior · concrete durability · reinforced concrete

1 Introduction

The Basque Country has been at the core of the steel industry for centuries. Its iron mines and forests made this region one of the largest steel producers at a European level [1]. Over 40% of all steel production in Spain has taken place within this region [2]. Although steel production has been falling, it is still of some importance within a region of a 7234 km^2. While positive for the regional economy, the generation and management of iron and steelmaking slag has been a contentious environmental issue.

Since 1996 when “Altos Hornos de Vizcaya” closed down, the Electric Arc Furnace (EAF) has been the preferred technology for steel produced in the Basque Country. The main waste streams are Electric arc furnace (EAF) slag and subsequently, Ladle furnace (LF) slag. In harmony with European directives [3, 4], the Basque Country has adopted policies to reduce, reuse and recycle waste over the past decade [5, 6].

Following this trend, a group of researchers located in the north of Spain (University of Burgos, University of Cantabria, University of Basque Country, Tecnalia Research center, and Gikesa) started to work with the main objective of looking for the way to reuse EAF and LF slag.

Geiseler, Motz and Koros were the first researchers who perceived the opportunity for the reuse of steel slag within the construction sector [7–9]. Following their example, this group of researchers began to study the reuse of EAF and LF slag and its incorporation in cement, concrete, and bituminous mixes. The research group published its first works in the late 90s and the first years of the 2000 [10–12], after which several works were developed with the same objective: the use of EAF slag and LF slag in cement-based materials [13–15] and bituminous mixes [16, 17]. The soil stabilization properties of LF slag have also been studied [18].

Following the innovative proposals of the abovementioned pioneers, the work of this research group has been focused on the "massive" use of EAF slag and LF slag in construction applications, and sharing the knowledge learnt over the 25 years of working with these aggregate materials. The use of the term "massive" implies an eventual large-scale utilization. Since the start of research within this area, our work has built on the initial approach of the pioneers: both EAF and LF slag are excellent aggregate materials in themselves, which when complemented with other "more conventional" materials, can enhance and optimize performance.

2 EAF Slag

EAF slag is a hard stony by-product of steel refining processes. The molten slag at 1560 °C is poured from the tilting furnace on the deslagging side and then cooled, either after continuously dousing the slag with water or after pouring the slag into a large pit and then sprinkling cold water onto its surface. It has been observed that the cooling method can affect slag porosity. When cold dousing the slag, its porosity is higher as it cools, due to the entrapment of gases within the hot slag that could not escape; on the contrary, the slag cooled after sprinkling the surface is less porous and thicker. The cooling rate also affects the resultant gradation of the slag particles. With fast cooling, particles smaller than 40 mm are formed and with slower cooling, the particles are larger than 40 mm. Nevertheless, in both cases a crushing process is needed to obtain different grades. The gradation of gravel sizes is good and the distributions that are normally obtained are similar to natural aggregates. In the gradation of sand sizes, the content of fines is generally, very limited, and it is difficult to find an EAF fine slag with 20% or more particles smaller than 1 mm.

EAF slag normally has a higher density than natural aggregates: the different values recorded are between 3–4 t/m^3. The main parameters that affect the density of EAF slag are the content of metallic iron and iron-manganese oxides and the porosity of the slag.

The chemical composition of the slag depends on the raw materials and processes used to manufacture the steel. In Table 1, the typical chemical compounds found in

EAF slag are shown alongside their proportions. It may be observed that the ratio of the different compounds can significantly vary, but the main compounds are iron, calcium and silicon oxides.

Table 1. Chemical composition

Compounds (%)	Top
Fe_2O_3	15–40
CaO	26–43
SiO_2	8–20
Al_2O_3	3,5–12
MgO	3–6.5
MnO	3–5
SO_3	0.01–0.4
P_2O_5	0.4–0.6
TiO_2	0.5–0.8
$Na_2O + K_2O$	0.1–0.2

It is possible to find free lime in EAF slag, generally in proportions smaller than 5%. It could be the main problem for the use of EAF slag as aggregate in cement-based material, due to its expansiveness. However, it has been demonstrated in the literature that the initial expansivity of the slag can be reduced to acceptable values, after crushing and magnetic separation of metallic fragments, if it is periodically turned and sprinkled with water while left to weather for 90 days [19].

3 Mix Preparation

Insufficient attention may have been paid to aspects of mix design in the first experimental campaigns developed to evaluate the behavior of EAF slag [20]. The usual proportions and procedures for natural aggregates were used. Nowadays, there is far greater knowledge of mix design in EAF slag concrete [21, 22] and there are three aspects that should be highlighted.

As has been mentioned above, EAF slag normally has insufficient fine aggregate fractions smaller than 1 mm; so if EAF slag is used as sand replacement, 100% of the natural aggregates cannot be replaced, it being necessary to complement the finer fraction with 0–1 mm sized natural aggregates. In addition, it has been demonstrated that the role of the fine fraction is even more important in EAF slag concrete than in natural aggregate concrete. So, the addition of this fine natural aggregate is mandatory to obtain good concrete.

Second, not all the superplasticizer/plasticizer admixtures work suitably in the presence of EAF slag. Although it is supposed that the superplasticizers/plasticizer admixtures react only with the cement, there is interaction between some of them and the EAF slag. It has been seen that the effect of this admixture is sometimes decreased or even annulled when EAF slag is used. So, before starting any experimental campaign, it is recommended that interaction between the superplasticizer/plasticizers and EAF slag be tested.

Finally, it is important to consider slag water absorption levels when the mix design is prepared. If the slag is used with storage humidity it is important to measure it and add more water to the mix if too dry. Humidity must be measured every time a mix is prepared, to avoid possible humidity changes in the place of storage. Also, good results are obtained, if the EAF slag is doused with water the day before its incorporation in a concrete mix.

4 Fresh Properties

The consistency of the concretes manufactured with EAF slag has commonly been a problem for its use. It is more difficult for cement paste to transport EAF aggregate particles than to transport natural aggregates, due both to their higher superficial roughness and density. Therefore, the consistency of mortars and concretes manufactured with EAF slag is, in general, worse than the consistency of mortars or concretes manufactured with natural aggregates.

However, after several years of research, it was observed that concrete and mortar could be manufactured with the desired consistency when the mix design was carefully calculated. If the aspects mentioned in the previous section are considered, it is even possible to manufacture self-compacting concrete using EAF slag as aggregate [21], as can be seen in Fig. 1. The most important aspect is the addition of natural fine fractions. In this case, it is necessary to design a cement paste with increased viscosity to transport the aggregates, which can be done by increasing the fine fraction of the concrete. Hence, the greater importance of the fine fraction in EAF slag concrete, as mentioned in the previous section, than in ordinary concrete manufactured with natural aggregates.

Fig. 1. Self-compacting concrete manufactured with EAF slag concrete

5 Hardened Properties

In general, all the studies developed in the last 25 years have shown that the hardened properties of concretes manufactured with EAF slag are similar to the properties of concretes manufactured with natural aggregates [20, 21, 23–25].

The density of EAF slag concretes is higher than the density of natural aggregates concretes, as may be expected considering the density of both aggregates (3–4 t/m^3 for EAF slag and around 2.7 t/m^3 for natural aggregates). In all the elements that work by gravity this is advantageous, but in structural concrete the higher density of the concrete can be a weakness. For this reason, some attempts to decrease the density of EAF slag cement mixes have involved air entrainment admixtures. However, it was observed that this admixture decreased the strength of the mixes, and the decreased density hardly compensated the decreased strength [22, 26]. The conclusion was that the option of heavier concretes without air entrainment admixtures was the preferable option.

The mechanical behavior of concretes manufactured with EAF slag is normally similar to the behavior of natural aggregate concrete and when a good mix design is used even better mechanical properties have been found in EAF slag concretes than in natural aggregates concrete.

In the literature it has been concluded that the main reason for obtaining higher strengths using EAF slag is the denser ITZ that is generated between the EAF slag and cement paste than natural aggregate and cement paste [14, 27]. The properties of the slag mean it has better adhesion with the cement paste. In addition, it has been demonstrated that there is a migration of free lime from the core to the periphery of the aggregate sizes in stockpiled EAF slags. A transition that contributes to a denser Interfacial Transition Zone (ITZ) when the calcium oxide or free lime, CaO, that migrates to the aggregate surface reacts with water and is converted into calcium carbonate, $CaCO_3$. In Fig. 2, the differences between the ITZ of a natural and an EAF slag aggregate concretes may be seen.

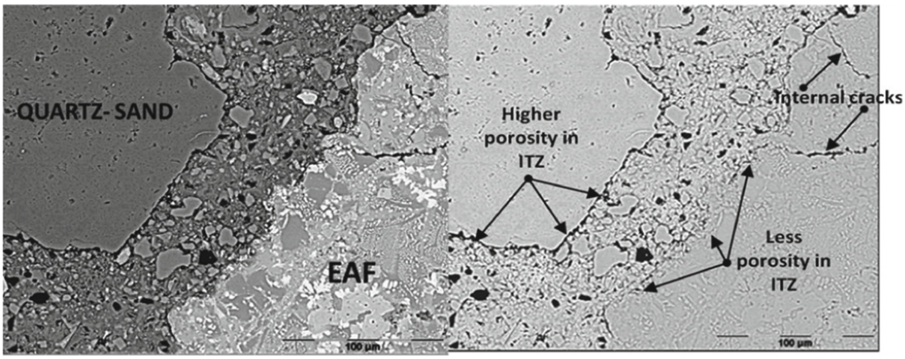

Fig. 2. Microstructure of EAF slag concrete [14]

Furthermore, it is understood that the morphology of the ITZ also plays an important role in the permeability and, therefore in the durability of the mixes. The durability of EAF slag concretes has been studied in many experimental campaigns [19, 28–30]. Different accelerated ageing tests have been developed to study it, among which the autoclave test and the study of the behavior of EAF concrete in marine environments are worth mentioning.

The autoclave test has been used to study the dimensional stability of the mixes, the specimens were placed in an autoclave at 130 °C and 0.2 MPa [21, 22]. The main objective was to accelerate the hydration/carbonation of the free lime and free magnesia. In Fig. 3a, a sample may be seen before performing the autoclave test. In Fig. 3b, a mix with only EAF slag as aggregate is shown, which maintains its volumetric stability after having performed the test. If the mixes have expansive compounds which can damage the specimens, the appearance of the sample after performing the test is similar to Fig. 3c.

Fig. 3. a. (Sample A5 before testing); b (Sample A3 after testing); c (Sample A5 after testing).

It has therefore been demonstrated that if the EAF slag aggregate is used after a suitable weathering period, no problems of dimensional stability will be found.

The importance of the study of the behavior of the EAF slag concrete in marine environment, is because the Port Authority of Bilbao has encouraged the use of this material for building sea walls to protect the docks and the foundation of the Puntasollana dock [31]. In tests for that purpose, various specimens were placed in a cage suspended from a sea wall in the port of Pasaia in an inter-tidal zone (Fig. 4). When the tide comes in, the specimens were submerged under the water and when the tide went out, the cage and its contents were exposed to the air. The specimens were broken into two halves and the chlorine and sulfate ion concentrations were measured. The results were in all cases similar to natural aggregate concretes [28].

6 In-Service Behavior

In the territory of the Basque Country there are several practical examples of real hydraulic and bituminous engineering projects and soils stabilizations (buildings, docks, pavements…), which include large amounts of slags [32]. Although they each deserve their own description, the durability analysis and the mechanical behavior of structural elements, derived from previous tests, are indispensable to verify the utility of these sorts of bound mixtures.

Fig. 4. Cages suspended in an inter-tidal zone at the port of Pasaia

Several works on the study of the durability of these mixtures after the standard tests, such as freezing-thawing, wetting-drying, sulfate attack… and other more innovative tests such as accelerated aging under temperature, carbonation of concrete, pH evolution, reinforcement protection… have been performed and this research group has published the results in various papers [30]. The results have advanced notably in terms of durability enhancement from the initial studies of [19] to more recent ones [28, 29]; as mix designs and the global know-how increased, so too did mix durability.

After learning how to manufacture high quality concretes with EAF slag as aggregate, the goal was to manufacture real scale elements and study the suitability of reinforced EAF slag concrete components *in situ*. In recent years, one focus of this research group has been to analyze the structural behavior of EAF slag reinforced concretes.

Several 4 and 5.4 m beams with cross sections of 200 mm × 300 mm were manufactured for testing. The beams were submitted to bending tests [33], shear strength tests [34], and long-term deflection under sustained loading tests [35]. In-depth analyses of different test results may be found in the literature, but a brief conclusion is that in general the structural behavior of EAF slag reinforced concrete beams is good and the presence of EAF slag is a favorable factor in the assessment. An especially excellent result was the behavior withstanding delayed deflections in service under sustained loading of usual intensity.

It has also been shown that the current structural code can be used in the design process of these reinforced concrete components. The final result showed that these concrete mixtures are ready to be used in any structural components. A subsequent research objective is to pour and to test post-stressed type beam and slab elements. The research group are confident that good results may be obtained.

7 Conclusions

After 25 years working with EAF slag (and LF slag) as aggregate in cement-based material mixes, the utility of this waste stream and its suitability for use in such applications is beyond doubt. If the measures presented in this paper are followed, high quality concrete mixtures can be produced. The performance of each mix is not so very different from natural aggregate concretes, and it has been shown that existing codes can be use when reinforced concrete is manufactured with EAF slag aggregates.

This group of researchers is convinced of the utility of this material and is researching new applications, which not only replace the natural raw materials, but also obtain added value from their use. The idea is to study its electrical conductivity, thermal conductivity, and magnetic properties, and to look for new applications in which the characteristics of the EAF slag could be advantageous.

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