Behavior of real scale beams manufactured with electric arc furnace slag concrete.

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Abstract. We live in a consumer society that generates excessive amounts of waste. Innovative techniques to reduce these volumes of waste are therefore important lines of research in engineering. The Electric Arc Furnace steelmaking industry in the Basque Country produces almost 1% of global electric-arc-steel production. Although driving the economy, it also implies the generation of a huge amounts of waste that has to be managed within a small region. Concrete is an extensively used product, which can absorb notable amounts of Electric Arc Furnace slag but, at the moment, there are only applications for use in unreinforced concrete. In this research work, real scale concrete beams containing electric arc furnace slag concrete are manufactured, in order to study their structural behavior. Our results showed that reinforced concrete elements containing electric arc furnace slag can be safely manufactured using current design standards.

Keywords: Electric arc furnace slag, Real scale beams, Reinforced concretes, Standards.

1 Introduction

Sustainability has become a recurrent topic at conferences over the past few years. Since the industrial revolution, ton upon ton of waste has been dumped throughout the world. In response to the pervasive presence of waste, not only in landfills, conceptual changes, such as the circular economy, have been devised to alter industrial practice. In consequence, as researchers and engineers, we would do well to look for solutions in which waste may be recycled rather than solutions that increase the already inevitable production of waste in industrial processes. Imprudent storage of toxic waste has led to a string of disasters, such as the Zaldibar (Basque Country) landslide where two people lost their lives and the Doñana disaster (Andalusia) that contaminated water courses with toxic mine tailings, to name but a few in Spain.

Since the 1990s, many researchers have focused their studies on the reuse of steel slag in the construction industry [1-3]. In the Basque Country, efforts have been focused on the reuse of Electric Arc Furnace (EAF) slag[4], due to the fact that the steelmaking industry located in this region uses electric furnaces for steel production.

The main uses of EAF slag have been as aggregate in concrete and bituminous mixes [5-7]. The mechanical behavior of EAF slag concretes is similar or slightly better, in comparison with concrete manufactured with natural aggregates [8], mainly due to its denser interfacial transition zone, created between slag particles and the cementitious matrix [9]. In addition, it has been found that the durability of natural concrete and EAF slag concrete is also similar [10].

Most studies presenting similar conclusions have included tests on mass concrete. The different studies under development have encouraged some organizations to use it in real construction works. Examples are the marine sea-breaks that protect the docks in the port of Bilbao [11] and the construction of a temporary bus station in Bilbao.

Now the challenge is to persuade constructors to use EAF slag concrete not only in mass concrete but also in reinforced concrete [12], which is the objective of the present research. Real-scale EAF-slag reinforced-concrete beams were manufactured to study their behavior and to compare their experimental test results with the theoretical predictions according to specific standards.

2 Materials and Methods

Mix water from the urban mains supply of the city of Burgos, two different types of Portland cement, commercial natural limestone and electric arc furnace slag were used to manufacture the concrete.

The two cements were Portland cement type I 52.5 R and Portland cement with fly ash type IV/B-V 32.5-N; both as specified in the UNE-EN 197-1 standard. The limestone had a maximum aggregate size of 1.18 mm (ASTM Nº 16 sieve) and a fineness modulus of 1.5 units. The Electric Arc furnace was used in two different size fractions (0-4.75, 4.75-12.5) with fineness moduli of around 4 and 6 units, respectively.

Four different concrete mixes were designed, which differed in consistency and type of cement used. Two mixes with a pumpable consistency and another two self-compacting mixes were manufactured; in both sets, the difference between mixes is the cement type used. The proportion of aggregates, cement and water in both sets is shown in Table 1. The two pumpable mixes and the two self-compacting mixes were labeled PI and PIV and SI and SIV, respectively.

Table 1. Mix design.

Materials	P [kg/m^3]	S [kg/m^3]
Cement	330	330
Water	160	165

Limestone	650	900
EAF slag (0-4.75)	690	550
EAF slag (4.75-12.5)	950	760
Plasticizer (% cement weight)	1.5	2

AP 500 S ribbed steel bars of different diameters, with a tensile yield strength of 525MPa, were used as reinforcement.

An Abram's cone was used to evaluate the consistency reached by the fresh concretes. To evaluate the compressive strength and the elastic modulus of the concretes used for manufacturing the beams, 100x200 cylindrical specimens were used, following the test procedure included in the EN standards.

Measurements of the flexural behavior and the long-term deflection of the reinforced beams were taken. The methodology used to do so is explained in the following section.

3 Specimen details and test setup

One of the challenges of this research was to manufacture beams trying to imitate the real conditions of a construction site. So, it was decided to prepare 600-liter mixes. An industrial concrete mixer, shown in Figure 1, was used in this research. The blue hopper, also visible in the same figure, funneled the materials into the mixer and was also used to pour the concrete into the space surrounded by formwork to mold the specimen beams.

Fig. 1. Industrial Mixer.

Two different type of beams were performed with each mix type. One beam was used to evaluate flexural behavior (referred to as the flexural beam) and the other one for long-term deflection tests (referred to as the deflection beam). In this last beam type, after performing the long-term deflection tests, they were used to evaluate the shear behavior of the concrete. The length of each beams was 4.4 m with a cross-sectional height and width of 300 mm and 200 mm, respectively.

The difference between the beams was the reinforcement. In the flexural beam 3 bars of 25mm were used for tensile reinforcement, 2 bars of 8mm for compressive reinforcement and 8 mm stirrups placed at 100mm intervals acted as shear reinforcements. Two 25mm bars were used for tensile reinforcement in the deflection beam, two 8mm bars for compressive reinforcement, and stirrups of 6 mm were placed every 200mm to serve as shear reinforcement.

3.1 Flexural test set up.

The four-point bending test until rupture was performed on the four manufactured flexural beams for evaluating flexural behavior. The load was applied by controlling the stroke displacement. This testing method made it possible to control the increase in the deflection of the beam. In this way, the inspection of any grooving on the cracked beams was also safer.

Independent electronic equipment processed the signals from the transducer, strain gauges and the Linear Variable Differential Transformer (LVDT) to record the load values. In Figure 2, a real image of the flexural test depicts all the equipment used and its layout.

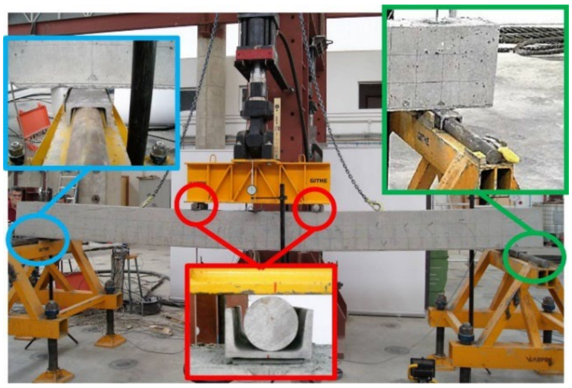

Figure 2: Four-point bending test image.

The independent electronic equipment had 20 linked transducers to measure and to record the different deformations, the cracks in the concrete, the strain of the reinforcement, the atmospheric temperature, the load and the displacement of the actuator in the hydraulic cylinder.

In addition, with the aim of doubling the data on the vertical deformations, four vertical dial gauges were located on the upper face of the beam. In Figure 3, the position of the LVDTs and dial gauges are shown and in Figure 4 the positions of the strain gauges are shown. Two more dial gauges were added to the SIV and PI beams below E6, as it had been observed that the location of the neutral axis at the moment of failure was lower than E6. The data were recorded using CATMAN software.

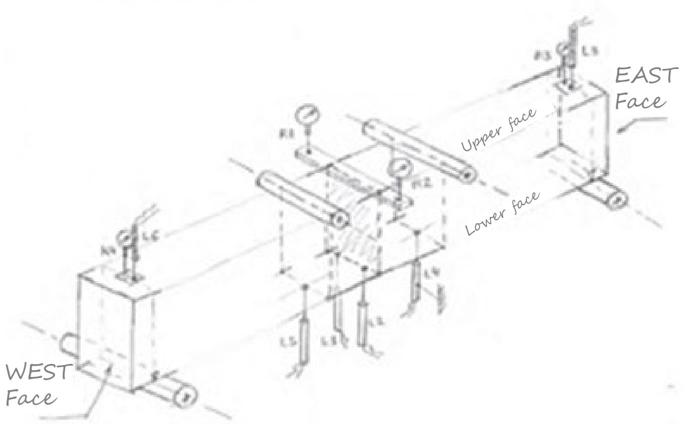

Figure 3: Position of LVDTs and Dial gauges [Courtesy of Bengo]

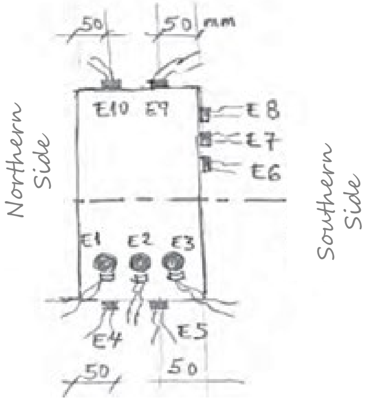

Figure 4: Position of strain gauges [Courtesy of Bengo]

The initial measurements were taken while the beam was supported with no load applied, so as to gauge the influence of its own weight on any eventual deformation. Displacement of the central actuator was applied at three different speeds. At first, a loading rate of 0.5 mm/min was applied; when the first cracks began to appear, the speed was increased to 1 mm/min and, in the final moments of the test, a load rate of 2 mm/min was applied.

3.2 Long-term deformation under sustained load test

The four beams designed for the long-term deflection test were submitted to a centered constant load of 40kN for one year, to analyze the creep of the materials at room temperature. The lay-out of the beams during that period is shown in Figure 5.

Figure 5: Arrangement of the beams in the long-term deformation test

A load transducer was located on the top face of each beam at the point where the force was applied by a hydraulic system, to monitor the load value over time. To measure the deformation of the beams, an LVDT was located mid-span on the lower face of each beam. At the same point, but on the top face, a dial gauge was located, and two other dial gauges were located at the ends of the beams, to measure possible displacements of the supporting systems. A strain gauge was also located in the mid-span of each beam on its lower face to detect the cracks.

The data were recorded using CATMAN software which recorded one measurement every second in the first month of the test and after that period it recorded one measurement per minute.

Atmospheric temperature was recorded throughout the time that the test was run. This parameter should not influence the behavior of the beams very much, but sometimes small deformations can occur due to temperature changes.

4 Results

4.1 Concrete properties

In Table 2, the results of the Abrams Cone, the compressive strength of the concrete measured at 28 days and the Elastic modulus measured at 180 days are all shown. Reasonable slumps were obtained both for self-compacting and for pumpable concretes. The hardened properties of the concretes were used to calculate the theoretical behavior of the beams.

Table 2. Fresh and Hardened properties of the concretes

	Slump [mm] or Spreading [mm]	Compressive Strength [MPa]	Elastic modulus [GPa]

PI	160	53	38.6
PIV	180	29	31.4
SI	680	53	39.9
SIV	700	31	33.8

4.2 Three-point bending test

In the analysis of the flexural behavior of the beams the neutral axis depth and the ultimate load was obtained using the domain model included in the EHE-08 Spanish Standard. The beams were designed for failure to occur in the 3rd domain, meaning that beam failure occurred due to the concrete reaching its maximum deformation point and the steel reaching its yield point. However, in the case of the beams manufactured with cement type IV, the expected results were not obtained and the beams failed in the 4th domain, which meant that the steel had yet to reach its yield point. In both cases the following formulas were used:

$$N_u = \psi b x f_c + A_2 f_y - A_1 f_y \quad (1)$$

$$M_d = \psi b x f_c (d - \lambda x) + A_2 f_y (d - d_2) \quad (2)$$

In EHE08 standard, the values of ψ and λ are constant for the 3rd and 4th domain and equal to 0.8095 and 0.416, respectively. The difference between both domains was the value f_y where, in the case of domain 3, the steel reached its maximum stress level and the value 525MPa was therefore recorded. In the case of the beam that failed in the 4th domain, the stress of the steel at the failure moment was obtained from the deformation measured with the dial gauges stuck to the ribbed bars, E1, E2 and E3, as shown in figure 4. In the case of PIV, 480MPa, and in the case of SIV, 490MPa. Applying Eq (1) and (2) the theoretical values for neutral axis depth (X) and collapse load (P) are shown in Table 3, in which experimental values for the four-point bending test were also included. No security factor was applied to obtain the theoretical values, neither to the strength of the material, nor to the loads.

Table 3. Mix design.

Beams	X_{Theo} [mm]	X_{Exp} [mm]	Pu_{Theo} [kN]	Pu_{Exp} [kN]
PI	81	97	227	231
PIV	134	168	187	175
SI	81	100	227	233
SIV	128	147	193	195

The values obtained in beams PI, SI and SIV were good. Despite the values of the neutral axis depth being quite different, both the experimental and the analytical values of the ultimate load were very similar. Measurement of the correct point of the neutral axis where failure occurred was quite difficult. It was measured using the deformation values obtained from the dial gauges stuck to the side of the beam when the maximum load was reached. The case of PIV is worth mentioning where the experimental results were somewhat poor, a result which might be explained by problems during the preparation of the concrete mix. Even so, the results obtained in this study were encouraging, in so far as they showed that current standards may be used for the design of EAF slag reinforced concrete elements.

4.3 Long-term deformation test

The method proposed in the EHE-08 (and ACI standard) was used for calculating the analytical behavior of long-term deflection. In this standard, a λ parameter, as shown in Eq (3), is proposed. Multiplying this parameter by the instantaneous deformation, the long-term deflection yielded:

$$\lambda = \frac{\xi}{1+50\rho'} \tag{3}$$

where:

ρ'= The geometrical proportion of compressive reinforcement, $\rho' = \frac{As'}{bd}$

ξ= Parameter related to the duration of the load; a value obtained from Table 4.

Table 4. ξ values

Load duration	ξ
2 weeks	0.5
1 month	0.7
3 months	1
6 months	1.2
1 year	1.4
5 or more years	2

As the definition of λ indicates, long term deformation at different times must be divided by instantaneous deformation to obtain the experimental values of λ. The analytical and the experimental values of λ at 180 days and 365 days are collected in table 5.

Table 5. λ parameter analytical and experimental values

Beams	λ 180 days		λ 365 days	
	Theo	Exp	Theo	Exp
PI	1.09	0.59	1.28	0.66
PIV	1.09	0.59	1.28	0.68
SI	1.09	0.45	1.28	0.52
SIV	1.09	0.44	1.28	0.52

Observing the data collected in Table 5, the experimental values are much better than the analytical ones. The difference is noticeable, but this situation can be explained, due to the fact that the standard specified that the long-term deflection calculated by this mode is due to the simultaneous occurrence of two phenomenon: shrinkage and creep. In this case, the beams had been stored for six months in the laboratory test shed before starting the test, so in the experimental case only the creep effect was appreciated and not the effect of shrinkage. Also, the experimental λ value in Table 5 showed a significantly different behavior between the P and the SC beams. It is difficult to try to explain this question by referring to the mechanical behavior of the concretes, because the strength and the elastic moduli of the concretes manufactured with cement, I and cement IV differ. The explanation of this effect could be due to the different microstructure-porosity of the SC concretes compared with the P concretes, due to the higher amount of cementitious matrix in the SC mixes.

5 Conclusions

After the result obtained in the test and its comparison with the analytical results, the following conclusions can be drawn:

- The results obtained in the four-point bending test, for evaluating the flexural behavior of the concretes, were very similar to the analytical ones, in most cases with higher experimental than analytical values.
- In the case of long-term deflection, the experimental results were lower than the analytical values. However, in this case, it was difficult to compare the results, as the beams had been kept in storage in the lab for six months before testing and any deformation due to shrinkage had not been recorded.

Summarizing, the general conclusion of this study, it appears that the design of reinforced concrete elements, manufactured with EAF slag, is possible when applying the procedures described in the EHE-08 standard. In general, safe results were obtained throughout the experimental procedure.

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