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Durability of concrete made with EAF slag as aggregate

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Abstract

Electric arc furnace (EAF) slag, a by-product of steelmaking recovered after the oxidizing process, is useful when employed as aggregate in hydraulic concrete and bituminous mixtures. Concrete made with EAF oxidizing slag as an aggregate shows good physical and mechanical properties and further study of its durability will ensure greater reliability in its usage. This paper details a systematic study of slag concrete behaviour under severe test conditions. The tests were designed to evaluate the internal expansivity of the slag, its chemical reactivity with some components of the cement and its resistance to environmental agents, ice and moisture. The results indicate that the durability of slag concrete is acceptable, though slightly lower than that of conventional concrete. When the mix proportions are adequate, both the mechanical strength and the durability of slag concrete are satisfactory, although in less care mixes durability is likely to be impaired.

Finally, leaching tests were performed to determine the environmental impact of the concrete, which, in comparison to results obtained directly from the slag, confirmed an important cloistering effect of the cementitious matrix on contaminant elements.

Keywords: Steelmaking slag; Concrete; Durability; Weathering; Mechanical testing

1. Introduction

Iron and steelmaking slag has been employed in the European Union (EU) as a component of both cement and concrete. The use of ground granulated blast furnace slag in the manufacture of cement as a partial substitute for Portland cement clinker is a well-known practice – see EN 197-1 standard [1] – as is the use of other kinds of slag as aggregates in concrete, especially in the field of civil engineering [2,3].

Over recent decades, the steelmaking industry in Spain has been transformed, as electric arc furnaces have largely replaced blast furnaces and LD (Linz-Donawitz) converters, leading to the appearance of a new by-product: electric arc furnace (EAF) oxidizing slag or black slag. Its characteristics differ from those of other slags and 1.5 M tons of this type of slag are produced annually in Spain. Similar changes have also taken place in other EU countries, and electric arc furnaces currently account for more than 40% of global steel production (41.1 M tons in 2002) [4]. In the interests of sustainable development efforts must be made to reuse this product in various ways so as to contribute to a recycling-orientated society and to avoid excessive amounts being dumped in the environment.

Several studies have been made of the characteristics of EAF oxidizing slag with respect to its application in the construction industry, in particular of its attributes as a material [5–7], its potential expansivity [8] and its chemical reactivity [9]. The possibility of EAF slag being used satisfactorily in concrete has been demonstrated [10–12]. The principal problems in this field remain the durability of this type of concrete [13,14] and its environmental tolerance [15]. Correctly manufactured EAF slag concrete has good

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mechanical properties, and its high density is an advantageous property where weight is a key factor, in such constructions as breakwater blocks, foundations, shoring walls, noise barriers, and radiation insulators, among others.

A detailed study has been reported to define and analyse the properties of EAF oxidizing slag, its performance as an aggregate, and the attributes of the concrete in which it is a component [16]. The manufacturing process and results related to the physical and mechanical properties of this type of concrete have also been presented in a previous paper [17]. In the present paper, a further aspect is examined to evaluate its reliability as a concrete aggregate: the effect of detrimental processes, or in other words, the durability of concrete produced with EAF slag aggregate.

2. Materials

2.1. Cement, water and limestone aggregate

Portland cement type I/42,5 R, the chemical composition of which is given in Table 1, and tap water were used for the production of the concrete, as was crushed limestone. This was extracted from local quarries, in the form of fine and coarse aggregate, widely used in the manufacture of structural concrete.

2.2. Electric arc furnace slag

Oxidizing slag taken from the EAF has to undergo the following conditioning process prior to its use as an aggregate:

- Reduction to standard aggregate sizes following appropriate crushing.
- Stabilisation by exposure to weathering over several weeks.

Appropriate crushing produces a maximum-sized aggregate of between 20 and 30 mm, and its grading presents a low proportion of fine fractions. Crushing performed to obtain maximum sizes of up to 30 mm is inadvisable – the results of the Los Angeles test show higher than permitted losses [16]. Crushing the slag more severely to obtain a larger proportion of fine sizes has also been found to be disadvantageous [16]. Such production methods are made all the more expensive by the need for several controlled stages in the milling process. In addition, a decrease is predictable in the cloistering effect on the heavy metals contained in the slag.

In view of these factors, the most advantageous solution is, firstly, to subject the slag to a primary crushing process and then to complete its grading by the addition of a suitable proportion of mineral filler. The same solution has been employed in several other studies [10,11,18]. In this study, limestone filler, a very cheap by-product from local quarries, has been used but many other possibilities also exist. This solution also achieves a further important goal, insofar as all the available EAF slag is recycled.

Table 1
Physical properties and chemical composition of EAF slag and cement

Property	Coarse slag	Fine slag
Size (mm)	4–20	0–4
Proportion after primary crushing %	76	24
Apparent specific gravity (Mg/m^3)	3.35	3.70
Water absorption (%)	10.5	–
Los Angeles loss (%)	<20	–
Expansion average (ASTM D-4792)	0.25%	0.25%
Chemical composition	Percentage weight	
	EAF Slag	P. cement
Σ Iron oxides	42.5	3.7
SiO_2	15.3	21.9
CaO	23.9	64.2
Al_2O_3	7.4	5.1
MgO	5.1	0.9
MnO	4.5	0.01
SO_3	0.1	3.3
Others ($P_2O_5 + TiO_2 + Na_2O + K_2O$)	1.0	0.9
Free CaO	0.45	Not measured
Free MgO	~1.0	Not measured
Glassy phase	<5.0	Not measured

Following the crushing process, it has been shown [16,19] that when the stabilization treatment is correctly performed [3] (permanent wetting, homogenization through periodic turning of the heaps and a minimum weathering period of 90 days), significant improvements are noted in the expansive behaviour of the slag. The original expansion values of between 0.5% and 2.5%, obtained immediately after crushing, are reduced to values of between 0.15% and 0.4% in tests using ASTM D 4792 standard [20]. Several alternative methods have been formulated to perform this operation [21,22] that are, in general, more expensive than the option presented in this paper.

Table 1 shows the main physical properties and chemical composition of EAF slag ready to be used as concrete aggregate. Figs. 1a and 1b contain the grading curves of coarse and fine slag aggregate obtained after crushing.

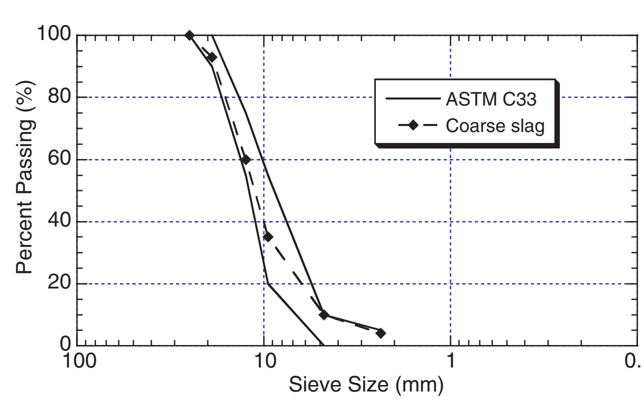

Fig. 1a. Sieve analysis of coarse slag aggregate.

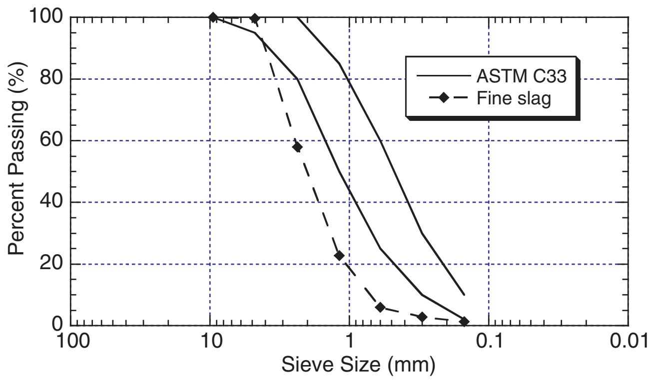

Fig. 1b. Sieve analysis of fine slag aggregate.

Free lime content was determined according to EN 1744-1 standard [1]. Periclase content was estimated by X-ray diffraction analysis using the peak at 2.11 Å. Estimation based on X-ray diffraction diagrams [23] found that the presence of glassy phase was under 5%.

3. Concrete mixtures

Six experimental concrete mixtures were designed, all subject to the following initial conditions:

- cement content: 310 kg/m^3,
- ratio w/c: $\leqslant 0.6$,
- workability: 60–90 mm (slump test),
- no admixtures.

In each case, 15–150 mm cubes were used in various experiments to analyse their properties and durability.

As shown in Table 2, the M-1 mixture is a standard structural concrete made with crushed limestone aggregates, and serves as a reference. M-2 is a concrete prepared with only crushed slag as aggregate. The M-3, M-4, M-5 and M-6 mixtures are variants in the search for the optimal solution. M-3 has the same fine aggregate (<4 mm) as M-1. In M-4, M-5, and M-6 the fine aggregate was prepared as detailed above.

The results obtained from an exhaustive analysis of the features of each concrete are summarized in Table 3, in which tests to determine apparent specific gravity, water absorption and porosity were performed on different mixes stored in a moist room for 28 days.

The values, in general, show satisfactory compressive strength, being in all cases above 30 MPa at 28 days, except for mixture M-2. Mixture M-1 is the strongest concrete at 7 and 28 days, and those mixtures containing EAF slag present a slightly lower strength. However, after 90 days or 1 year in a moist room, the strength of the best EAF slag concrete reaches values comparable to that of the reference concrete. Mix proportions, as set out in Table 2, are an extremely important factor, whenever EAF slag is used as aggregate.

In the water penetration test, the M-4 and M-5 mixtures, both of which are made with a fine aggregate compound of 50% EAF slag and 50% filler limestone, show greater impermeability. M-6 has the highest total porosity from among the correct mixtures (excluding M-2), giving a value

Table 2
Composition of concrete mixtures

Mixture	Water (kg)	Cement (kg)	Aggregate 0/4 (kg)		Aggregate 4/20 (kg)		Slump test (mm)
			Limestone	Slag	Limestone	Slag	
M-1	186	310	930	–	935	–	70
M-2	186	310	–	950	–	945	Collapse
M-3	186	310	960	–	–	895	50
M-4	186	310	480[a]	480	–	895	70
M-5	186	310	480[a]	480	–	620	120
M-6	186	310	330[a]	630	–	620	70

[a] Indicates limestone aggregate of low size (less than 1 mm) employed as limestone filler mixed with slag fine aggregate.

Table 3
Properties of EAF slag concretes

Mixture	Apparent specific gravity (Mg/m^3)[a]	Water absorption (%)[a]	Porosity (%)[a]	Compressive strength (MPa)[b]				Water penetration (mm)[c]	
				7 days	28 days	90 days	1 year	Maximum	Average
M-1	2.34	5.5	13.0	31.6	38.5	41.9	42.7	50	32
M-2	2.39	12.7	30.4	12.8	20.6	22.4	–	Total	Total
M-3	2.38	6.8	16.2	27.4	33.7	39.2	41.1	70	45
M-4	2.50	6.5	16.0	28.1	35.3	43.8	45.6	11	5
M-5	2.56	6.9	17.6	23.8	30.2	38.3	40.5	7	5
M-6	2.59	7.6	19.6	25.1	30.7	38.1	40.2	35	25

Test performed according [a]EN 12390-7 Standard, [b]EN 12390-3 Standard, [c]EN 12390-8 Standard.

for water penetration slightly lower than reference concrete M1.

4. Durability of concrete

4.1. Accelerated ageing test. (Batch test related to possible internal damage of concrete due own composition)

4.1.1. Autoclave test

Two cube specimens of each mixture cured in a moist room over 28 days were subjected to an autoclave test, using the following parameters:

- initial warming-up, for 1 h reaching 2 MPa,
- maintaining 2 MPa for 3 h,
- secondary warming-up reaching 4 MPa,
- maintaining 4 MPa for 2 h,
- slow cooling and immersion in water at 90 °C,
- cooling at room temperature,
- weathering for 90 days, protected from direct sunlight and rain.

This test is based on the autoclave test to detect the presence of expansive compounds, free lime or free magnesia in Portland cement according to ASTM C-151 [20]. In this case, the parameters applied for pressure and time differ from those originally proposed in the standard, although the intention remains the same.

The test, as performed here, is a very severe one, not only during the maintenance of specimens in the autoclave but also throughout the subsequent period of weathering. During this period, expansive chemical reactions of compounds present in the concrete during the exposure period in the autoclave and the environment can occur.

The results are summarized in Table 4 for mixtures M-1, M-3 and M-4. Immediately after the autoclave test, the superficial appearance was normal in all cases and the results show lack of expansivity in the specimens, the behaviour of the reference concrete being similar to the EAF slag concrete.

After 90 days of weathering, the mixtures showed slight (M-3 and M-4) or medium (M-1) superficial cracking. The reference concrete M-1 made with limestone coarse aggregate was more susceptible to loss of mechanical strength. The cementitious matrix is weakened and, in all probability, the greater compressive strength of the EAF slag concretes may be explained in terms of the convex geometric form of limestone aggregate particles set against the concoidal, cavernous and vesicular geometrical form of the slag. In fact, the compressive rupture of M-1 showed a non-cohesive separation between the matrix and aggregate, a situation that was not so clearly observed in mixtures M-3 and M-4. In the case of M-3, in which the fine aggregate is made up only of crushed limestone, its performance is slightly worse than that of M-4, in which the fine aggregate is composed of equal proportions (50–50%) of EAF slag and limestone.

Table 4
Properties of slag concretes after autoclave test and 90 days weathering period

Mixture	Variation in weight (%)	Compressive strength (MPa)		Loss of strength (%)	Appearance
		Before	After		
M-1	−0.48	38.5	18.4	52	Superficial cracking
M-3	−0.15	33.7	20.9	38	Slight superficial cracking
M-4	−0.28	35.3	23.8	33	Slight superficial cracking

4.1.2. Accelerated ageing

As a complement to the autoclave test, a further durability test was performed, based on the methodology proposed in the ASTM D-4792 standard [20], allowing a final evaluation of concrete strength [16] instead of measuring the vertical expansion of the specimen (less significant than the vertical expansion of a properly compacted granular material).

In this case, cube specimens, having been stored for 28 days in a moist room, were kept under water at a temperature of 70 °C for 32 days. Following this, they were exposed to the weather for 90 days under moist atmospheric conditions, avoiding any direct exposure to sunlight and rain. The objective of this test is to provoke the hydration of free lime and periclase within the slag aggregate through expansion in hot water. Subsequently, the specimens were left for 90 days to allow the effects to be fully extended into the concrete.

Table 5 shows the results for compressive strength and highlights improvements after testing. Improvements in the strength of these concretes, after being held for 90 days in a moist room (see Table 3), are greater than those obtained after this test from 150-day-old specimens. However, it should be observed that the behaviour of the reference concrete is in general similar to concretes made with EAF slag, and it can therefore be concluded that the use of the slag aggregate is not significant in this test.

Other authors [24] have proposed alternative methodologies to evaluate the effects on this kind of concrete under

Table 5
Properties of slag concretes after accelerated ageing

Mixture	Change in weight (%)	Compressive strength (MPa)		Superficial appearance
		Before	After	
M-1	−0.26	38.5	39.6	Good
M-3	−0.70	33.7	35.9	Flakes
M-4	−0.90	35.3	39.4	Flakes
M-5	−0.60	30.2	33.5	Good
M-6	−0.80	30.7	34.1	Good

accelerated ageing, measuring dimensional transformations after leaving specimens in a climatic chamber for several weeks at a controlled temperature and humidity. This is an interesting avenue of research that should be further explored.

4.2. Chemical reactivity test (a batch test related to possible reactions between the slag aggregate and other components of the concrete)

4.2.1. Alkali-aggregate reaction

This test evaluates the potential damage in the concrete mass due to the possibility of a chemical reaction between alkaline hydroxides and certain EAF slag components.

In general, the silicates present in the slag (larnite, melilite, merwinite, diopside...) are quite stable when in contact with alkalis. However, the slag has an appreciable proportion of glassy phase, which is usually capable of producing a reaction with the alkalis in cement. Moreover, because of the variable nature of the chemical and microstructural components of EAF oxidizing slag, any possible reactivity with alkalis must be taken into account. It is therefore advisable to perform this test on each different batch of EAF slag.

The tests were performed according to ASTM C-1260 standard [20], and were evaluated as per ASTM C-227 standard [20].

The average value of expansion after 16 days was 0.14%. After 28 days, the value of 0.15% was below the critical value of 0.2%, set as the ASTM C-227 limit, which suggests low alkali-slag aggregate reactivity. However, the result is significant, and points to some sort of activity within the concrete. The comments written in ASTM C-227 standard, Section 3.3, indicate that the effect of free lime, periclase and sulphates, if they are presents in the aggregate, overlap the alkali-aggregate expansive reaction and contribute to total expansion at the end of the test. Despite the low proportions of free lime and periclase in the slag, their presence probably explains the expansion of 0.15%.

4.3. Environmental test (batch test related to possible environmental degradation of concrete)

4.3.1. Freezing and thawing cycles

In this test, three specimens of each mixture stored in a moist room for 28 days, were subjected to 25 cycles of freezing and thawing:

- immersed in water at 4 °C for 6 h,
- maintained in frost storage at −17 °C for 18 h.

These conditions, guided by past experience, are sufficiently severe to highlight differences among concretes, for which compressive strength at 28 days is in the range of 30–40 MPa. At the end of the test, the superficial appearance, variation in weight and compressive strength were all recorded. The results are summarized in Table 6.

Table 6
Properties of slag concretes after freezing and thawing cycles

Mixture	Variation in weight (%)	Compressive strength (MPa)		Loss of strength (%)	Superficial appearance
		Before	After		
M-1	−0.14	38.5	32.7	15	Good
M-3	−1.02	33.7	20.6	39	Noteworthy damage
M-4	−0.27	35.3	27.2	23	Slight damage
M-5	−0.94	30.2	16.9	44	One sample cracked
M-6	−1.18	30.7	16.0	48	Noteworthy damage

The internal pressure of ice in the accessible pores of the concrete (matrix and aggregates) accompanied by the thermal changes produce superficial spalling in the samples and leads to a dramatic decrease in their compressive strength (see also Figs. 2a and 2b). The test severity level, as was desired, is very high.

Fig. 2a. Mixture M-3. Noteworthy damage after freezing and thawing cycles.

Fig. 2b. Mixture M-5. Cracked sample after freezing and thawing cycles.

The most resistant concrete is M-1, which has the best initial strength. The concretes made with EAF slag show variable degrees of damage. Mixture M-4 is the best of the EAF slag concretes, probably due to its greater strength and lower water penetration. The results show the influence of greater porosity and the slightly lower strength of mixtures M-3, M-5 and M-6. The use of air-entraining admixtures should increase their resistance to freezing.

4.3.2. Wetting and drying test

Three specimens of each mixture, cured in a moist room for 28 days, were subjected to 30 cycles of wetting and drying as follows:

- immersion in potable water for 16 h,
- oven drying at 110 °C for 8 h.

The severity level of this test is also intended to be high. Following the test, the main parameters were monitored and the results are summarized in Table 7. In this case, damage is produced by two combined effects: thermal dilation and contraction, and shrinkage due to variations in humidity.

Loss of particular characteristics is evident in all of the mixtures, though M-1 and M-4 are less susceptible to loss of strength. The superficial damage is low in almost all cases.

Strength is also considered to be a critical factor, and similar results for percentage strength loss between M-1 and M-4 suggest that the deleterious effects on the cementitious matrix are comparable and noteworthy in both cases, but occur less so than in other mixtures.

Table 7
Properties of slag concretes after wetting and drying cycles

Mixture	Variation in weight (%)	Compressive strength (MPa)		Loss of strength (%)	Superficial appearance
		Before	After		
M-1	−0.08	38.5	27.3	29	Good
M-3	−0.12	33.7	19.9	41	Slight damage
M-4	−0.15	35.3	24.7	30	Good
M-5	−0.16	30.2	16.6	45	Slight damage
M-6	−0.28	30.7	15.6	49	One sample cracked

4.4. Environmental test (test related to possible attack of concrete to environment. Leaching test)

Nowadays, industrial by-products require a study of their potential toxicity. In the case of steelmaking slag, there are several dangerous heavy metals and salts which can be present after a manufacturing process that involves scrap steel. A leaching test is required prior to EAF slag being used directly as a filling material.

Table 8 shows the results of the analysis of leached water from crushed slag – coarse and fine aggregates – used in the M-1 and M-4 mixtures, to detect sulphate, fluoride and total chromium. The leached water was obtained according to EN 12457 standard [1].

It can be observed that the smaller sizes of crushed slag produce higher concentrations of dangerous substances in the leached water than the larger sizes, in which the cloistering effect is greater. It can be expected that the use of EAF slag as an aggregate in concrete will allow its potential toxicity to be reduced. A beneficial cloistering role of concrete on fluorides and chromium can be appreciated in the results of Table 8. In the case of sulphates, the results correspond to the mass dilution of slag in the total concrete. All values are under the maximum limits stipulated by local legislation.

5. Concluding comments

Electric arc furnace oxidizing slag, obtained from the manufacture of plain and low-alloy carbon steels, can be used as aggregate in concrete following appropriate conditioning. Special attention must be paid to the crushing process to produce a suitable grading to obtain the best results in Los Angeles test. In this study, an adequate grading has been achieved by adding mineral fillers to complete the fine fraction.

When using EAF slag concrete, it is important to produce appropriate mixtures to guarantee the correct level of durability. High compressive strength and low water penetration should be the main characteristics. Systematic testing to verify the efficiency of slag stabilization treatment

Table 8
Leaching test on concrete and crushed slag

Mixture	Sulphates (mg/kg)			Fluorides (mg/kg)			Cr_{total} (mg/kg)		
	A_2[a]	A_{2-10}[b]	Maximum limit	A_2[a]	A_{2-10}[b]	Maximum limit	A_2[a]	A_{2-10}[b]	Maximum limit
M-1	14.1	58.5	377	0.11	0.81	18	0.03	0.12	2.6
M-4	6.2	38.6	377	0.12	0.36	18	0.02	0.10	2.6
CS[c] (0/4 mm)	93.7	115.4	377	6.60	12.40	18	0.20	1.02	2.6
CS[c] (>4 mm)	76.4	95.1	377	5.30	10.10	18	0.16	0.80	2.6

[a] Ratio liquid/solid = 2.
[b] Ratio liquid/solid = 2, in addition with ratio liquid/solid = 10.
[c] CS = crushed slag.

is strongly suggested as such measures allow any possible expansivity to be carefully monitored.

The results show that the performance of EAF slag concretes is similar to that of a more traditional concrete in terms of its strength and slightly less so in terms of its durability.

The high porosity of EAF slag is an obstacle to making a concrete resistant to freezing. Eventual improvements in this field could be further analysed by adding specific admixtures.

Finally, the leaching test is seen as compulsory and this study shows a substantial cloistering effect of concrete on the toxic products present in EAF slag.

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References

[1] CEN. European Committee for Standardization. Rue de Stassart, 36. Brussels B-1050.

[2] Motz H, Geiseler J. Products of steel slags: an opportunity to save natural resources. Waste Manage. 2001;21:285–93.

[3] Dunster AM. The use of blast furnace slag and steel slag as aggregates. In: Zoorab, Collop, Brown, editors. Performance of bituminous and hydraulic materials in pavements. Lisse: Swets and Zeitlinger; 2002, ISBN 90 5809 375 1. p. 257–60.

[4] www.worldsteel.org/media/ssy. Steel Statistical Yearbook 2003. International Iron and Steel Institute, Brussels.

[5] López FA, López-Delgado A, Balcázar N. Physico-chemical and mineralogical properties of EAF and AOD slags. Afinidad LIII 1996; 461:39–46.

[6] Luxán MP, Sotolongo R, Dorrego F, Herrero E. Characteristics of the slags produced in the fusion of scrap steel by EAF. Cem Concr Res 2000;30(4):517–9.

[7] San José JT. Reutilización y valoración en obra civil de escorias de horno eléctrico de arco producidas en la CAPV. Arte y Cemento 2000:124–6.

[8] Frias Rojas M, Sánchez de Rojas MI, Uria A. Study of the instability of black slags from EAF steel industry. Mater Construcc 2002; 52(267):79–83.

[9] Vázquez-Ramonich E, Barra M. Reactivity and expansion of electric arc furnace slag in their application in construction. Mater Construcc 2001;51(263–264):137–48.

[10] Maslehuddin M, Sharif AM, Shameem M, Ibrahim M, Barry MS. Comparison of properties of steel slag and crushed limestone aggregate concretes. Constr Build Mater 2003;17:105–12.

[11] Moon Han Young, Yoo Jung Hoon, Kim Seong Soo. A fundamental study on the steel slag aggregate concrete. Geosyst Eng 2002;5(2): 38–45.

[12] Beshr H, Almusallam AA, Maslehuddin M. Effect of coarse aggregate quality on the mechanical properties of high strength concrete. Constr Build Mater 2003;17:97–103.

[13] Morino K, Iwatsuki E. Durability of concrete using electric arc furnace oxidizing slag aggregates. In: Swamy N, editor. Proceedings international conference, Sheffield 1999:213–22.

[14] Geyer RT, Dal Molin D, Vilella A. Availaçao da durabilidade do concreto armado com adicao de escoria d'aciaria eletrica 56° Congreso ABM, Belo Horizonte, July 2001. p. 127–36.

[15] Hino M, Miki T. New role of steelmaking slags for the environmental protection of ocean. Shiraishi Memorial Lecture of the Iron Institute of Japan, Tokyo 2001;44–45:99.

[16] Manso JM. Fabricación de hormigón hidráulico con escorias de horno eléctrico de arco. Ph.D. Engineering Thesis. University of Burgos, Spain, 2001.

[17] Manso JM, González JJ, Polanco JA. EAF slag in concrete. J Mater Civil Eng 2004;16(6):639–45.

[18] Papayianni I, Anastasiou E. Concrete incorporating high volumes of industrial by-products. Aristotle University Greece. In: Dhir RK, Newlands MD, Payne KA, editors. Role of concrete in sustainable development, Proceedings of international symposium dedicated to Professor Surendra Shah. Dundee, United Kingdom, September 2003, Thomas Telford Publ. p. 595–604.

[19] Oliveira da Silveira N, Almeida Melo e Silva MV, Agrizzi EJ, Fernandes de Lana M, Antonio da Silva E, Lacourt de Mendoca R. Acerita – steel slag with reduced expansion potential. La Revue de Metallurgie – CIT. October 2004. p. 779–85.

[20] Annual Book of ASTM Standards. West Conshohocken, PA, 19428-2959 USA.

[21] Cen Y, Chen Q. Experiment on crushing EAF slag. SEAISI Quart 1993;22(4):81–5.

[22] Watanabe T, Okamoto T, Takahashi H. Development of a new dust and slag treatment technology. In: SEAISI 2000 Australia Conference. Perth, May 2000, Proceedings vol 1, S3, P6.

[23] Bish DL, Howard SA. Quantitative phase analysis using the Rietveld method. J Appl Crystallogr 1988(21):86–91.

[24] Vazquez-Ramonich E, Barra M. Durability of concretes with steel slag as aggregates. Workshop on R + D + I in Technology of concrete structures – a tribute to Dr. Ravindra Gettu. Barcelona. October 2004. p. 23–30.