APPLICATION OF STAINLESS STEEL SLAG WASTE AS A PARTIAL REPLACEMENT TO MANUFACTURE CEMENT MORTARS

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Abstract

Stainless steel production involves today one of the most dynamic sectors of the manufacturing industry, due to a large increase of this product in construction and industrial sector. In this manufacturing process a lot of wastes were generated. For every three tons of stainless steel produced, one ton of slag approximately is generated.

In this study, cementation and pozzolanic reaction characteristics of this waste was analysed. Recent studies have discussed applying stainless steel slag to cement material but have only with a 10% of cement replacement. In this study, cement was replaced with stainless steel slag waste untreated and processed, produced like fine crushed waste. Testing different substitution percentages to determine this optimum replacement ratio was observed, which increases the compressive strength and bending cement. The results showed that it is possible to replace cement by stainless steel slag waste with proper treatment for the manufacture of mortars, showing successful results of mechanical strength, and with no environmentally negative aspects.

Keywords

Stainless steel slag waste; Cement; Compressive strength; Leaching.

1. Introduction.

Stainless steel production involves today one of the most dynamic sectors of the manufacturing industry, due to a large increase of this product in construction and industrial sector. In this manufacturing process, a lot of waste is generated. For every three tons of stainless steel produced, one ton of slag approximately is generated [1]. In the production of stainless steel are generated various types of steel slag waste, according to the stage of processing. Melting of scrap for the production of steel is applied in a basic oxygen furnace (BOF) or an Electric Arc Furnace (EAF). In this first process, steel slags are obtained as a by-product of aggregate [2,3]. There is a later stage in the production process, based on the refined steel from the furnace; this process generates stainless steel slag powder. This slag powder requires more storage space and also has less value in the market than the slag used as aggregate for road construction [4].

At present, both slags are generally treated as waste and dumped in landfills. Alternative uses for these stainless steel slags could be applied. There are several previous studies for the application of steel slags [5]. Stainless slag could be used as the cement adhesives and roadbed materials after the treatment of stabilization/solidification process or other methods [5,6] or as landfill liner materials. In practice, in comparison with blast furnace slag, the application scope of steel making slag is essentially limited in production of aggregates for road pavement or concrete [7], [8] and [9].

It must be considered the amount of waste produced from stainless steel industry, as well as toxic waste generated by storage in dump, such as nickel, lead, chromium or cadmium [3,10]. These toxic elements can present environmental damages.

This study aims to observe the cementitious properties that stainless steel slag waste has. Other studies previously demonstrated that these waste exhibits cementitious properties under the influence of chemical activators [11]. According to its microstructural morphology, chemical composition and X-ray diffraction spectrum, typically, Stainless Steel Slag Waste (Sw) is composed mainly of calcium oxide and silica, magnesium and aluminum oxides. The potential value and the fineness of the waste, suggests that these can be used as a supplementary cementitious material [12, 13]. Recent studies have discussed about the application of stainless steel slag to cement material, but only with 10% of cement replacement [14].

It is also possible to use Sw as a part of sand and cement in mortar manufacturing for construction industry, replacing until 30% of cement [15]. In order to increase final strength, researchers have suggested several ways of processing the raw material such as re-melting [13], use of activators [16] or crushing and screening [17,18]. It should be noted that the presence of free lime and magnesia, could cause problems in restrained structural members due to delayed expansions phenomena [19].

Applying crush processes in Sw, it is possible to improve the reactivity and strength of cementitious components [20, 21]. In this study, the possibility of using of Sw in mortar slag is analyzed. A study of environmental effects applying leaching test in mortar manufactured with Sw were carried out. Different percentages of Sw, crushed (Sw-C) and non-crushed (Sw), were applied in the manufacture of mortars, in order to determine the optimal replacement rate to increase the economic value of this waste. The reduction of the cement content were calculated too.

2. Materials and methods.

2.1 Cement.

The cement used in this study according to the ASTM-C150 was CEM I 52,5R. The chemical properties of the cement are shown in Table 1.

Table 1: Properties of the cement.

CEM I	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Granul. 45µm (%)	Granul. 32µm (%)	Blaine E. S. (cm^2/g)	Loss of ignition (975ºC)
	19.58	4.41	2.5	64.18	0.94	3.37	0.93	0.31	6.8	17.4	4106	2.58

This cement does not contain mineral additions, therefore the behavior of ash mortar with addition of stainless steel is not conditioned by the components present in the cement.

2.2 Natural Standard Sand.

Standard sand (NS) comes from Beckum (Germany) was used. Such sand presented a granulometry density and optimal and specific absorption. Physical characterization was performed as verification (EN 196-1) [22]. Table 2 shows the information concerning the properties tested in the laboratory: density and water absorption (UNE-EN 1097-6) [23]. The chemical characterization was not necessary to perform because the material is packaged and certified.

Table 2: Physical characterization of the Standard sand.

Density (Kg/dm^3)	Water absorption (%)
2.653	0.5

2.3 Stainless steel slag waste

The stainless steel slag waste used in this investigation was obtained from a producer of ferritic stainless steel produced by a steel plant Acerinox in Algeciras, Cádiz, Spain. The steel slag is produced during the direct reduction of iron in an electric arc furnace.

Two different samples were obtained in laboratory for analysis of the properties of the stainless steel slag and the ability to fabrication cement mortars. It was obtained stainless steel slag waste unprocessed (Sw) directly from the steel plant. Sw was crushed by grinder then sieved and the fraction finer than 125 µm, obtaining Sw-crushed (Sw-C) , which was used for this work.

The physical and chemical characteristics of Sw and Sw-C depend on the kinds of treatment that have applied in laboratory.

Table 3 shows the information concerning the properties tested in the laboratory: the particle density of the slag and the absorption was determined by pycnometer analysis, applying UNE-EN 1097-6 [23]. The properties of this by-products must be determined, because the mechanical behavior of Sw is affected. For this reason, friability coefficient, coefficient of sand (UNE 83-115) [24], water-soluble and acid-soluble sulphate contents (UNE-EN 1744-1) [25] and the major component of each material were determined according UNE-EN 196-2. [26]

Table 3: Physical and chemical properties

PROPERTIES		Sw	Sw-C	test method
Density-SSD (kg/m3)				
	0-4 mm	2.105	1.842	**UNE - EN 1097 - 01**
Water absorption (%)				
	0-4 mm	5.841	4.648	
Friability ratio (%)		14.60	12.20	**UNE 83-115**
Elemental content (%)	**Si**	22.49	20.70	**UNE-EN 196-2**
	Ca	27.26	27.98	
	K	0.75	0.02	
	Mg	6.07	6.30	
	Fe	0.63	1.13	
	Al	2.06	1.96	
	Na	0.26	0.04	
	Ti	0.85	0.98	
sulphate (%SO4)		0.1	0.1	**UNE - EN 1744-1**

The chemical analysis of the slag was determined by wavelength dis-persive X-ray fluorescence (XRF) spectrometry (UNE-EN 196-2) [26]. Table 4 shows the oxide composition of the slag determined by XRF analysis.

Table 4: Oxide composition and physical properties of stainless steel slag

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Loss on ignition (975°C)	Free lime (CaO)	Cl^-
Sw	31.34	5.18	1.25	46.26	10.90	0.37	0.00	0.75	0.15	0.01
Sw-C	30.31	5.01	0.93	46.45	11.51	0.36	0.00	1.11	0.15	0.01

It was observed that the values obtained concerning the composition of oxide materials each is similar in both studies. The range established by the UNE-EN 196-2, and the MgO values for stainless steel slag treated of Sw-C were displayed out.

Sw presented a very variable chemical composition, as it has been shown in previous studies [10, 27]. In Sw the metal oxides presented a chemical composition (CaO, SiO_2, and Al_2O_3) similar to granulated blast furnace slag [28]. Sw has higher values of CaO and Al_2O_3, and lower values of FeO and Fe_2O_3, which is more common in ashes used such as an addition to cement [27].

The particle size distribution of the slag was determined by wet laser diffraction (Malvern Mastersizer). The morphology of the slag particles in Fig.1 shows the variations in particle shape and size.

Figure 1: Particle size distribution

We observed a continuous distribution. The Sw-C material has a finer distribution of the remaining material particles. This fact was expected because of the processing that this material has suffered, which were crushing and sieving.

It was also carried out a study of insoluble residues in each of the materials studied featured the values are showed in Table 5.

Table 5: Insoluble residues of stainless steel slag

	IR-HCl (%)	EDTA (%)	test method
Sw	10.51	78.16	**UNE 80216**
Sw-C	9.92	66.82	

3. Mortar mix proportions

Seven mixtures of mortars were produced in laboratory, and different dosage were used. The different quantities of materials applied in the mixtures used for this performance are showed in Table 6.

The method used for the design of the dosages is set according to UNE-EN 197-1[29] and UNE-EN 196-1[22].

A mortar control was performed following the dosages indicated by UNE-EN 196-1. Other mixtures are made using different percentages of Sw instead of cement, applying different substitutions. Three series were performed, Series 1 by replacing 10% of weight cement by waste, Series 2 by replacing 20%, Series by replacing 30%. In Serie 3 the highest percentage was applied, according to the standard UNE-EN 197-1, where fly ashes for manufacturing cement are used.

Table 6: Mortar mix proportions

		DOSAGE (g)				
		NS	Sw	Cement	Water	%Cement
Control	Control	1350	-	450	225	25
Series 1 (10%)	S10-Sw	1350	45	405	225	22.5
	S10-Sw-C	1350	45	405	225	22.5
Series 2 (20%)	S20-Sw	1350	90	360	225	20
	S20-Sw-C	1350	90	360	225	20
Series 3 (30%)	S30-Sw	1350	135	315	225	17.5
	S30-Sw-C	1350	135	315	225	17.5

This study was conducted to ascertain the mechanical properties and durability characteristics of mortars cement prepared with stainless steel slag. It is for this reason that series with different degree of substitution for the manufacture of cement mortar are performed. This study aims at analyzing the cementitious capacity of the stainless steel slag waste.

4. Experimental methods and results

4.1 Compressive strength

The compressive and flexural strengths were applied using a hydraulic press, which was applied at a constant speed load. The compressive strength was applied using the standard UNE-EN 196-1 on prismatic specimens with 40 x 40 x 160 mm^3 sides, for 1, 7, 28 and 90 days.

Table 7 shows the results for the compressive strength of the different series of mortars made. The compressive strength increases progressively along time. An increase of the strength values was observed according to the curing age (Fig. 2).

Table 7: Compressive strength results in MPa

		Age (Days)			
		1	**7**	**28**	**90**
Control Mixture	**Control**	19.68	46.74	57.03	63.03
Series 1 (10% replacement of cement)	**S1-Sw**	18.24	46.01	57.37	63.22
	S1-Sw-C	18.96	46.13	57.47	63.69
Series 2 (20% replacement of cement)	**S2-Sw**	12.26	41.28	51.64	57.40
	S2-Sw-C	11.54	41.10	53.55	58.24
Series 3 (30% replacement of cement)	**S3-Sw**	5.28	26.88	33.55	39.51
	S3-Sw-C	9.07	36.78	41.73	47.81

In series 1, the Sw addiction improves significantly the compressive strength. When Sw processed was applied, compressive strength obtained was higher.

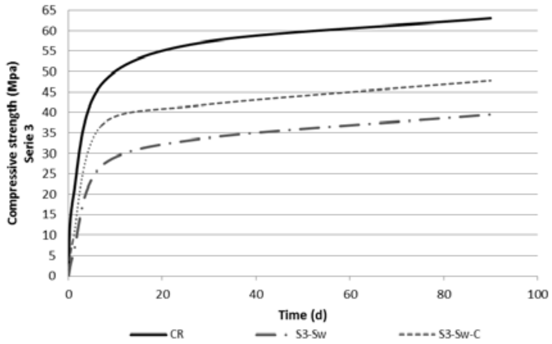

Figure 2: Compressive strength evolution

Higher values in compressive strength were obtained when cement substitutions by Sw-C in Serie 1 were applied, and these values were above 3% respect to the control Mixture. The mechanical behaviour in Compressive strength after 28 days was exceeded in all cases except in series 3 with applying of cement substitutions of 30% of Sw.

Alternatively, Compressive strength decreased respect to the Control in series 2 and 3, and an increase in the mixtures where Sw were applied was obtained at all ages (Table 7 and Fig. 3). In the mixtures were Sw-C was applied, lower values of loss relative to the control were obtained.

The addition of processed Sw (Sw-C) in mixtures produced better results than those where Sw was applied (Fig. 3).

Figure 3: Comparison of compressive strength at 28 day

4.2 Flexural strength

Flexural strength was determined using prismatic specimens. The dimensions of the specimens were 40 × 40 × 160 mm^3 and the results were obtained at 1, 7 and 28 days. This property was determined according to UNE-EN 196-1. The values of flexural strength obtained are shown in Table 8.

Table 8: Flexural strength results in MPa

		Age (Days)			
		1	**7**	**28**	**90**
Control Mixture	**Control**	5.07	8.85	11.09	13.01
Series 1 (10% replacement of cement)	**S1-Sw**	4.64	6.50	12.12	14.10
	S1-Sw-C	6.11	9.68	12.50	14.14

Series 2 (20% replacement of cement)	**S2-Sw**	3.28	7.25	10.79	13.39
	S2-Sw-C	4.57	7.73	10.83	13.65
Series 3 (30% replacement of cement)	**S3-Sw**	1.55	8.07	9.58	10.21
	S3-Sw-C	2.26	7.28	9.55	10.16

As occurred with the compressive strength results, the flexural strength values in mixtures increased with the incorporation of 10% of Sw in mixtures. S1-Sw presented an increase in flexural strength of 9%, and S1-Sw-C an increase of 12.5% respect to the Control (Table 7 and Fig. 4).

Figure 4: Comparison of flexural strength at 28 day

As shown in Figure 4, the highest flexural strength values were obtained with the addition of 10% Sw, at Series 1. As the addition was increased, the mechanical behavior in flexural strength decreased. These values were lower than those in the Control Mixture.

4.3 Dimensional inestability (shrinkage)

To study the durability of the mortars, drying shrinkage measurements were obtained on the mortars prisms measuring 40 × 40 × 160 mm, according to UNE 83831[30]. The specimens were exposed to conditions of 65% relative humidity and 20 °C and the measurements were taken for 1, 7, 14, 28, 56 and 90 days.

The results showed a similar trend in the linear shrinkage (µm/m) over time (Fig. 5).

Figure 5: Shrinkage of the mortar as a function of age in days

The results showed a high shrinkage values when replacing 20% and 30% of cement by the Sw and Sw-C, compared with the Control mixture, in additions of 10% substitution. Sw and Sw-C presented contraction values similar to the Control mixture..

The results obtained differ from previously studies. Emery JJ. [19] explained that the addition of Sw produced expansions about 5% in mortars.

4.4 Leaching test: compliance batch test EN 12457-3

The procedure UNE- EN 12457-3[31] consisted of a two-step batch leaching test that uses a solution of 175 gr of a dry sample of the material, two liquid/solid ratios (an L/S of 2 and an L/S of 10) and deionised water as a leaching fluid. This method involves stirring the solution in two steps. In the first step, the solution is shaken for 6 ± 0.5 h with an L/S of 2, and the second step uses the same fraction with stirring of the solution for an additional 18 ± 0.5 h, after having added water to obtain an L/S ratio of 10. In both stages, the samples were left to decant, and the pH, conductivity and temperature were measured. The solution was filtered using a membrane filter (0.45 lm), and a subsample of the leachate was taken for each material. The test is performed at natural pH. Elemental concentrations were determined in the laboratory using inductively coupled plasma mass spectrometry (ICP-MS). The analysis of the leaching behaviour of the tested materials is focused on the measurement of the elements regulated by the EU Landfill Directive: ten heavy metals (As, Pb, Cd. Cr, Cu, Hg, Ni, Zn, Ca, Mg, Se and Sb) and sulphate ion. According to that European document (Table 8), a residue can be classified as an inert, non-hazardous or hazardous material.

Table 8: Acceptance criteria (EU Landfill Directive) for L/S = 10 L/kg.

	Leached maximum concentrations (mg/kg) depending on landfill class		
	Inert	**Non hazardous**	**Hazardous**
Cr total	0.5	10	70
Ni	0.4	10	40
Cu	2	50	100
Zn	4	50	200
As	0.5	2	25
Se	0.1	0.5	7
Mo	0.5	10	30
Cd	0.04	1	5
Sb	0.06	0.7	5
Ba	20	100	300
Hg	0.01	0.2	2
Pb	0.5	10	50

This leaching test is performed to evaluate the polluting potential of each of the material associated with the legal limits indicated by the Landfill Directive of the EU (Table 8). Table 9 shows the classification of each material sample studied by comparing them with established legal standards for heavy metal concentration. The stainless steel slags crushed (Sw-C) were classified as non-hazardous. According to the data obtained by the compliance test (Table 9), the concentration on leachates of the elements As, Sb, Hg and Pb were negligible and inferior to the detection limit. For this reason, they are not included in Table 9.

Table 9: Concentrations of metals and sulphate on leachate at L/S=10 L/kg and L/S=2 L/kg and classification according to concentration on heavy metals

	Metals (mg/kg)								**Classification**
L/S=2	**Cr**	**Ni**	**Cu**	**Zn**	**Se**	**Mo**	**Cd**	**Ba**	
Sw	1.0089	0.0021	0.0016	0.0123	0.0114	0.6199	0.0006	2.9060	Non hazardous
Sw-C	1.1953	0.0016	0.0027	0.0150	0.0173	0.5906	0.0008	1.3885	Non hazardous
L/S=10	**Cr**	**Ni**	**Cu**	**Zn**	**Se**	**Mo**	**Cd**	**Ba**	

Sw	3.9874	0.0006	0.0041	0.0886	0.0486	1.3015	0.0011	4.1063	Non hazardous
Sw-C	4.7040	0.0014	0.0065	0.0925	0.0317	1.2858	0.0014	1.7157	Non hazardous

According to the results, in Figure 5 we can observe the limits of each heavy metal surpassed by each of the materials. We note that for the L/S = 2, Sw and Sw-C exceed the limits for inert material considered non-hazardous. They exhibit higher values of Cr and Mo.

Figure 5: Concentration in leachate in stainless steel slags

As in previous studies [32], chromium values exceeded the limits established by law. According to the results, mainly of molybdenum and chrome values, it is possible to state that Sw and Sw-C can be classified as non-hazardous material.

5. Conclusions

This research evaluates the properties and characteristics of stainless steel slag waste for the manufacture of mortars and the mechanical and environmental properties of these mortars containing replacement rates of cement by stainless steel waste to identify whether the replacement ratio had a significant effect on the measured properties.

The following conclusions were obtained:

- Sw and Sw-C present a high water absorption capacity and a high density too. These values decrease when the Sw are processed trough crushed, obtaining Sw-C. A suitable particle size distribution was obtained for both materials, so that it is possible to use as an addition of the cement.
- Respecting the chemical properties, Sw presents a high content in the composition of metal oxides, similar to the values obtained in conventional fly ash. These results let show the applicability of Sw in mortars and concretes.
- Regarding the physical and mechanical properties, the cement replacement by Sw provides an increased in behavior in compressive strength and flexural if the substitution percentage is around 10%, improving this behavior in mechanical properties if Sw-C are applied. Shrinkage behaviour is similar in Mortars made with 10% of addition of Sw and Sw-C in comparison to the Control Mixture.
- However, with increasing substitution of the cement by Sw and Sw-C, the values of behaviour in Compressive and Flexural strength decrease and the values of shrinkage increase.

- When 30% of cement is replaced by Sw-C, the behaviour in Compressive strength decreases less than 25% compared to control, but if the stainless steel slag waste is not processed (Sw), the values of behaviour in Compressive and Flexural strength are smaller than Sw-C.
- Concerning the analysis of heavy metals that is observed by leaching Sw and Sw-C have high chromium values, yet these values are within the limits of non-hazardous material.

In conclusion, replacement cement by Sw and Sw-C for the manufacture of mortar improves the mechanical properties to some degree of substitution. In this way giving value to the large amount of waste produced and reducing the consumption of raw materials. Obtaining as a result a product that not environmentally affects according to the leachates analysis.

References

[1] *Das B., Prakash S. An overview of utilization of slag and sludge from steel industries. Resources, Conservation and Recycling, 2007; 50: 40-57.*

[2] Geiseler J. Use of steelworks slag in Europe. Waste Manage Res 1999;16:59–63.

[3] *Motz H., Geiseler J. Products of steel slags an opportunity to save natural resources. Waste Materials in Construction Wascon, 2000; vol.1: 207-220.*

[4] *Maslehuddin M., Sharif A.M., Shameem M., Ibrahim M., Barry M.S. Comparison of properties of steel slag and crushed limestone aggregate concretes. Construction and Building Materials. 2003; 17: 105–112*

[5] *Zhang X. Y., Zhang H., He P. J., Shao L. M.; Wang R. Y., Chen R. H. Beneficial reuse of stainless steel slag and its heavy metals pollution risk. Resources, Conservation and Recycling, 2008; 4: 33-37.*

[6] *Huiting S., Forssberg E. Physicochemical and mineralogical properties of stainless steel slag oriented to metal recovery. Resource Conservation Recycled, 2004; 40:245–27.*

[7] *Kriskova L., Pontikes Y., Cizer Ö., Mertens G., Veulemans W., Geysen D.,. Effect of mechanical activation on the hydraulic properties of stainless steel slags. Cement and Concrete Resources, 2012; 42: 778–788.*

[8] *Pellegrino C., Cavagnis P., Faleschini F., Brunelli K. Properties of concretes with Black/Oxidizing Electric Arc Furnace slag aggregate. Cement and Concrete Composite, 2013; 37:232–240*

[9] *Sheen Y.-N., Wang H.-Y., Sun T.-H. Properties of green concrete containing stainless steel oxidizing slag resource materials. Construction and Building Material, 2014; 50:22–27.*

[10] *Huaiwei Z., Xin H. An overview for the utilization of wastes from stainless steel industries. Resources, Conservation and Recycling, 2011; 55: 745–754.*

[11] *Shi C., Qian J. High performance cementing materials from industrial slags. Resource, Conservation and Recycling. 2000; 29: 195–207.*

[12] *Akinmusuru JO. Potential beneficial uses of steel slag wastes for civil engineering purposes. Resources, Conservation and Recycling. 1991; 5: 73–80.*

[13] *Muhmood L, Vitta S, Venkateswaran D. Cementitious and pozzolanic behaviour of electric arc furnace steel slags. Cement and Concrete Resource. 2009; 39:102–9.*

[14] *Sheen Y.-N, Wang H.-Y, Shiao F.-T., Kuan SL, Sun T.-H., Huang J.-W., et al. Engineering properties of cement mortar with different EAF and VOD. In: The Corrosion Engineering Association of the Republic of China 2003 conference, vol. C12, Kenting, ROC; 2003. p. P67.*

[15] *Rodriguez Á., Manso J.M., Aragón Á., Gonzalez J.J.. Strength and workability of masonry mortars manufactured with ladle furnace slag. Resource Conservation and Recycling. 2009; 53:645–65.*

[16] *Shi C., Hu S. Cementitious properties of ladle slag fines under autoclave curing conditions. Cement and Concrete Resource. 2003, 33:1851–1856.*

[17] *Shi C. Characteristics and cementitious properties of ladle slag fines from steel production. Cement and Concrete Resource. 2002; 32: 459–462*

[18] *Papayianni I., Anastasiou E. Optimization of ladle furnace slag for use as a supplementary cementing material. M.S. Konsta-Gdoutos (Ed.), Measuring, monitoring and modeling concrete properties, Springer, The Netherlands. 2006, pp. 419–426.*

[19] *Emery JJ. Slag utilization in pavement construction. In: Hotaling WW, editor. Extending aggregate resources. ASTM STP 774. 1982; 95–118.*

[20] *Fathollah* S. *Mechanical activation of cement–slag mortars. Construction and Building Materials. 2012;26:41–48.*

[21] *Sheen Y.-N., Wang H.-Y., Sun T.-H. A study of engineering properties of cement mortar with stainless steel oxidizing slag and reducing slag resource materials. Construction and Building Materials. 2013; 40: 239–245.*

[22] *UNE-EN 196-1:2000: Methods of testing cement - Part 1: Determination of strength.*

[23] *UNE-EN 1097-6:2001: Tests for mechanical and physical properties of aggregates - Part 6: Determination of particle density and water absorption.*

[24] *UNE 83115:1989 EX: Aggregates for concrete. Measuring coefficient of friability of the sands.*

[25] *UNE-EN 1744-1:2010: Tests for chemical properties of aggregates - Part 1: Chemical analysis*

[26] *UNE-EN 196-2:2014: Method of testing cement - Part 2: Chemical analysis of cement*

[27] *Setién J., Hernández D., González J.J. Characterization of ladle furnace basic slag for use as a construction material. Construction and Building Materials. 2009;23: 1788–1794.*

[28] *Sheen Y.-N., Leb D.-H., Sun T.-H. Greener self-compacting concrete using stainless steel reducing slag. Construction and Building Materials.2015; 82: 341-350.*

[29] *UNE-EN 197-1:2011: Cement - Part 1: Composition, specifications and conformity criteria for common cements.*

[30] *UNE 83831:2010: Methods of test for hardened mortar for masonry - Determination of dimensional stability of hardened mortar for masonry.*

[31] *UNE-EN 12457-3:2003: 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).*

[32] *M. Salman, Ö. Cizera, Y. Pontikesb, R. Snellingsc, L. Vandewallea,B. Blanpainb, K. Van Balena. Cementitious binders from activated stainless steel refining slag and the effect of alkali solutions. Journal of Hazardous Materials. 2015; 286:211-219.*