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Article

Concrete Properties Comparison When Substituting a 25% Cement with Slag from Different Provenances

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Abstract: Concrete consumption greatly exceeds the use of any other material in engineering. This is due to its good properties as construction material and the availability of its components. Nevertheless, the present worldwide construction increase and the high-energy consumption for cement production means a high environmental impact. On the other hand, one of the main problem in iron and steel industry is waste generation and by-products that must be properly processed or reused to promote the environmental sustainability. One of these by-products are blast furnace slag. Cement substitution by slag strategy achieves two goals, raw materials consumption reduction and waste management. In the present work, four different concrete mixtures are evaluated. 25% cement is substituted by different blast furnace slag. Tests are made to evaluate the advantages and drawbacks of each mixture. Depending on the origin, characteristics and treatment of the slag, concrete properties change. Certain mixtures provide proper concrete properties. Stainless steel slag produces a fluent mortar that reduces the water consumption whit a slight mechanical strength loss. Mixture with electric arc slag furnace properties are better to the reference concrete (without slag) when slag is treated similarly to the cement.

Keywords: concrete; slag; valorization; cement; circular economy

1. Introduction

Nowadays the increasing growth of waste generated as a result of the industrial activity is unavoidable, so dealing with this complex problem has become a difficult issue in part because of increasingly strict environmental regulations and policies. For some decades, we have started to see how social awareness about protecting our environment has increased and activities such as waste valorization has become more and more important. The analysis of industrial and construction waste and its transformation into raw materials in order to be introduced again into the production chain is part of the Circular Economy, a trend in economics initiated by Kenneth Boulding in 1965 [1]. He defined the economy of how to deal with our resources in two ways: the cowboy and the spaceman economies. The "cowboy economy" or open economy lives on the plain with limitless resources with no need to recycle anything. The "spaceman economy" or closed economy has completely limited resources, thus the ecosystem has become the economy—everything is recycled, controlled, and measured, and the only problem is allocation—scale is irrelevant. These ideas did not gain much attention when Boulding published then, in part because the "spaceman economy" was unconceivable at that time, at least on Earth, so the measures he proposed would not have much effect in the economy. Nowadays, we can still define our economy as open or lineal [2]. Raw materials are extracted from earth and are manufactured, transformed, sold, used and then they become waste.

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However, this is starting to change as resources in Earth are not limitless and the industrial production of our age has reached a magnitude never seen before. In 1987 the Brundlandt report was published by the United Nations General Assembly in which these problems were discussed and some measures were proposed in order to transform our economy into a sustainable economy, able to satisfy our needs but without compromising the future generations [3]. That was the turning point where scientists, policymakers and the society as a whole started to see the right use of resources as a main objective, and thus the valorization of waste as a very effective way to reach a sustainable economy.

Regarding the specific case of steel slag waste valorization, in the European Union, the steel slag has been used as an addition to the mix of cement manufactured in plant [4–6] to make up the cements CEM II and CEM III. They have been used in various applications, mainly in aggressive environments (maritime and hydraulic facilities) because of its resistance against salt water and sulphates. Since the 80s, much research [7–12] has been conducted in order to use steel slag as additives or as aggregate substitutes with fine and coarse arid [13–22].

Steel slag is a by-product of steel making, produced during the separation of the molten steel from impurities in steel-making furnaces. The slag occurs as a molten liquid melt and is a complex solution of silicates and oxides that solidifies upon cooling.

There are two well differentiated types of slag: electric arc furnace (EAF) and Ladle furnace basic salg (LFS) [23]. Electric arc furnace (EAF) slag is a strong, dense, none porous aggregate that is cubical in shape, has good resistance to polishing and has an excellent affinity to bitumen. This makes it an ideal aggregate for asphalt surface materials and road surface treatments as it produces materials that are resistant to deformation (rutting), safe and durable.

During the manufacturing process of steel 110–130 kg per metric ton of electric EAF and 20–30 kg per metric ton of LFS are generated [24]. The latter are less suitable for engineering purposes due to its high expansiveness, especially when used in roads as aggregate substitute [25,26].

The aim of this paper is to make a comparison between several types of electric arc furnace slags produced in still mills from different locations in Spain (some of them previously treated) and to determine their suitability as cement substitutes studying their influence on concrete properties.

Different processes of manufacturing produce slag with conglomerating properties that, in an adequate proportion, can be used as raw materials abandoning its steel waste condition.

Portland cement is an hydraulic cement produced by pulverizing clinkers which consist essentially of hydraulic calcium silicates, usually containing one or more of the forms of calcium sulphate as an inter-ground addition [17].

On this paper, a comparative analysis of different concrete mixtures will be carried out, substituting cement with several types of steel slag. The results of this paper are part of a wide program intended to elaborate a standard to guide the use of steel slag as cement substitute on infrastructure building.

This investigation is an extend to the patent "Steelmaking slag valorization from landflill as a substitute for cement in the manufacture of concret" [27], in which a manufacture process for the production of concrete is developed with stainless steel addition or cement substitution, obtaining a concrete mixture proportioning especially indicated for the construction of retaining walls reducing energy and resources consumption.

2. Materials

Four different concrete mixes have been designed by substituting a 25% of cement with slag obtained from four different blast furnaces in Spain. Chemical composition is shown in Table 1. The mix proportion shown in Table 2 will be used as reference. The following materials are used to make the mixtures:

- Cement: Portland Cement CEM I 52.5 R, with the composition given in Table 1. This cement is selected due to the absence of any kind of additive that could mask the results. It is used as reference pattern.
- Sand: crushed limestone sand is used. Size ratio is: fine aggregate 0/2, medium aggregate (sand) 0/4 and gravel 4/16.

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- Water: domestic tap water.
- Additive: Gelium Ace 324. Concrete additive UNE EN 934-2.

The water-cement ratio is 0.5, with a dry consistency.
The different slag used for the test are the following:

- Electric arc blast furnace with mechanical processing (M2): Initial aggregates are like sand type 0/3 with a high humidity content (around 8–10%). They are dried and grinded in origin. This is made by means of vertical roller mills specific for this material, which dries during grinding.
- Unprocessed blast furnace slag. Two different materials (with different compositions) are tested, coming from two different steel mills (used in M3 and M4 respectively). They are collected from landfills and the only process they are subject to is sieving in the lab with a 0.063 mm sieve.
- Stainless steel slag, from electric arc blast furnace (M4), they are also unprocessed excepting sieving in the lab with a 0.063 mm sieve.

Chemical composition is shown in Table 1. The different mortar mixtures will be named as follow:

Mix 1 (M1): Ordinary concrete without slag.
Mix 2 (M2): Concrete with a 25% cement replaced with processed slag.
Mix 3 (M3): Concrete with a 25% cement replaced with unprocessed slag.
Mix 4 (M4): Concrete with a 25% cement replaced with unprocessed slag.
Mix 5 (M5): Concrete with a 25% cement replaced with stainless steel slag.

Table 1. Cement and slag chemical Composition (data provided by the supplying company).

Slag Origin/Chemical Composition	SiO_2	AL_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	S	TiO_2	Cl	Limestone	P_2O_5	Cr_2O_3	MnO	Fe
	%	%	%	%	%	%	%	%	%	%	%	%	%		
Cement (M1)	20–22	4–10	4	55–62	2	0.3	0.3	-	-	-	-	-	-	-	-
Processed slag (M2)	35.9	11.2	0.3	40	7.7	0.2	0.4	0.8	0.6	<0.1	0.5	-	-	-	-
Unprocessed slag type 1 (M3)	15.85	16.53	0.83	57	7.7	-	-	1.46	-	-	-	<0.1	<0.1	0.53	-
Unprocessed slag type 2 (M4)	22.28	9.37	0.84	56.94	7.37	0	-	-	0.46	-	-	0	0	0.44	0.58
Stainless steel slag (M5)	11–37	2–8	0.4-0.8	22–60	4–12	-	-	-	0.6–2	-	-	<0.1	1–8	1–4	-

Table 2. Concrete mixture proportion.

Mixture Proportion		
Material	**Weight**	**Density**
Water/Cement ratio	0.5	
% Additive S.P.C.	1.3%	1.01
% Fine sand 0–2	15.00 %	2.7
% Sand 0–4	35.00 %	2.7
% Gravel 4–16	50.00 %	2.7

3. Tests Description

The different mixed described in previous section are subject to different standard tests. The goal of these tests is to evaluate how cement-slag substitution may affect the main properties as consistency and workability (slump test) and mechanical capabilities (compressive strength). Additionally, as one of the main use of this kind of concrete is in marine environment, depth of penetration of water became a key characteristic to study.

Concrete has been made with the mixture proportions shown in Table 2 where a 25% of the cement has been substituted by the different slag according to Table 1, providing the 5 different mixes previously described.

Concrete mixture proportion has been made according to the norm EN 12390-2 [28] for testing hardened concrete where the making and curing of specimens for strength tests is described. It covers the preparation and filling of moulds, compaction of the concrete, levelling the surface, curing of test specimens and transporting test specimens.

The compressive strength test specimen was a cube with 10 cm size. Four concrete mixtures have been made for each mix type. From each mixture 10 specimen was made, 2 was tested at 7, 28 and 90 days, leaving the other as reserve. The depth of penetration of water test was made with a cylindrical specimen with 15 cm diameter and 30 cm height. Two different specimen were tested for every mix obtaining the average mean value.

3.1. Slump Test

The consistency of fresh concrete is determined by the slump test according to the norm EN 12350-2 [29]. A truncated conical mould is used where the fresh concrete is poured and compacted. The mould is placed over a base and is raised upwards. The concrete cone slumps and the distance slumped provides a measure of the consistency of the concrete. Table 3 presents the results of these tests.

These tests evaluate the workability of the concrete. It is intended to evaluate how the cement-slag substitution alter the consistency, leading indirectly to change the water cement ratio or suggesting different uses.

Table 3. Slump test results.

Mix	Slump	Standard Deviation	Consistency
M1	2.02	0.27	Dry
M2	2.00	0.15	Dry
M3	0.98	0.29	Dry
M4	0.14	0.11	Dry
M5	8.03	0.34	Soft

3.2. Compressive Strength Test

Compressive strength tests were performed according to norms EN 12390-3 [30] y EN 12390-4 [31]. The test has been carry out with a servo-controlled compact Compression Testing Machine with a maximum capacity of 2000 kN (ETIMATIC-Proetisa H0224). The load control system emulates a servo-valve using a pump that accurately controls oil flow to the piston, controlling the rotation speed of the pump motor and the load gradient. The superior compression plate is supported by a spherical bearing ring that accommodates the alignment inaccuracy and avoid any lateral force. Once the specimen is placed, the display continuously shows the load, the failure load and the strength calculation in real time (Figure 1).

Figure 1. Compressive strength (a) test and (b) specimens.

These tests provided the results shown in Table 4. Tests were performed at 7, 28 and 90 days to evaluate the behaviour of slag in time. It was performed with cubic specimen (10 cm size) and the load is applied at a constant speed of 0.5 MPa/s.

Table 4. Compressive strength test results and Standard deviation.

Days/Mixes	7	Standard Deviation (7)	28	Standard Deviation (28)	90	Standard Deviation (90)	% Strength Loss
M1	52.12	5.23	59.34	3.87	66.05	2.38	0%
M2	54.73	2.52	63.69	3.08	71.51	5.15	8%
M3	34.22	1.65	37.07	0.98	45.01	5.69	−32%
M4	44.48	1.02	48.42	0.34	51.54	0.54	−22%
M5	37.04	4.54	44.38	4.66	48.94	5.64	−26%

3.3. Depth of Penetration of Water under Pressure Test

This test was made according to norm EN 12390-8 [32], depth of penetration of water under pressure, with a cylindrical specimen with 15 cm diameter and 30 cm height.

The test is performed with 28 days cured specimen. As a first step, the specimen is placed in a drying oven during 24–48 h to be completely dried.

Then, the specimen is placed in the apparatus and a water pressure of (500 ± 50) kPa is applied during (72 ± 2) h. The appearance of the surfaces are controlled during the test in order to detect any water leakage.

At the end of the test, the specimen is taken from the system, excess of water is removed and wiped. Then the specimen is broken in two halves perpendicularly to the face where the water pressure was applied. Water penetration front can be clearly seen and marked on the specimen (as seen in Figure 2). Maximum depth of penetration is measured in mm.

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Figure 2. Depth of penetration of water under pressure (a) test and (b) specimens.

4. Results and Discussion

Result obtained with the different mixed shown in Section 2 will be analysed and discussed in this section.

4.1. Consistency

Slump test results are shown in Table 3. The main appreciation is that most of the mixtures appear unaltered, compared to the reference M1, excepting mixture M5 where a higher fluency and workability can be observed (Figure 3c). It corresponds to the stainless steel slag. This is the reason the water-cement ratio were kept low. Consequently, the other mixtures show a dry consistency, being especially extreme the case corresponding to the M4. A slump below half a centimeter was observed in the different tests. The material became very thick with a high presence of internal and external pores (Figure 3d). This behaviour can be compared in Figure 3 with the other mixtures.

This represents that the stainless steel slag provokes a low level of friction in the material causing high fluency as well as keeping the necessary viscosity to ensure the proper cohesion of the particle avoiding segregation. This is the effect produced in self-compacting concrete [33] where fluency and viscosity is achieved by means of additives [34]. The opposite effect is observed in mix M4 where the material becomes denser and thicker, with a reduction in fluency and cohesion, promoting internal hollows, penalizing its strength and permeability (as will be shown on the following subsections).

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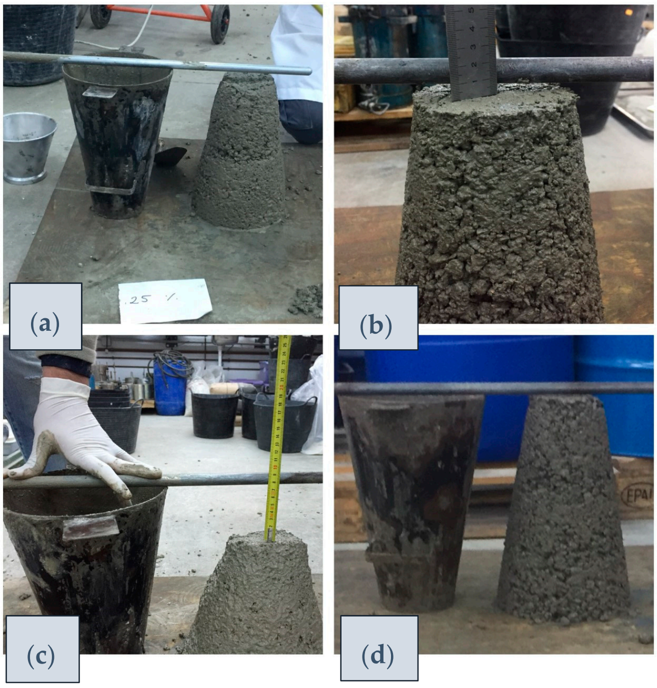

Figure 3. Concrete consistency. Slump test. (**a**) M1, (**b**) M2, (**c**) M5 and (**d**) M4.

Figure 4 shows the standard deviation values of the experiment. Average values are considered in the range from 0.5 to 2 cm. Three mixtures are present within this range while M4 is below and M5 very above.

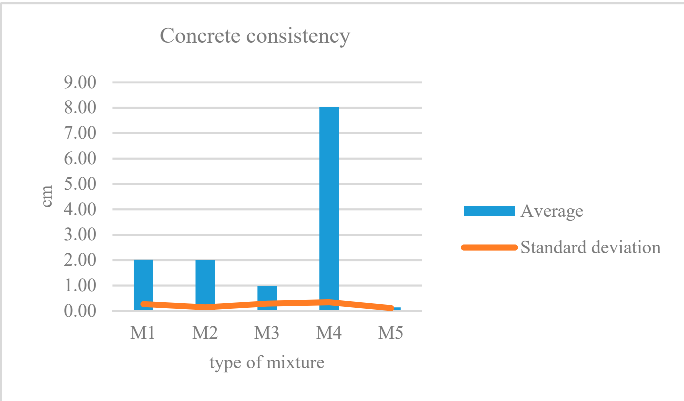

Figure 4. Consistency Standard deviation.

4.2. Compressive Strength

Compressive strength test results are shown in Table 4 and plotted in Figure 5 comparatively.

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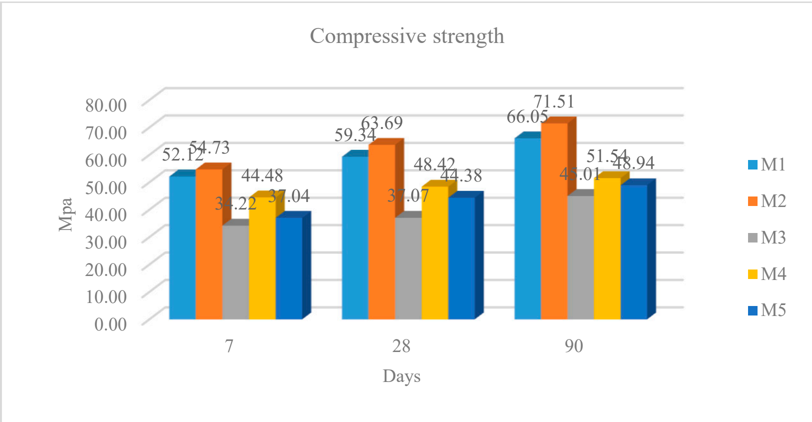
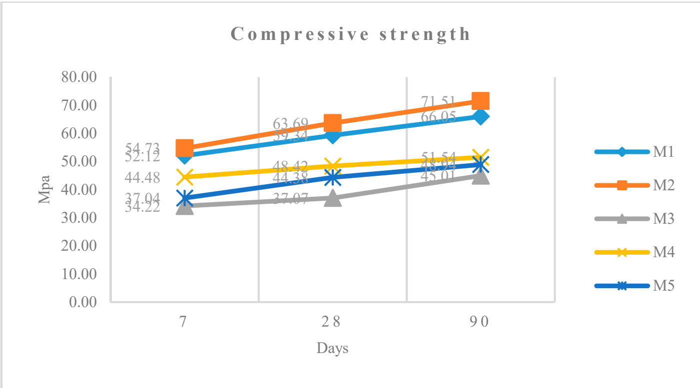
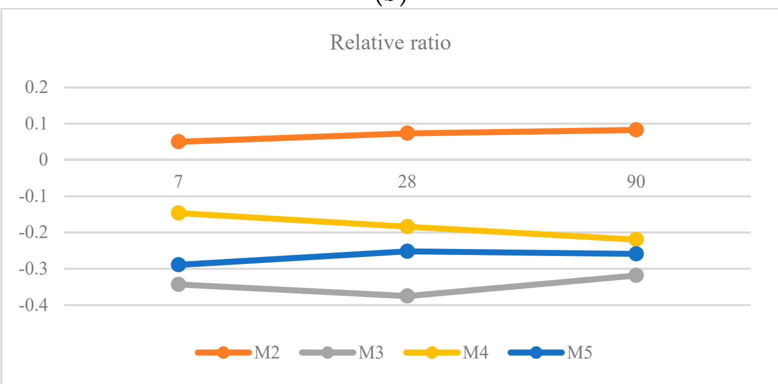


(a)



(b)



(c)

Figure 5. Compressive strength test results comparison: (a) different mixes (b) evolution along time and (c) relative ratio respect M1.

This experimental data shows how M2 mixture provides a good compressive strength, even slightly above the reference sample, an 8% higher than M1. In Figure 5c can be seen how this relative compressive strength improvement is sustained along the time. The other mixtures present certain strength loss, ranging from 32% for M3 to 22% for M4. This broad range, 40% considering the four mixtures, prove that the origin, characteristic and the treatment given provide very different mechanical properties.

Regarding chemical composition, the proportion of SiO_2 is the main factor to consider. Mix M4 with similar SiO_2 content to the reference M1 (cement) shows the lower strength loss and in the case of M2, where there is a strength gain, the SiO_2 percentage is higher (Table 1). On the other hand M2 and M5 with higher strength loss, has lower SiO_2 content.

According to Canovas et al. [35], materials with a high content in SiO_2 present a high capacity to yield tobermorita (calcium hydrosilicates (C-S-H)) which when reacting with portlandite (concrete hydration mineral compound) in cementitious materials, provide additional strength [36]. Compressive

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strength results are in agreement with this sentence. The slag used in M2, which provide the maximum strength, has a higher percentage of SiO_2 than the others. This slag has been treated in origin (dried and grinded) instead of taken from landfill.

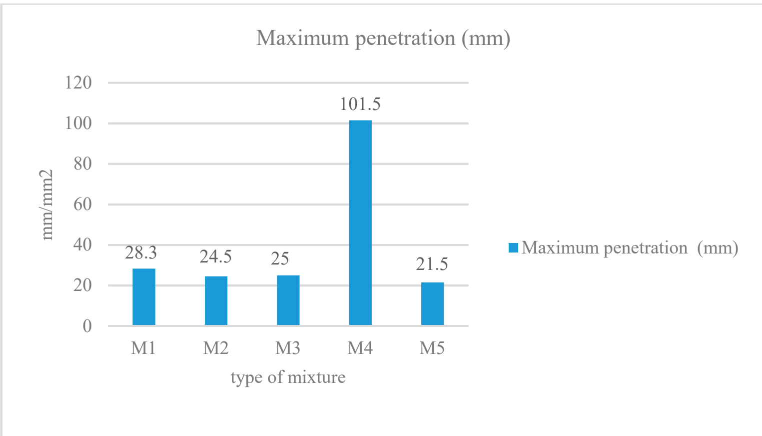
4.3. Depth of Penetration of Water

Depth of penetration of water under pressure test results are shown in Table 5 and plotted in Figure 7. Maximum and average penetration values are provided.

Excepting M4, all of the mixtures are in accordance with the norm EN 12390-8 [32]. The maximum deeper penetration is below the 30 mm limit established and the average values does not exceed the 20 mm limit. M4 doubles both limits (Figure 6). As seen in Section 4.1, it is the consequence of the appearance of pores and cavities (Figure 4) due to the very dry consistency of the mortar, which cannot be eliminated by vibration. Water penetration is favoured by this circumstance.

On the other extreme, we find the results obtained for the M5 mixture. In this case, penetration is below the average of the other samples. It is provoked by a reduction in the number and size of cavities due to the good fluency and workability of this mortar.

Figure 6. Penetration of water under pressure, M4.



(a)

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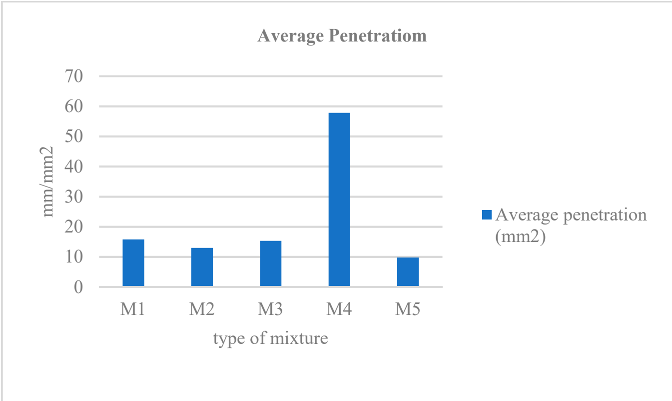

(**b**)

Figure 7. Depth of penetration of water under pressure results (**a**) maximum and (**b**) average.

Table 5. Depth of penetration of water under pressure test results.

Mix	Maximum Penetration (mm)	Standard Deviation (mm)	Average Penetration (mm²)	Standard Deviation (mm²)
M1	28.3	12.09	15.8	6.42
M2	24.5	7.83	13.0	4.43
M3	25.0	3	15.3	2.91
M4	101.5	2.5	57.8	1.5
M5	21.5	3.5	9.8	0.015

The average values and the standard deviation of the experiment results are shown in Figure 8. M4 has not been considered in the statistic calculation to avoid distortion.

Average values are considered in the range from 0.5 to 2 cm. Three mixtures are present within this range while M5 is below and M4 very above.

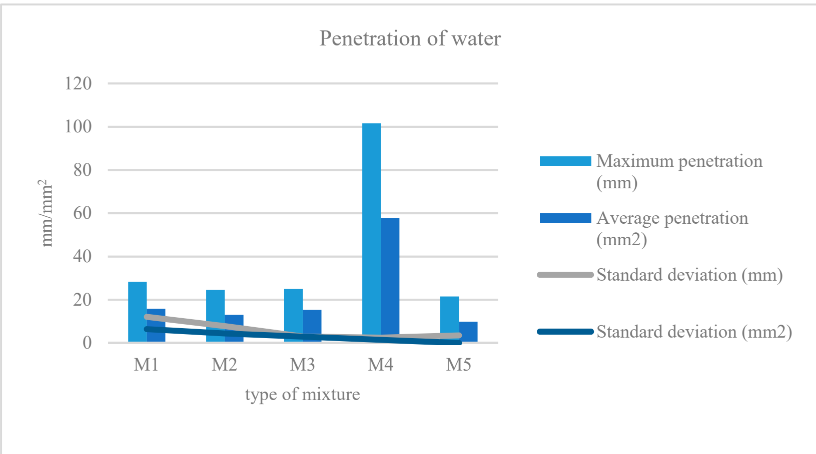

Figure 8. Average and standard deviation of the depth of penetration of water under pressure tests.

5. Conclusions

According to the results described, we can outline the following conclusions:

(1) Regarding concrete consistency, stainless steel slag furnaces (M5) provide excellent properties with a higher fluency and correct viscosity, keeping a low water-cement ratio. On the other extreme, mixture M4 provide a consistency extremely dry with cavities that undermine its properties. The other mixtures provide dry consistency similar to that obtained with the reference mix (formulated with a low water-cement ratio).

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(2) The main conclusion obtained from compressive strength tests is that, in general term, a slight strength loss (approximately 20%) is observed. Nevertheless it is remarkable that, when the slag furnace are treated in a similar way to the cement (drying and grinding in origin, M2), the compressive strength improves, been even higher to the reference concrete (M1). This mixture (M2) also acquires greater resistance by having a greater amount of SiO_2, thus increasing compounds in its microstructure that give it a stronger compressive strength.

(3) Excepting mixture M4, water penetration tests provide similar results for the different mixtures. In some cases penetration is lower (M2 and M5) than the reference, being remarkable the reduction observed with M5 due to its exceptional fluency and workability. M4 is the great exception; due to the porosity, it presents a high penetration.

Summarizing, we can conclude that stainless steel slag furnace (M5) provides a good concrete formula, with excellent workability and a low water consumption. The negative point is a reduction in compressive stress. Regarding electric arc slag furnace, it is found that when they are treated in a similar way to the cement (M2), their properties are better than those obtained with the reference concrete (without slag) especially regarding the compressive strength, with the consequent saving in cement consumption.

As a final conclusion, we can say that cement substitution with slag can be considered as a good strategy to reduce cement consumption while solving a waste management problem. Promising results have been obtained for certain mixture where the properties of the resultant concrete are even improved compared with the reference mix. This conclusion has been proved with 25% of cement substitution. More experimental work must be done in future in order to identify proper alternative mortar formulations.

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