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Effect of Mechanical Behaviour of Steel Making Slags on the Blended Cements by Experimental Study

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Abstract: *Original method for steel production, which is implemented for close up to 90 percent of steel production, is the transformation of iron ore into iron in the blast furnace after the formation of steel in basic oxygen furnace. Today, the high volume of steel slags has become a critical problem in waste management. However, blast furnace slag due to its pozzolanic properties can be used for partial replacement of Portland cement. The purpose of this article is to process blast furnace slag and turn it into an effective material in the cement industry. The results showed that the physical processing of slag by grinding it into 75 microns and increasing alkalinity state by adding lime can lead to an increase of 117 percent in 11-day compressive strength of slag cement against unprocessed one. This conclusion is achieved through experiments conducted on 18 different samples.*

Keywords: *steel slag, Mechanical activation, Analytical hierarchy process, Slag cement.*

1. Introduction

Slags have different chemical and mineralogical composition according to the variant steelmaking methods and cooling conditions. If slags cool slowly, their crystalline structure results in inappropriate properties for partial replacement in Portland cement. On the other hand rapid cooling makes slag amorphous and glassy with little or no crystalline structure which is highly reactive and appropriate in partial replacement of Portland cement. There are two different methods for slag replacement in Portland cement: First, is a simple replacement of slag with raw material in furnace and a combination with limestone and clay that doesn't have any special energy saving or economic benefit because a cheap material is replaced with another one and it still needs heating in the furnace. Second method that is an attractive approach involves adding slag after clinker making and mixing the combination of slag, gypsum and clinker physically. This cement mixture is a clear economic advantage due to significant savings in energy costs.[2-4]

The use of iron blast-furnace slag as a component in concrete has been extensively researched and applied for many years now. The first experience of combined cement happened when *Loriot* made a primitive form of cement consisting of ground granulated blast-furnace slag and slaked lime. Furthermore, blast-furnace slag has been used as an aggregate both in ready-mix and precast concrete and for lightweight applications. Today, GGBF slag is extensively used for partial Portland cement replacement because of its pozzolanic and cementation properties and it was proved that these combined cements have much more final compressive and bending strength and impermeability factor rather than Portland cement. Despite this, their lower initial compressive strength is a limiting factor which makes them appropriate in special application.

Unlike GGBF slag, the use of steel slag in cement industry has been much more complicated due to the different chemical and mineralogical properties depending on production method.

So far, numerous studies have been conducted on the utilization of steel slag in Portland cement replacement. Some of their results are listed below:

Altun. et al (2002) studied steel slag in high content of magnesium oxide in partial replacement for Portland cement. Steel slag was grinded to achieve 4000 to 4700 cm^2/gr specific surface and then added to cement powder in 15, 30 and 45 percent of weight. They recorded volume expansion, setting time, compressive and bending strength of mortar and found that compressive strength of mortar reduce when magnesium oxide increases in early stages and this reduction adjusts over time. The produced concrete was acceptable in physical and mechanical properties according to the Turkish standard institute.[1]

Kourounis. et al (2007) have studied properties and hydration rate of blended cement with steel slag. They used 0 to 5 millimeter aggregates of steel slag due to their high amount of calcium silicates and replaced it in cement powder without any process in three percentages of 15, 30 and 45. They recorded setting time, autoclaved expansion and compressive strength after 2, 7, 28 and 90-days prior curing of mortar and found that:

1-Slag cements show lower compressive strength both in final and early stages and growing slag replacement results in more reduction of compressive strength rather than Portland cement. However, cement with 15 and 30 percent slag in composition satisfy the requirements of 42.5 N strength classes in EN 197-1 and cement with 45 percent cement satisfies 32.5 N on it.

2-Setting time and water demand of mortar in slag cements are respectively longer and lower than reference Portland cement.

3-Hydration rate of mortar in slag cement is reduced due to slag replacement and it is probably related to crystal size and C2S existence in steel slag composition.[5]

M. Tossavainen. et al (2007) investigated properties of steel slag under different cooling conditions. They consider four types of slag including ladle furnace slag, basic oxygen furnace slag and two different types of slag from electric arc furnace and observed that water-cooled ladle furnace slags have a glassy structure with 98 percent or more volume stability.[6]

2. Method and materials

The first step in the investigation is identifying the proper slag as pozzolan in the cement structure. For this purpose five samples from dust and slags produced as byproduct in Khorasan steel complex company have been taken as follows:

1- Sponge iron dust ready for melting

2- Sponge pelletizing dust that is brought from Sirjan city for reclamation

3- Dust of FTB part through melting scrap and sponge iron

4- Slag took from scrap and sponge iron melting part

5- Slowly cooled blast furnace slag

The aforementioned samples have been sent to the standard office colleagues' laboratory, Binaloud Kansaran co. to identify components and to choose the best sample for using in the cement composition. It should be noted that no cooling equipment is embedded in Khorasan steel complex co. and slags are cooled in air and no granulation happens.

Slag performance as a hydraulic material is expressed by activation modulus ratio. Increasing alkaline means CaO to SiO_2 ratio (above one) and high aluminum oxide make it more desirable as a cement composition replacement applicant. Acidic slags with high content of SiO_2 and low alkaline ratio having less activation modulus and consequently undesirable in cement replacement. (Table 1)

Considering slag ingredients and according to activation modulus of each sample, the fifth one is chosen as pozzolan and due to the drawbacks of using steel slag in cement industry usage such as low initial compressive strength of slag cement, grinding impossibility of air-cooled slags and difficulties related to impurities in slag composition including free lime and magnesium oxide, steel slag was subjected to physical processing by a ball mill grinder.

TABLE I: XRF analysis of 5 samples from by-products of Khorasan steel complex co.

	SiO_2	Al_2O_3	Na_2O	MgO	K_2O	TiO_2	MnO	CaO	P_2O_5	Fe_2O_3	SO_3	Cl
1	3.03	0.42	0.19	2.56	0.02	0.18	0.03	1.88	0.18	91.37	0	174
2	3.36	0.55	0.19	1.71	0.05	0.26	0.03	1.34	0.2	91.35	0.08	264
3	22.5	3.27	0.34	13.36	0.06	0.93	0.42	30.9	0.85	27.04	0	758
4	3.06	--	--	8.69	4.64	--	0.83	9.38	0.8	47.99	2.65	212
5	20.37	--	0.61	2.78	0.11	0.82	0.37	31.48	0.71	46.26	0.4	--

The existence of iron metal in steel slag would decrease the grinding capability. In order to overcome this limitation, grinding was carried out several times and then sieved using a sieve of 250 micron. According to XRF and chemical analysis of samples passing the sieve and remaining on, it was found that total iron is reduced in 17.5 percent.

Secondly, in order to decrease iron oxides, the steel sags were divided into six categories and the resulting were 5, 10, 15, 20 and 25 percent magnetically purified.

One of the categories was examined with the initial percentage of magnetite without any magnetically purifying process. Properties of all categories are given in table 2.

TABLE II: Magnetite removal percent in slag samples

Slag code	**I1**	**I2**	**I3**	**I4**	**I5**	**I6**	**II1**	**II2**	**II3**	**II4**	**II5**	**II6**	**III1**	**III2**	**III3**	**III4**	**III5**	**III6**
Fe3O4 removal	15	15	15	25	25	25	0	0	0	20	20	20	5	5	5	10	10	10

In order to further reduce iron oxides (magnetite and hematite) and increase slag cement compressive strength, slag samples are mixed with different amount of lime to create a variety of lime content. All samples were analyzed both with XRF and chemical methods in the laboratory of quality control department of East Cement Company to identify the ingredients of each.

According to Iranian standard No. 3517 (Isiri-3517) for slag cements, the amount of slag additive in cement composition varies from 25 to 75 percent in anti-sulfate slag cements. And because the main target of this research is achieving high performance cement with low cost which is resistant to acid attacks. So all slag samples were added to ordinary Portland cement in the same amount of 50 percent and preparing mortars were done by using Standard Normen sand, EN 196-1 and drinking water that satisfies ASTM D1129. It should be noted that adding sand and water in mortar making procedure for all samples were 300 and 50 percent respectively. Summary of samples' components is given in table3.

TABLE III: Samples' component (all data are average of XRF and chemical analysis)

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Cl	Loss	C_3S	C_2S	C_4AF
I1	19.46	4.43	16.82	52.41	2.93	1.32	0.46	0.29	0.09	1.87	7.94	49.80	51.19
I2	18.22	4.37	14.14	54.85	2.94	1.34	0.46	0.32	0.11	3.35	31.37	28.59	43.03
I3	19	4.39	17.22	52.35	2.93	1.08	0.48	0.24	0.1	2.31	11.53	45.79	52.39
I4	15.46	4.25	12.36	57.03	2.91	1.17	0.48	0.31	0.17	6.42	68.49	-7.34	35
I5	15.10	4.23	11.71	58.43	2.91	1.17	0.48	0.31	0.19	6.80	75.96	-14.0	32.36
I6	14.43	4.21	11.11	60.88	2.92	1.17	0.47	0.32	0.20	7.12	89.41	-26.04	28.60
II1	19.86	4.44	17.36	51.56	2.94	1.31	0.46	0.29	0.08	1.78	0.52	56.56	52.82
II2	18.39	4.37	15.61	53.60	2.94	1.28	0.46	0.29	0.11	3.06	23.07	35.32	47.51
II3	18.90	4.37	18.49	51.45	2.92	1.05	0.48	0.22	0.09	2.12	6.99	48.92	56.27
II4	14.63	4.22	10.66	59.13	2.93	1.18	0.47	0.32	0.20	6.48	85.97	-22.89	30.66
II5	14.78	4.22	10.21	60.83	2.92	1.17	0.48	0.32	0.2	6.62	86.62	-22.96	29
II6	14.89	4.22	9.51	59.98	2.92	1.17	0.48	0.32	0.20	6.52	84.62	-21.11	29.54
III1	20.22	4.46	17.81	51.28	2.94	1.31	0.47	0.28	0.07	1.23	-4.07	61.04	54.18
III2	16.69	4.45	16.67	52.51	2.93	1.35	0.46	0.31	0.09	1.62	6.53	51.54	50.73
III3	21.31	4.64	20.43	48.51	2.89	1.07	0.53	0.41	0.10	0.21	-27.93	82.16	62.17
III4	14.60	4.21	8.16	60.28	2.92	1.17	0.47	0.33	0.19	7.04	88.5	-24.36	28.41
III5	14.54	4.22	8.76	59.58	2.92	1.17	0.47	0.33	0.20	7.10	89.70	-25.97	27.79
III6	14.19	4.20	8.16	61.63	2.92	1.17	0.48	0.33	0.21	7.24	96.18	-31.85	26.19

In all experiments, two samples were taken as control. The first one belongs to East Mashhad Cement co. named I0 and the second one is the mixture of 50 percent Portland cement and non-processing steel slag named H, that XRF analysis of both are given in table 4 and table 5.

TABLE IV: Control samples properties

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Cl	Loss	C_3S	C_2S	C_4AF
H	20.49	4.45	25.04	47.02	2.87	1.14	0.53	0.22	0.07	-1.72	- 3.19	83.75	76.19
I0	20.60	4.61	3.82	62.55	2.95	1.87	0.44	0.6	0.08	2.57	56.35	16.57	11.61

TABLE V: Physical properties of control samples

	Compressive strength(kg/cm^2)			**Setting time(min)**		**Density(gr/lit)**	**Blain(cm^2/gr)**
	3-day	7-day	11-day	initial	Final		
H	49.02	68.4	78.45	270	370	3.44	**3585**
I_0	178.8	73.6	320	217	310	3.15	**3264**

Physical tests include compressive strength in 3, 7 and 11th day, initial and final setting time, blain and density are done for all samples. After considering trends between different items, results analyze with Analytical Hierarchy Process (AHP) model based on five factors including: 11-day compressive strength of mortar, density of slag cement powder, magnetite removal percent, percentage of added calcium oxide and average setting time and the optimum sample is chosen.

3. Results and discussion

Figure 1 shows the compressive strength development of mortars over time. The results were obtained from samples that had 50 percent steel slag and were prepared with a water to cement ratio of 0.5. Samples were then tested at an age of 3 days, 7 days and 11 days in order to understand the development of the compressive strength with time and whether or not physical processing had a positive effect on any property of the slag cement. The overall trends show that samples including I1, I2, I3, II1, II2, II3, III1, III2 and III3 have experienced compressive strength blow for minimum limit (100 kg/cm^2 in ISIRI 3517) in y-day results, so these data are not considered in the final conclusion. With the exception of mentioned samples, all data are in standard range and have experienced a significant increase of compressive strength after 7 days and noticeable increase regarding I6 that is 117.2 percent more than the original slag cement. It seems to be so because of mechanical activation of slag and increasing calcium oxide which results in much more activation and compaction of slags and hence compressive strength improvement but as expected, there is a large distance between slag cement and ordinary Portland cement in compressive strength in early ages. And correlation of these two values probably happens in 90 days and over due to the formation of hydration products in the paste, which fills the pores of the microstructure, and contributes to the overall compressive strength.

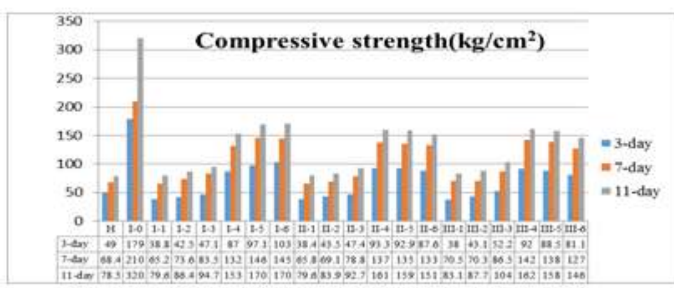

Fig. 1: Compress strength of steel slag mortars with age

A comparison between initial and final setting time of all samples is shown in figure 2. As expected all steel slag cements have longer setting time both in initial and final terms. There are several items that effect setting time such as air temperature, cement type, relative humidity and solar radiation into the shell during tests, percentage and type of additive materials. Given a fixed environmental factors and cement type, it can be concluded that different setting times is a result of slag additive and hence reduction of hydration rate. The slow rate of hydration in steel slag can be accelerated by increasing fineness of particles and curing temperature or more alkaline solution.

It should be noted that a tangible reduction in hydration heat happens with at least 50 percent slag replacement.

Fig. 2: Comparison of slag cement mortars setting time with control samples

Specific gravity of samples is measured and resulting trends are followed. There are no significant differences between values as observed in figure 3, almost all data variety are in range of 2.9 to 3.3 gr/lit. Slight increase in specific gravity in some samples is due to high percentage of iron oxides or heavy metals in them.

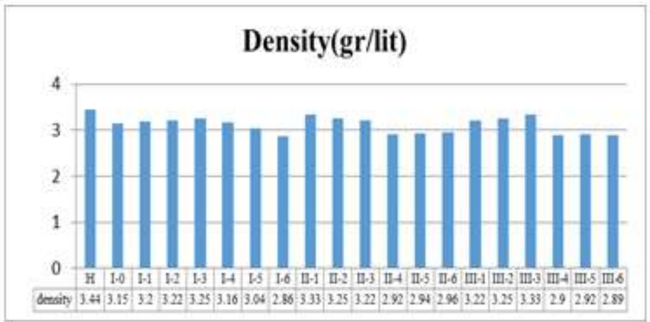

Fig. 3: Specific gravity of slag cements versus control sample

4. Using the analytical hierarchy process for determining of optimum steel slag cement

In many engineering applications, the final decision depends on the evaluation of a set of alternatives in terms of number of decision criteria. This may be a difficult task and the analytical hierarchy process seems to provide an effective way for properly quantifying the pertinent data.

There are ten alternative slag cements described earlier which need to be evaluated in terms of the five decision criteria: magnetite removal percent, calcium oxide percent, setting time, 11-day compressive strength and density.

The structure of decision problem consists of ten alternatives and five decision criteria. Each alternative can be evaluated in terms of the decision criteria and the relative importance (or weight) of each criterion can be estimated as well.

Finally, the following is the judgment matrix for the case of comparing the importance of the four decision criteria and priority vector after normalization. (Table 6)

TABLE VI: Judgment matrix for the case of comparing the importance of the four decision criteria and priority vector after normalization

	Magnetite removal	**Calcium oxide**	**Setting time**	**Compressive strength**	**Density**	**Priority vector**
Magnetite removal	1	3	0.125	0.11	2	**0.098**
Calcium oxide	0.33	1	0.25	0.16	1	**0.058**
Setting time	8	4	1	0.5	4	**0.3**
Compressive strength	9	6	2	1	5	**0.45**
density	0.5	1	0.25	0.2	1	**0.064**

The previous priority vectors are used to form the entries of the decision matrix. The decision matrix and the resulted final priorities are as follows:

TABLE VII: Final priorities vector

samples	I4	I5	I6	II4	II5	II6	III4	III5	III6	H
priority	0.056	0.192	0.207	0.081	0.097	0.088	0.139	0.083	0.037	0.090

5. Conclusion

According to the analytical hierarchy process results, the I6 sample with the priority of 0.207 is the best slag cement rather than other samples based on five criteria including magnetite removal percent, calcium oxide, average setting time, 11-day compressive strength and density. Magnetically purifying slags is the main factor that makes difference between the samples. As observed, increasing magnetite removal results in more compressive strength (except in 15 percent removal item) and made it twice by 25 percent magnetite removal and this means physical processing has a dramatic effect on mortar properties.

6. References

[1] Akin Altun, İ. and Yilmaz ,İ. (2002). "Study on steel furnace slags with high MgO as additive in Portland cement." *Cement and Concrete Research* 32(8): 1247-1249

http://dx.doi.org/10.1016/S0008-8846(02)00763-9

[2] American Society for Testing and Materials International (2013). ASTM D1129- Standard Terminology Relating to Water.

[3] Dongxue, L. Xinhua, F. "Durability study of steel slag cement", Cement and Concrete Research (1997)

http://dx.doi.org/10.1016/S0008-8846(97)00084-7

[4] European Standard (June 2000). EN 197-1- Cement - Part 1: Composition, specifications and conformity criteria for common cements

[5] Kourounis, S. Tsivilis, S. Tsakiris, PE. Papadimitrioum GD and Tsibouki, Z. (2007). "Properties and hydration of blended cements with steelmaking slag." Cement and Concrete Research 37(6): 815-822.

http://dx.doi.org/10.1016/j.cemconres.2007.03.008

[6] Tossavainen, M. Engstrom, F. "Characteristics of steel slag under different cooling conditions", Waste Management (2007)