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EVALUATION OF STEEL FURNACE SLAGS AS CEMENT ADDITIVES

M. Tüfekçi,* A. Demirbaş,† and H. Genç†
*Technical University of the Black Sea, Department of Chemistry, Trabzon, Türkiye
†Technical University of the Black Sea, Department of Science Education, 61335 Akçaabat, Trabzon, Türkiye

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ABSTRACT

Chemical and physical properties and strength development have been studied for six granulated steel furnace slags from the normal steelmaking process. This paper reports results of research performed to develop cement mixture proportions using these slags. The influence of slag proportions, specific surface, and water demand on compressive strength and bulk density of cement blends are presented in this paper. The different test results, which were compared with the Turkish Standards, in general, were found to be within the limits. © *1997 Elsevier Science Ltd*

Introduction

Reutilization of industrial by-products has been a thrust area of research, both ecologially and economically, in recent decades. The cementitious materials presently used for that purpose are silica fume, fly ash, and blast furnace slag (1).

The use of iron blast furnace slag as a cementitious material has been practised in Europe since the late 1800s. It was not until World War II, when slag cement was used extensively as an energy saving measure, that its excellent performance and durability properties were fully appreciated. Today, slag cement in Europe represents nearly 20% of the total cement production (2). In comparison, acceptance of slag cements in the United States has been considerably slower, with only about 1.0% of total cement produced using slag. Slag cements employing blends of Portland cement, with large fractions of ground granulated blast furnace slag, have great potential to affect structure development. The properties of the hardened hydration products, however, must be thoroughly understood (3) for utilizing industrial by-products and saving energy in cement production.

By the treatment of cement additives, production theory of building materials has been developed very rapidly all over the world. Various slags, fly ashes, borogypsum, phosphogypsum, and other by-products have been investigated as additives in the production of cements and concretes (3–12). The composition of steel by-products can change through technological development and the quality of produced steel (9).

The aim of this paper is to study the utilization of some by-products of the iron and steel making processes in cement production. Numerous reports have been presented regarding these efforts in the proceedings of different Symposia (13–21).

TABLE 1
Chemical Compositions of TS 19 and Steel Furnace Slags (SFS-A and SFS-B) and Their Mixtures

Material	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3	Loss on Ignition
Control mix (TS 19)	22.82	5.28	5.85	62.95	1.45	1.05	0.60
SFS-A1	41.39	21.39	3.58	4.22	0.66	0.20	18.46
SFS-A2	42.09	21.30	3.36	4.08	0.64	0.24	18.05
SFS-A3	41.86	21.42	3.48	4.17	0.65	0.23	18.36
SFS-B1	57.48	33.73	2.19	1.53	0.47	0.14	2.39
SFS-B2	56.45	34.07	2.15	1.54	0.45	0.12	2.14
SFS-B3	57.29	32.98	2.18	1.52	0.46	0.15	2.41
10% SFS-A1 + 90% C	24.67	6.78	5.63	57.08	1.44	1.04	3.25
5% SFS-A1 + 95% C	23.75	6.09	5.75	60.01	1.41	1.03	0.97
10% SFS-B1 + 90% C	26.22	8.14	5.49	56.83	1.37	0.95	0.90
5% SFS-B1 + 95% C	24.55	6.70	5.67	59.97	1.40	0.98	0.73

Materials and Methods

All by-products and their mixtures used in this study were provided by Simkent Production Industry in Kazakhstan. Physical and chemical tests were done in the Trabzon Cement Factory in Türkiye. Steel furnace slags (SFSs) were used as additives to cement.

Table 1 shows the chemical compositions of cement SFSs. The control mixture (TS 19), Class A and Class B (SFS-A and SFS-B), and slag were mixed and ground to a specific surface of 2870–2900 cm^2/g. Cement test mixtures were prepared according to Turkish Standards TS (22). The physical tests were carried out according to TS 24.

Results and Discussion

The physical properties of the mixtures are shown in Table 2. The results for compressive strength, volume expansion, and setting time for cement mixtures are summarized in Table 3. The aggregate data and compressive strength test results for cement mixes compared to the control mix are given in Table 4.

It is not sufficient to test only one or two samples to obtain information on its suitability

TABLE 2
Physical Properties of Cement

Properties	Control mixture	10% SFS-A1 + 90% C	5% SFS-B1 + 95% C
Specific gravity (g/cm^3)	3.20	3.15	3.23
Specific surface (cm^2/g)	2800.00	2902.00	2872.00
Weight per Volume (g/L)	1080.00	1035.00	1078.00
Water requirement (% of control)	100	98	96
Moisture content (% by weight)	0.38	0.44	0.35

TABLE 3
Results of Cement Mortar Tests

	Compressive Strength (MPa)			Volume Expansion	Vicat Set. Time Hour : Minute	
Cement Mix	3 days	7 days	28 days	Total (mm)	Initial	Final
Control mixture	26.2	34.8	45.4	10 (max.)	1:00	10:00
10% SFS-A1 + 90% C	22.9	31.0	41.3	9	3:05	4:15
5% SFS-B1 + 95% C	25.5	33.5	44.5	4	3:00	4:15

as a secondary constituent of a cement and to then assign the same category with a material approved over a long period. The essential precondition for utilization of any secondary material in cement is that it is sufficiently uniform. For concrete, it is not sufficient to determine compressive and bending strengths, setting time, and soundness. For ready-mix concrete, data on the water demand of cement, and its variation with composition, specific surface area, and grain size distribution should be available. Moreover, for the introduction of a new material, it is advisable to determine its origin and chemical and mineralogical composition.

The data in Table 3 indicate that the compressive strength of the cement mix, 10% SFS-A1 + 90% C, increases slowly when compared with 5% SFS-B1 + 95% C mortar mix. This is due to the 5% higher replacement of cement by a less reactive material. Some researchers (15) have used CaO instead of Portland cement for simplicity in investigating the hydration behaviour of slag, which provides essential information, but there are significant differences between the effects of CaO and cement clinker on slag hydration. In order to obtain the most fully applicable information, the direct study of slag cement samples is important.

Compressive strength generally increases with the decreasing amount of impurities in the cement mix (6). Thus, as seen in Table 4, the strength decreases with the increasing percents of SFS-A and SFS-B, especially for SFS-1, in the mixtures.

It has been stated (23) that slag cements have lower early strength, which is attributable to the slow growth of C-S-H gel. In the case of very high-strength concrete, however, this is compensated by the density of the solid body.

A number of researchers (24–26) have observed AFt rods on slag particles during their

TABLE 4
Compressive Strength Test Results for Concretes from Cement and Slag Mixtures

Cement (g)	SFS-A1 (g)	SFS-B1 (g)	Natural Sand (g)	Crush Stone (g)	Water (g)	Compressive Strength (MPa) 1-day	7-day	28-day	56-day	90-day
410	0	0	1215	1540	260	10.7	26.3	32.9	35.6	38.7
390	21	-	1210	1520	250	8.9	19.1	26.7	28.0	30.5
370	42	-	1210	1530	240	7.9	22.1	28.7	30.0	34.5
350	60	-	1212	1520	232	7.3	19.1	26.7	28.6	30.9
390	-	21	1213	1522	245	9.9	25.2	31.7	34.9	37.6
370	-	42	1210	1525	235	9.7	24.8	30.9	33.7	37.0
350	-	60	1212	1530	225	9.4	24.2	30.1	32.8	36.7

TABLE 5
Correlation Matrix (R) for 3-, 7-, and 28-Day Compressive Strength with Granulated Slag Composition Parameters (Eight Sample, Laboratory Grind)

Parameter	SiO_2	Al_2O_3	S	CaO	MgO	Fe	Mn
3-day compressive strength	−0.93	0.75	0.43	−0.08	0.58	0.55	−0.60
7-day compressive strength	−0.90	0.76	0.46	−0.04	0.63	0.52	−0.72
28-day compressive strength	0.34	0.01	−0.48	−0.43	0.18	−0.13	0.44

R = 0.71 for 95% probability of a correlation.
R = 0.79 for 98% probability of a correlation.

initial hydration. In a concrete with low lime slag, ettringite may be lower. The hydration of slag is basically the dissolution of the silicate chain structure and aluminate (in the slag) by hydroxyl attack (24). For the slag to continue hydrating, Ca^{2+} and OH^- from the slag are not enough, so an external supply becomes necessary (26). In low w/c concrete, the supply of external OH^- is drastically diminished. The elution of selective ions is therefore delayed; the reaction rim only begins to be visible from day 7 of hydration (26).

According to Cook et al. (2), ettringite crystal formation in the early stages of ordinary slag hydration in concrete acts as a binder, resulting in the higher strength.

To determine what operating parameters and slag properties affect product quality, a linear correlation coefficient study (28) was performed using the 3-, 7-, and 28-day compressive strengths of the 50/50 mortars containing the laboratory-ground slag.

A few significant correlations were observed between the slag composition parameters and the 3-, 7-, and 28-day compressive strengths (Table 5) (9). For the 3- and 7-day compressive strengths, strong negative correlations were found to exist with SiO_2, along with somewhat weaker positive correlations with Al_2O_3. High SiO_2 concentrations have been demonstrated to be detrimental to the compressive strength, which explains the SiO_2 correlations. No significant correlations were found to exist between the 28-days compressive strengths and any of the slag composition parameters.

As can been seen in Table 1, the chemical compositions of the SFS-Class A are quite different from the SFS-Class B; SiO_2, and especially Fe_2O_3, contents are much higher in SFS-Class B.

Specific density, specific surface, and weight per volume values of cement mixes are very reasonable with the Turkish Standard, TS 19 (22).

Conclusions

The results obtained from the present study lead to the following general conclusions: 1) that steelmaking by-products could be used as a partial replacement of cement, without decreasing the compressive strength significantly; and 2) that the specific surface and water requirement values of the ground-granulated slags and the cement used in the mixtures have marginal differences.

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