APPLICABILITY OF ECW* STEEL SLAG IN CONCRETE

Adel Kurdi
Dept. of Struct. Eng, Faculty of Engineering,
Alexandria University, Alexandria, Egypt.

Aly Eldarwish
College of Engineering & Technology,
Arab Academy for Science & Technology

Rafic Abbas
Arab Contractors, Alexandria, Egypt.

* Egyptian Copper Works Company, Alexandria, Egypt.

ABSTRACT

An experimental program aiming at characterizing the Egyptian Copper Works Company (ECW) steel slag and studying its applicability in concrete was carried out. ECW steel slag proved to be mainly composed of CaO, FeO, SiO_2, and MgO and was also characterized by its basicity. The mineralogical composition of steel slag showed the predominant presence of the RO-phases, dicalcium silicate, dicalcium ferrite, and free calcium oxide and/or hydroxide. Water spraying proved to be effective in accelerating the hydration of free lime. Compared with lime stone concrete, steel slag concrete exhibited higher modulus of elasticity and compressive strength, while showing statistically comparable splitting tensile and flexural strength. Besides, steel slag provided higher restraint to shrinkage of cement paste, leading to lower shrinkage strain than lime stone high-strength concrete. X-Ray diffraction analysis of the hydration products at the interfacial zone of steel slag concrete revealed the presence of chemical interaction between the steel slag and the cement paste, as well as pink lime stone concrete.

Keywords: ***Steel slag, Mechanical Properties, Differential thermal analysis, Heavy weight high strength concrete, X-Ray diffraction.***

INTRODUCTION

Rapid urbanization and industrialization have led to severe pollution, water that is unfit for human use, extreme levels of air contamination, and growing quantities of industrial wastes are disposed improperly. Environmental management encompasses a variety of strategies for dealing with wastes. A hierarchy has been developed to prioritize these strategies. This hierarchy is Pollution prevention, waste recycling or reusing, waste treatment and waste disposal. The second priority in the hierarchy, is waste recycling, in order to utilize it to a greatest extent. It has been reported that; " Egypt suffers from a number of serious environmental problems that has occurred through the industrial and commercial growth without regard to the environment" [1]. However, the Egyptian Government has made progress in environmental protection by developing an Environmental Action Plan, creating an environmental regulatory agency, and promulgating new regulations for the Omnibus Environmental Law. Meanwhile, it is the duty of the Egyptian industrialists themselves to reduce their environmental impact. Metallurgical slag, arising as a waste product of metals refining processes, is one of the crucial problems facing many different industries. From the quantitative point of view, steel slag is considered to be the second waste product of the metallurgical processes.

In Alexandria, the Egyptian Copper Works Company (ECW), produces 10 000 m^3/annually of steel slag. Steel slag damping area occupies about 40% of the total ECW territory. Besides, the existing cost of slag disposal is about 5.0 LE/ton for transportation. This might solve the internal ECW problem, but it actually transfers the problem outside its fence. In a previous investigation [2] on a representative batch of steel slag which was aimed to study the applicability of steel slag as coarse aggregate in concrete. Results were very encouraging, and the following concepts were realized; No incompatibility was noticed from the use of steel slag with Portland cement; Properties of fresh slag concrete were significantly affected by the use of slag as coarse aggregate. In addition, unit weight of slag concrete was higher than that of gravel by an average value of 15 percent. Moreover, when compared to ordinary gravel concrete, short term properties of concrete were improved by using slag as coarse aggregate. For instance, the 28-day compressive strength of slag concrete was higher than of gravel concrete by 22%. In addition, slag concrete mixes with 450 Kg/m^3 cement content and a water cement ratio of 0.4, achieved a compressive strength in the order of 530 Kg/cm^2 after 28 days, this concrete could be regarded as heavy-weight high-strength concrete (where the lower limit of the cylinder compressive strength of high strength concrete is in the range of 410 Kg/cm^2) [3].

RESEARCH SIGNIFICANCE

This study aims to carry out a comprehensive investigation of the chemical, mineralogical, physical, and mechanical properties of different batches of the steel slag produced at the Egyptian Copper Works Company, Alexandria, Egypt (ECW). In addition, the susceptibility of producing heavy-weight high-strength concrete incorporating steel slag as coarse aggregate was also investigated.

EXPERIMENTAL PROGRAM

Characterization of Slag

This paper presents the experimental results on studying the chemical, mineralogical, physical and mechanical properties of steel slag produced at the Egyptian Copper Works Company, Alexandria, Egypt (ECW).

Chemical and Mineralogical Composition

The chemical analysis of forty-seven different batches assembled from the dump area and the furnaces (i.e., the open-hearth and the electric-arc furnaces) was carried out at the ECW Lab. The effect of furnace type on steel slag composition was also examined statistically. The one-way analysis of variance was performed at three levels, each representing one furnace type. The X-ray diffraction analysis (XRD) was carried out to identify the crystalline phases of steel slag. Four samples were examined representing the three furnaces and the dump area.

Determination of Slag Stability

The following test methods were carried out to determine the effect of free calcium and magnesium oxides on the volume stability of steel slag.

-Free Lime:

The volume stability, in terms of free lime content, of four different batches of steel slag was examined according to ASTM C-114 [4]. The effect of natural weathering and artificial weathering (i.e., by water spraying) on the hydration speed of free lime was determined. The free lime content of each of the four batches was calculated and recorded. The artificial weathering was accomplished by spraying two different amounts of water for a period of 90 days (10 and 20% of the sample weight). The decrease in the amount of free lime for each batch and under different weathering conditions was determined versus time. Statistical analysis (two-way analysis of variance) was performed to determine the interaction between the initial free lime content, as one factor, and the amount of water used to accelerate the lime hydration, as second factor.

-Free Magnesia:

The effect of free magnesia on volume stability of steel slag was examined according to the autoclave test (ASTM C-151) [4]. The autoclave test was carried out on three weathered steel slag samples collected from three different batches and ground to a fineness similar to that of OPC. Four series of specimens were casted, the first was composed of OPC only (control). For the other three series, each was composed of a mixture of OPC and one of the slag samples, with a proportion of one to one. It is important to note that the mixing proportion was chosen to simulate the portion of slag in concrete, and the OPC was used as a binding material. Three specimens were casted for each of the four series. The autoclave test was then performed on the four series. After completion of the test, the specimens length were measured and the percentage of expansion was calculated.

Physical and Mechanical Properties of Steel Slag

The physical and mechanical properties of nine steel slag batches were tested and also compared with the properties of natural aggregates (gravel and lime stone) gathered from different quarries. The gravel samples were from El-Khatatba and El-Yarmouk quarries. The lime stone samples were from Alam El-Markab, El-Hammam and El-Dabaa quarries. The following standard tests were performed; specific gravity and absorption (ASTM C-127) [4], unit weight and voids (ASTM C-29) [4], soundness by using sodium sulfate (ASTM C-88) [4], resistance to degradation by Los-Angeles machine (ASTM C-131) [4], and crushing value (BS 812) [5]. Means and standard deviations of all results and for each type of aggregates were also calculated.

Differential Thermal Analysis of Steel Slag

Differential thermal analysis (DTA) was used to determine the phase transformation of the powder scraped from the surface of the slag particles, with a wire brush, at the end of the weathering period. DTA was carried out on a Shimadzu thermal analysis instrument (DTA-30). The conditions used were; sample weight 20 mg, heating rate of 20 °C/min, and sensitivity of 25 μv.

Steel Slag Concrete

Ordinary Portland cement, and natural siliceous sand from El-Khatatba quarry were used in all mixtures. The unit weight, specific gravity and fineness modulus of fine aggregate were 1.7 t/m^3, 2.6 and 2.7, respectively. Superplasticizer (sikament FF3), polymer type was used in this study to achieve the recommended slump (10 $\pm$ 0.5 cm). Coarse aggregate; pink lime stone and steel slag were used as coarse aggregate. The maximum aggregate size was 19 mm. The unit weight, specific gravity and absorption of pink lime stone were 1.55 t/m^3, 2.61 and 2.6%, respectively. To keep the grading of lime stone similar to that of slag, manual sieving with different mesh sizes were used to separate grains into different sizes. Then, the retained weights in each sieve were recombined in a reverse way to replicate the grading of steel slag. The latter was taken from the damp area at the ECW (weathered slag). Grading of steel slag, excluding huge particles, was used as provided by the ECW. Grading of steel slag was; 0% was retained on a 3/4 in. sieve, 58% passed from 1/2 in. sieve, 22% passed from 3/8 in. sieve and 0.15% was passed on No.4 sieve. Table (1) shows the comparison between the physical and mechanical properties of steel slag and natural coarse aggregates used in this investigation.

Mix Proportions

The mix proportions were determined according to the American Concrete Institute Committee 211. Table (2) shows the mix proportions used in this study. Concrete specimens were cast and cured according to ASTM C-192 [4].

Tests on Steel Slag Concrete

Fresh Properties of lime stone and slag concretes were determined by carrying the following tests; slump test (ASTM C-143) [4], fresh unit weight (ASTM C-138) [4], compacting factor (BS No 1881) [6], and Vebe test (BS No. 1881) [6].

The following tests were performed on hardened lime stone concrete (control) and slag concrete; compressive strength (BS 1881) [6] at 1, 3, 7, 28, 56, 90, 180 and 365 days on 100mm. cube specimens, splitting tensile strength(ASTM C-496) [4] at 7, 28 and 56 days on 75*150mm. cylindrical specimens, flexural strength (ASTM C-293) [4] at 7 and 28 days on 100 * 100 * 500 mm. beams, static modulus of elasticity (ASTM C-469) [4] at 7 and 28 days on 150 * 300mm. cylinders, and drying shrinkage (ASTM C-157) [4] on 75 * 75 * 285mm. beams. The hydration products of cement at the interface of both types of aggregate were examined by means of X-ray diffraction analysis (XRD). Statistical analysis for all the results were performed at each age. The two-way analysis of variance were carried out by using a 2 x 5 factorial combination of coarse aggregate type and cement content.

Table 1. Comparison between physical and mechanical properties of steel slag and natural aggregates.

Property	Gravel	Lime stone	Steel slag	ASTM Limits
Bulk specific weight Bulk specific weight (SSD) Apparent specific weight	2.61 2.64 2.68	2.55 2.61 2.69	3.44 3.48 3.53	
Bulk unit weight, compacted t/m3	1.65	1.52	1.91	
Voids ratio, %	33.4	39.2	37.4	
Water absorption, %	0.87	2.17	1.91	
Soundness by Na_2SO_4, % loss after 5 cycles	1.12	1.45	0.90	< 12 %
Los-Angeles test % loss after 100 revolutions % loss after 500 revolutions Ratio = % loss at 100/ loss at 500	 4.01 20.4 0.19	 7.87 26.3 0.28	 3.12 13.07 0.24	 < 50 % 0.20
Crushing value, % (BS No. 812)	16.8	19.6	12.5	< 40 %

Table 2. Mix proportions for lime stone (L) and steel slag (S) high strength concretes.

Mix	Cement kg/m3	Water L/m3	Coarse kg/m3	Sand kg/m3	Admix. L/m3	W/C	A/C
L1	550	160	1100	600	6.65	0.29	3.1
S1	500	160	1475	590	8.6	0.29	3.74
L2	500	160	1100	640	6.04	0.32	3.48
S2	500	160	1475	630	7.85	0.32	4.21
L3	450	160	1100	685	5.45	0.35	3.96
S3	450	160	1475	675	7.1	0.35	4.7
L4	400	160	1100	725	5.1	0.4	4.56
S4	400	160	1475	720	6.75	0.4	5.48
L5	350	160	1100	770	4.5	0.45	5.34
S5	350	160	1475	765	6.0	0.45	6.4

RESULTS AND DISCUSSION

Characterization of Steel Slag

Shape and Surface Texture

The external characteristics of slag particles is an important factor when dealing with its use as aggregate. According to the BS 812 [5], steel slag particles may be described as irregular particles, besides some particles may have well-defined edges (angular). Slag particles show rough and honeycombed (i.e., with visible pores and cavities) surface. Generally, steel slag particles have the appearance of an igneous rock.

Chemical Analysis

An overall statistical analysis of 47 slag samples collected from different sources (the three different furnaces and the dump area) is given in Table (3). Basicity (expressed in terms of [CaO% + MgO%] / SiO_2%) is also given. Chemical compositions of slag vary a good deal, even between samples from the same process. Large and varying amounts of iron are usually retained in the slag. The iron content which is reported as FeO, is actually present in the ferrous (FeO) and ferric (Fe_2O_3) states and ranges between 19 and 38 percent. The silica content ranges between 7.5 and 20 percent, depending on the amount of silica in the furnace charge, specially the steel scrap and pig iron. The latter may contain as high as 3% silica. The calcium oxide, which is one of the principal constituents of basic steel slag, ranges from 28 to 41 percent. The amount of calcium oxide added to the furnace charge is adjusted so as slag may perform its duty successfully (usually 50 kg of CaO per ton of furnace charge). Scarification of the lining (which is composed mainly of MgO) by the iron oxide formed during melting of the charge, is responsible for the high content of MgO in slag [7]. The magnesium oxide varies between 8 and 16.5 percent. Addition of ferromanganese to the furnace charge is essential to give the molten steel the required fluidity during casting. This is reflected on the manganese content in slag, where it ranges from 7 to 13 percent. Phosphorus, which is introduced to the furnace with steel scrap and pig iron (the latter may contain phosphorus up to 0.7 %), varies between 1.8 to 4.4 percent. Aluminum oxide, which is present as impurities in the furnace charge (Scrap, pig iron and lime), is usually found with contents ranging from traces up to 3.0 percent by weight.

Table 3. Statistical analysis of the chemical compositions of steel slag samples.

Chemical compositions	SiO_2	Fe_2O_3	CaO	MgO	MnO	P_2O_5	L.O.I	Basicity
Average content,%	12.1	26.6	33.8	12	9.0	3.3	2.1	4.0
Variance, %	10.1	21	9.1	7.4	1.3	0.8	0.1	1.0
S.Deviation, %	3.2	4.6	3.0	2.7	1.1	0.9	0.3	1.0
Standard Error, %	0.5	0.7	0.4	0.4	0.2	0.1	0.04	0.1
Min. Content, %	7.4	18.6	28.1	8.0	6.9	1.8	1.7	2.3
Max. Content, %	19.2	38.2	41.7	16.5	13.2	4.4	2.9	6.0
Range, %	11.8	19.6	13.6	8.5	6.4	2.6	1.2	3.7
Coefficient of variation, %	26.4	17.3	8.9	22.5	12.2	27.3	14.3	25

The basicity of steel slag also vary a good deal and ranges from 2.3 to 6.0 percent. Compared to the blastfurnace slag (which ranges between 1.2 to 1.4) [2]. This is due to the high content of lime and magnesia and to the low content of silica. Statistical analysis showed that the slag composition is not significantly affected by the furnace type. For instance, the variation in the silica content between the samples from different furnaces is not statistically significant. This is also true for all the oxides. Thus, the chemical analysis of slag depends mainly on the furnace charge.

X-Ray Diffraction Analysis of Steel Slag

The variation in the chemical analysis of steel slag is reflected on its mineralogy. Figure (1) shows the XRD patterns of two different slag samples. For the sake of simplicity, the different phases present in slag samples are presented in Table (4) as well as the relative amount of each phase is given, expressed in proportion to the main peak of the major phase. It is important to note that there is almost no possibility for the formation of glassy phases, owing to the high basicity and high fluidity of the steel slag [8].

Based on the investigated samples, the following phases are usually found:

- RO-phase, composed of solid solutions of FeO, MgO, and MnO, with great predominance of FeO.
- Dicalcium silicate
- Dicalcium ferrite
- Free calcium oxide in unweathered samples, and calcium hydroxide and/or calcium carbonate in weathered steel slag.

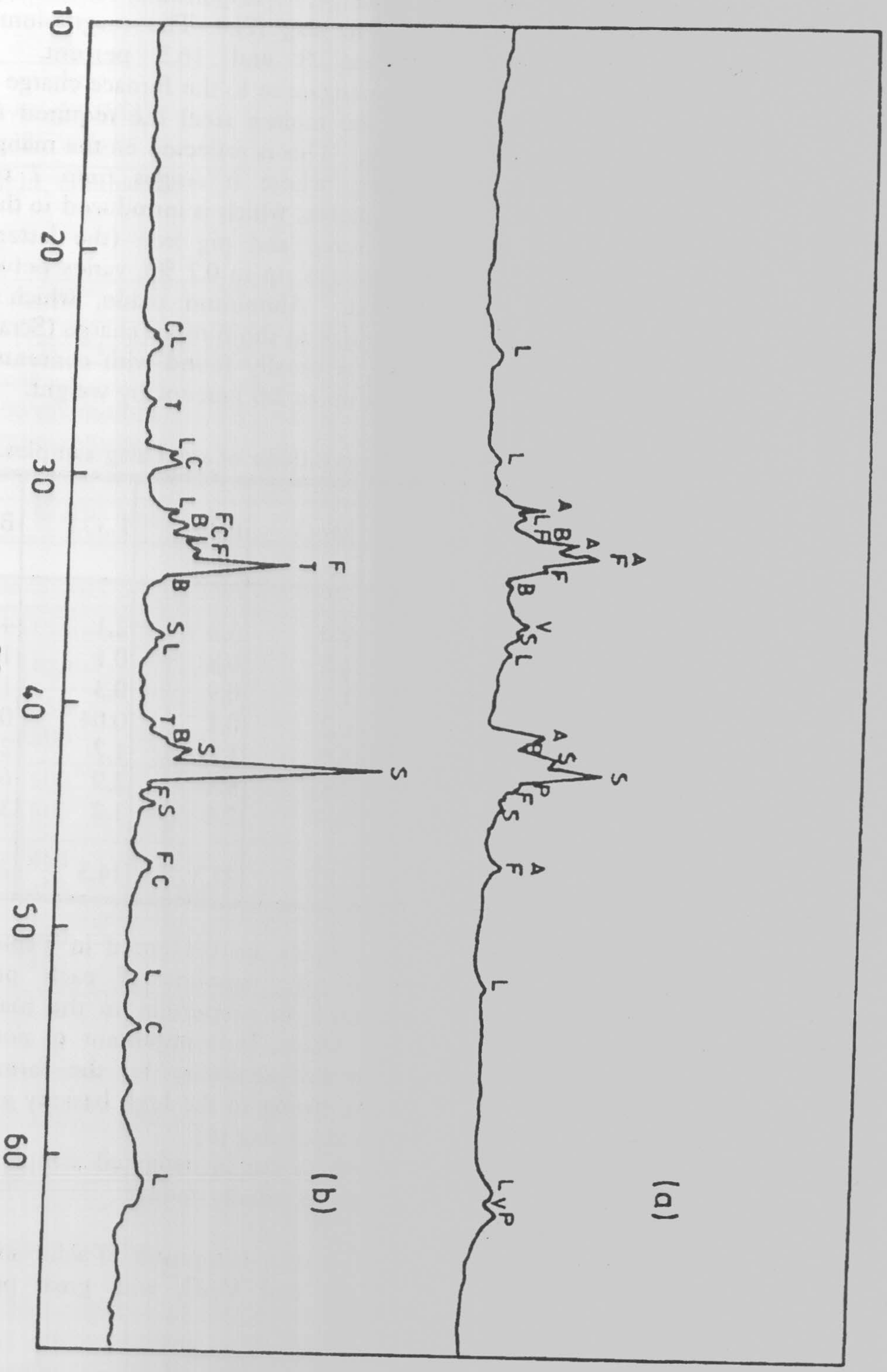

Figure 1. The X-ray diffraction pattern of two steel slag samples (a) and (b). Wustite (V), Periclase (P), Ro-phase (S), Alpha-dicalcium silicate (A), Beta-dicalcium silicate (B), Gemma-dicalcium silicate (C), Gehlinite (L), Mervinite (T), Dicalcium ferrite (F).

Table 4. The different phases present in steel slag.

Phases	Sample No.	
	(a)	(b)
Wustite (FeO), V	Low	-
Periclase (MgO), P	Low	-
Ro-phase [(Fe,Mg,Mn)O], S	High	High
Alpha-dicalcium silicate, A	High	-
Beta-dicalcium silicate, B	Low	Low
Gamma-dicalcium silicate, C	-	Low
Gehlinite ($2CaO.Al_2O_3.SiO_2$), L	Low	Low
Mervinite ($3CaO.MgO.2SiO_2$), T	-	Medium
Dicalcium ferrite ($2CaO.Fe_2O_3$), F	Medium	Medium

Hydration Rate of Free Lime

Four samples containing different free lime content were investigated. The content of free lime were 2.15, 3.82, 3.44 and 2.68 percent by weight. The effect of natural weathering on the amount of free lime is shown in figure (2.a).The effect of water spraying on the hydration speed of free lime was also examined. Figures (2.b and 2.c) illustrate the decrease in the amount of free lime under the effect of water spraying versus time. Natural weathered slag samples exhibit a decrease in the amount of free lime at high rate during the first 75 days. This could be attributed to the speedy hydration of free lime located at near the particles surface and/or around the surface of pores. Meanwhile, hydration of free lime away from particles surface may need longer time, so the curve begins to level off after the first 75 days. The content of free lime becomes constant after an aging period of 150 days. On the other hand, water spraying proved to accelerate the hydration process of free lime. Regardless of the amount of sprayed water, the decrease in free lime shows a higher rate than the first case. Besides, the time needed to achieve the lowest free lime content is affected by two main factors; the amount of sprayed water and the initial free lime content. Samples containing high free lime content reached the lowest content after 90 days. And samples containing free lime in the range of two percent reached the lowest content after 60 and 75 days, depending on the amount of sprayed water. It is important to note that neither the two-factors interaction (initial free lime content and water amount) nor the water amount factor are significant. However, the initial free lime content is highly significant. It may be concluded that the water amount is not effective on the weathering duration, and the lowest water content (10 percent of the sample weight) may be used. Besides, the initial free lime content has the main effect on the weathering time.

Effect of Free Magnesium Oxide on Slag Stability

The source of magnesium oxide in steel slag is mainly the furnace lining, which is composed essentially of dolomite. The autoclave test was carried out on three weathered steel slag samples according to ASTM C-151 [4]. Each sample was composed of a mixture of OPC and slag with a portion of one to one. The content of magnesium oxide in slag ranges between 8 to 16.5 percent by weight (with a mean of 11.95 percent). A portion of MgO occurs as crystalline MgO (Pericles). Although the free MgO was found as a minor phase, its hydration was taken into consideration and the autoclave test was carried out. The MgO content in OPC, which was used as binding material, is 2.25 percent by weight. For the tested slag samples, the content of MgO are 16.0, 11.2 and 14.7 percent by weight, respectively.

Results of autoclave test on OPC, and cement-slag combination are given in Table (5). According to the ASTM limits, the expansion must not exceed 0.8 percent of the initial bar length. Steel slag proved to be sound even with high content of MgO (e.g.; 16.0%). This may be due to the cooling rate of steel slag, where the size of pericles crystals is in direct relation with the former. Small grains of pericles hydrate more rapidly than larger ones and have less tendency to cause expansion. It was found that crystals of 30-60 μm in size produce expansion four times larger than that of crystals below 5 μm in size [9]. It is well known that steel slag when tapped from the furnace is usually treated with water (rapidly cooled), hence, may give rise to small pericles crystals. The latter may undergo rapid hydration during the weathering period, without any harmful expansion through the autoclave test.

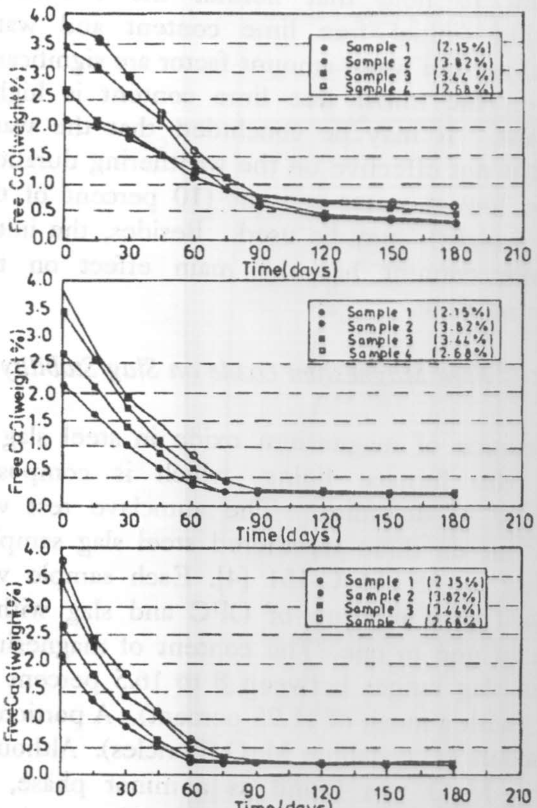

Figure 2. Effect of water spraying expressed as a percentage of the sample weight on the free calcium oxide content.
(a) Natural weathering (b) Sprayed water=10%
(c) Sprayed water=20%.

Physical and Mechanical Properties of Steel Slag

The specific gravity of steel slag typically ranges between 3.42 and 3.46. Compared to natural aggregates (e.g., gravel and lime stone) which have a specific weight ranging from 2.55 to 2.62. Steel slag may be classified as heavy weight aggregate. Natural heavy weight aggregates consist predominately of barium minerals and iron ores. The specific weight of natural heavy weight aggregates varies between 3.4 and 7.5 [10]. Although the specific weight of steel slag is very close to the lower limit of the heavy weight criterion, steel slag may substitute several iron ores which have a specific weight ranging from 3.4 to 4.0.

In addition to the specific weight, steel slag has a unit weight of 1.91 ton/m^3, which is higher than normal weight aggregate. For instance, typical values of gravel and lime stone are 1.65 and 1.53 ton/m^3, respectively. The difference in specific weight and unit weight between steel slag and natural aggregate may be attributed to the minerals composition of the former (e.g., iron, magnesium and manganese). Besides, other compounds present in slag such as dicalcium silicate and mervinite have specific weight of 3.28 and 3.6, respectively. Voids between slag particles is higher than gravel. This may be referred to the irregular shape of slag particles. In addition, water absorption of slag is higher than gravel and lower than lime stone. Results of soundness test of natural aggregates and steel slag by using sodium sulfate are presented in Table (1). As stated by Mehta [11], high water absorption and high porosity are often used as index for unsoundness. However the soundness of slag is lying within the ASTM limits and is of lower value than gravel and lime stone. This may be due to the high strength of slag particles, which could retain higher stresses without undergoing disruption.

It is evident from results given in Table (1) that steel slag exhibits high resistance to abrasion. This low abrasion value as compared to natural aggregate should be taken into consideration together with the crushing value, where slag shows its strength. Comparing these values with those of natural gravel and specifications limits, it becomes very clear that steel slag possesses high mechanical properties.

Table 5. The autoclave test results of ordinary portland cement (OPC) and OPC + steel slag combination (one to one).

Sample	MgO content (wt. %)	Expansion (%)
OPC	2.25	0.12
OPC + steel slag [sample No. 1]	16.0	0.41
OPC + steel slag [sample No. 2]	11.2	0.225
OPC + steel slag [sample No. 3]	14.7	0.37

ASTM limits: Expansion < 0.80 % of the initial specimen length.

Differential Thermal Analysis of Steel Slag

Differential thermal analysis (DTA) of powder scraped from the surface of the slag particles is given in Figure (3). Two endothermic peaks at about 70°C and 140°C, and a bulge at about 765°C. The first and second peaks appear to be attributed to the loss of free and interlayer water, which may be due to the loss of free and interlayer water, which may be present in slag phases undergoing hydration during weathering (e.g., diclacium silicate and dicalcium ferrite). The endothermic large peak at 765 °C may be referred to the decomposition of calcium carbonate. The latter may be present due to the carbonation, of calcium hydroxide derived from the hydration of free lime and/or slag phases, by CO_2 present in air. Besides, it is important to note that the powder scraped from the surface of the slag particles is consisted mainly of calcite. Where in DTA curve, the area of the peak is proportional to the amount of the material [12].

SLAG AS AGGREGATE FOR HEAVY WEIGHT HIGH-STRENGTH CONCRETE

Properties of Fresh Concrete

Fresh properties of both types of lime stone and steel slag concretes are presented in Table (6). Slump was kept constant in all mixtures (10±1.25cm). It is clear that steel slag concrete needs higher dosage of superplasticizer, with an average value of 0.7 percent of cement weight, in order to achieve similar consistency to lime stone concrete. Experimental test results (Table 6) showed that a higher amount of work was required for slag concrete to reach a similar workability to that of lime stone concrete. For instance, the time required for remolding slag concrete (Vebe test) is longer than that of lime stone concrete with an average value of 0.7 second. This may be attributed to the irregular shape and honeycombed surface of slag particles, which may lead to a higher internal friction between slag particles.

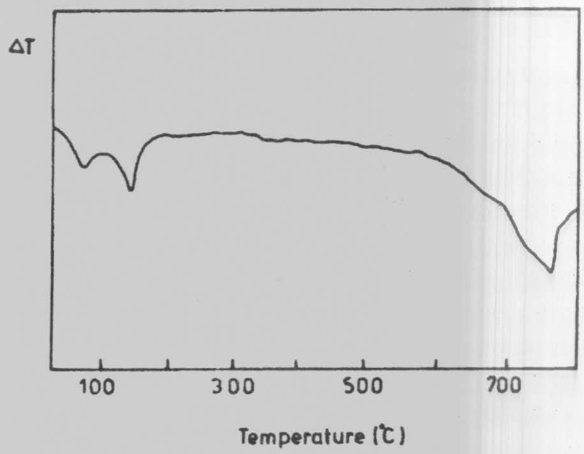

Figure 3. The deferential thermal analysis curve for powder scraped from the surface of steel slag particles.

The fresh unit weight of slag concrete ranges from 2.75 to 2.78 ton per cubic meter and 2.38 to 2.41 ton per cubic meter for lime stone concrete. The higher unit weight of slag concrete is attributed to the difference in specific weight between steel slag and lime stone (3.44 and 2.61, respectively), which is due to the difference in chemical composition and the higher metallic content of steel slag particles. It may be noted that no sign of segregation was detected, which is a common phenomenon encountered in other studies on heavy weight concrete, where the tendency of coarse aggregate to segregate in concrete increase with the density of the aggregate [13]. This may be referred to the shape and surface texture of slag particles which tend to gather the mortar around its surface during handling and placing, thus prevent segregation.

steel slag aggregate is characterized by its high modulus of elasticity and low compressibility. So, steel slag provided higher restraint to the shrinkage of cement paste, leading to lower drying shrinkage.

COMPARISON BETWEEN STEEL SLAG AND PINK LIME STONE HIGH-STRENGTH CONCRETES

One of the most common natural heavy weight aggregates is barite (barium sulfate) [13], however it tends to break up and dust so that care must be taken in handling and processing. Besides, concrete containing barite does not stand up well to weathering. Other types of heavy coarse aggregate are iron ore, magnetite, limonite and geothite which are used, and ilmenite ($FeTiO_3$) has been employed as fine aggregate [10]. Artificial heavy aggregates are also used, mostly steel and sometimes lead. Steel shots makes concrete with a very high density, but this type of aggregate is about six times dearer than natural heavy aggregates [10]. Steel punching and sheared bars are also used, but due to their shape additional difficulties in mixing the concrete are encountered [13]. Heavy-weight concrete are prone to segregation because of the disparity in specific gravities of coarse and fine aggregates. Consequently, the replaced aggregate method is a must to prevent segregation. On the contrary, steel slag proved to behave rather like natural crushed lime stone aggregate, and did not show any problems usually encountered with heavy aggregates.

According to the aforementioned results, lime stone high-strength concrete achieved high strength level. This order of strength was also achieved in concrete made with steel slag. Besides, concrete containing steel slag exhibited higher strength level than lime stone concrete. However, there are important differences in the characteristics of the fracture surface. The preceding discussion about cracking pattern implies that nature of matrix-aggregate bond for lime stone and steel slag are quite different. In the following, bond between both types of aggregate and the matrix, which may be due to chemical interaction and/or mechanical and physical effects will be discussed:

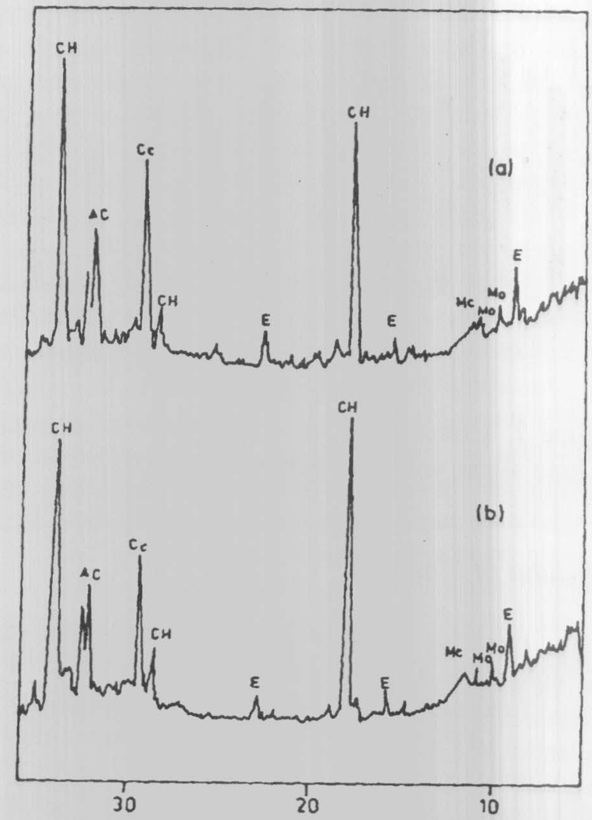

Figure 9. The X-ray diffraction patterns of hydrated cement paste from the interface of (a) lime stone. (b) steel slag. E: ettringite, Mo: monophases, Mc: monocaroaluminate, CH: calcium hydroxide, Cc: calcium carbonate, Ac: anhydrous cement.

Chemical Interactions

The X-ray diffraction (XRD) of the cement paste at the interfacial zone of both types of aggregate are given in Figure (9). The presence of monocarbo-aluminate hydrate (Mc, d-value 7.6 A°) and solutions with other monophases (Mo, d-value 7.9,8.9 A°) in lime stone concrete could be a reason for the higher bond. There are many examples in the literature of high-strength concrete made with lime stone [14,15]. In steel slag concrete, the aforementioned compounds are present and may be due to the reaction between the calcium carbonate formed at the surface of steel a slag particles (as detected by the DTA of powder scraped from the particles surface) and the hydration products of cement. So, those compounds may improve the density and strength of the transition zone, which in turn may affect the bond between the slag and surrounding matrix.

Mechanical and Physical Effects

The matrix and the transition zone in lime stone concrete are not of limited strength, on the contrary it is the strength of the lime stone aggregate it self that controls the concrete strength. This was judged by the numerous cases of transgranular fracture, where complete fracture of the test specimen occurred by bridging of the mortar and lime stone cracks. In steel slag concrete, cracking was mainly a result of the growth of bond cracks. And it seems that cracking in the mortar tends to connect bond cracks over the shortest distance between them, so that the resulting cracks continue for a minimum distance through the matrix. The effect of surface roughness of aggregate on concrete strength, particularly in strong aggregate was found to be more important than the effect of particle shape [22]. Steel slag particles are characterized by their higher strength compared to lime stone, and their honeycombed surface. The presence of strong aggregate particles may act as arresters and prevent crack propagation [22]. In other words, the presence of slag particles delay fracture and thereby increase the strength of concrete. Besides, the strength of the transition zone due to chemical interaction, as previously mentioned, together with the honeycombed surface of slag may also inhibit the crack growth. Whereas higher energy is needed, not only to enlarge and expand the bond cracks but also to overcome the honeycombed surface of steel slag particles.

CONCLUSIONS

This study aimed at carrying out a comprehensive investigation of the properties of different batches of steel slag produced at the Egyptian Copper Works Company. In addition, the susceptibility of producing heavy-weight high-strength concrete incorporating steel slag was studied. The following concepts were realized from the findings;

- Steel slag is composed mainly of CaO (33%), FeO (26.6%), SiO_2 (12.1%), and MgO (12%). Steel slag is also characterized by its high basicity, which has an average value of 4.0.
- The mineralogical composition of steel slag proved the predominant presence of the RO-phases, dicalcium silicate, dicalcium ferrite, and free calcium oxide and/or hydroxide.
- Water spraying is effective in accelerating the hydration rate of free lime. Statistical analysis showed that the weathering time needed to reduce the free lime content in steel slag is dependent on the initial free lime content. In addition, free magnesia did not show any adverse effect on the volume stability of steel slag. This was confirmed from the results of the autoclave test.
- The DTA of steel slag showed that the different phases composing steel slag are stable up to 800°C, and only small endothermic peaks representing the decomposition of calcium hydroxide and calcium carbonate were encountered. Moreover, the products formed on the surface of steel slag particles undergoing weathering consists mainly of calcite.
- Compared to pink lime stone concrete, steel slag concrete exhibited higher mechanical properties. This was also confirmed through the statistical analysis. For instance, at 28 days the compressive strength for steel slag concrete was higher than that of lime stone concrete by an average value of eight percent.
- Steel slag high-strength concrete showed approximately similar splitting tensile strength, and flexural strength to that of lime stone high-strength concrete. The modulus of elasticity of steel slag high-strength concrete exhibited higher values than lime stone high-strength concrete. Besides, steel slag provided higher restraint to the shrinkage of cement paste, leading to lower shrinkage strain than lime stone high-strength concrete.
- The XRD analysis of the hydration products at the interfacial zone of steel slag revealed the presence of chemical interaction between the slag and the cement paste. This was similar to that detected with the lime stone.

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