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Utilization of Local Steelmaking Slag in Concrete

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Abstract. In this study, the use of locally produced electrical arc furnace (EAF) steel slag in concrete manufacturing is investigated. The slag was used as coarse aggregate since it proved to be quite hard and did not contain any appreciable free chemical compounds of potentially adverse effects such as lime. For comparison, crushed wadi gravel was used in parallel to the slag. Mechanical properties as well as the drying shrinkage of both slag and gravel concrete were measured. The results showed compressive and flexural strengths for slag concrete to be similar to slightly higher than gravel concrete, splitting tensile strength and modulus of elasticity to be higher and drying shrinkage to be lower than that of gravel concrete. The results of this investigation are encouraging since they show that using slag as coarse aggregate in concrete has no negative effects on short term properties of hardened concrete. However, further investigation on the effect of steel slag on the long term properties of concrete is required before a recommendation can be given for using the steel slag as coarse aggregate in concrete.

Introduction

Industrial byproducts create problems of storage and environmental pollution; therefore, a vast amount of research has been conducted to investigate potential uses for them. The construction industry has proven to be a good place for the consumption of many industrial byproducts. In particular, concrete and asphaltic mixes are two major areas where many of these byproducts can be used.

Slag is a major byproducts in the iron and steelmaking industry. Slag produced is classified into two categories: blast furnace slag and steel making slag. Blast furnance slag is produced in the process of reducing iron ore to pig iron in a blast furnace, while steel slag is a byproduct of steel making processes. There are three basic steelmaking processes in use today. These are open hearth (OH), basic oxygen (BO), and electric arc (EA). The chemical composition of the steel making slag will vary depending upon the type of steelmaking process being used. Even greater variation can be introduced by the composition of the Iron-bearing feed and the batch nature of the steelmaking processes [1].

Blastfurnace slag has long been accepted for use by the construction industry [1-4]. Depending upon the manner in which the molten slag is cooled and solidified, three distinct types of blast furnace slag can be produced: air-cooled, foamed or expanded and granulated; however, air-cooled by far makes the bulk. Acceptance of blast furnace slag in concrete related applications was the result of extensive research on its effects on short as well as long term properties of concrete.

Steelmaking slag is not widely accepted for use in concrete by the construction industry. It, however, is used in order construction applications. The United States Bureau of Mines [5] reported the use of 4.3 million metric tons, valued at 14.6 million dollars, in 1982 for base and fill materials, ballast, bituminous paving, and soil conditioning. Volume changes of detrimental proportions have been observed in some field applications with some steel making slags [1,2]. This expansion is attributed to the hydration of free lime or magnesia, or the dicalcium silicate phase change, or a combination of these actions. Steelmaking slags are frequently weathered in stockpiles to allow the bulk of any volume change to take place prior to use in construction. The high bulk density in excess of 2.4 metric tons per cubic meter and high specific gravity (in excess of 3.0) of steelmaking slags are due to the presence of FeO and MnO.

In general, the uses of steelmaking slags have been traditionally limited to nonconfined applications due to the volume-change potential of some of the slags. Railroad ballast is one of these applications. The high weight and interlocking properties are of benefit for this use.

Steel slag has been investigated for use in asphalt pavement [5,6]. It was found to have all the qualities desirable in a road surfacing material, making an economical, stable, durable and skid resistance road surfacing [5]. To encourage the use of slag in pavement construction, the American Society for Testing and Materials (ASTM) published ASTM D5106 "Standard Specification for Steel Slag Aggregates for Bituminous Paving Mixtures" [7]. The publication of this standard was a milestone towards increased acceptance and use of steel slag as aggregate in asphaltic pavement. Its use as an aggregate will help eliminate the problem of disposing of large quantities of solid waste.

Research into using steel slag in concrete is very limited. Akinmusuru [8] reported a preliminary investigation on the use of steel slag as an aggregate for concrete mixes and in powder form as a stabilizer for soil. Steel slag from the Nigerian steel industry was investigated for replacement of cement, fine aggregate and coarse aggregate. Results showed that slag cannot be used as cementitious. However, the use of slag as both fine and coarse aggregates was more encouraging. Based on short-term results, compressive strengths of concrete made using slag were found to be higher than regular concrete. Also, using slag as a stabilizing agent was found to improve soil properties with increased dry weight, CBR, and strength coupled with implied decreased permeability.

The slag used in this investigation was obtained from Hadeed steel plant in Jubail, Saudi Arabia. The plant utilizes the direct reduction-electric arc furnace (DR-EAF) technology for steel making. Imported high quality iron ore is reduced to sponge iron in the direct reduction plant. The direct reduced iron (DRI) or sponge iron, as it is sometimes called, is used along with local scrap for the production of steel in three electrical arc furnaces in the plant. Oxygen and fluxing materials such as lime and limestone fines, and certain ferroalloy fines are injected into the furnace.

According to data provided by the steel plant, slag from the steelmaking process is generated at the rate of approximately 250,000 metric tons per year. Additionally, there is an accumulated stock of 1.2 million metric tons. The steel slag produced is relatively nonporous. The range of its chemical composition is given in Table 1. The chemical composition of the slag varies within small range as shown by the results of survey for the first 10 months of 1992 (Table 2). Also, variations in slag composition among the three electric arc furnaces in the plant are small as can be seen from Table 3.

Table 1. Chemical composition of local slag (by mass)

Lime (CaO)	20 - 40%
Silica (SiO_2)	10 - 20%
Alumina (Al_2O_3)	5 - 10%
Magnesia (MgO)	7 - 12%
Iron oxide (FeO)	13 - 3%
Manganous oxide (MnO)	2 - 4%

Table 2. Variation of the chemical composition of local slag produced during the first ten months of the year 1992

	Fe-TOT	FeO	SiO_2	Al_2O_3	CaO	MgO	MnO	B_2	V
Mean	20.09	18.33	17.43	7.85	30.53	13.19	2.66	1.75	1.73
Standard deviation	1.14	1.78	1.14	0.41	1.50	0.75	0.16	0.11	0.07

Table 3. Variation of the chemical composition of local slag from the three furnaces for the month of October 1992

Furnace	Fe-TOT	FeO	SiO_2	Al_2O_2	CaO	MgO	MnO	B_2	V
EAF 1	21.56	20.66	17.71	8.07	30.09	12.52	2.44	1.70	1.65
EAF 2	19.45	17.96	17.88	8.00	32.66	12.31	2.48	1.83	1.84
EAF 3	20.73	18.73	17.06	7.45	31.52	13.52	2.46	1.785	1.84
Average	20.58	19.12	17.55	7.84	31.42	12.78	2.46	1.79	1.74

The use of local steel slag in asphalt pavement has been investigated. Bayomy and Abdul Wahhab [9] concluded that steel slag can be used to replace coarse aggregate in asphalt concrete mixes. Slag mixes showed significantly better stability, better water damage resistance, higher splitting tensile strength and modulus of resilience than those made with natural crushed aggregate.

In a recent investigation by the materials laboratory of the Ministry of Communication (MOC) in Saudi Arabia on the use of locally produced steel slag as aggregate in asphalt pavement, it was found that slag improves skid resistance and Marshall Stability. However, the slag resulted in a reduction of indirect tensile strength and no improvement in the modulus of resilience. Based on this laboratory investigation, a field trial of slag in asphalt pavement was recommended to monitor its performance over time under actual field conditions [10].

Local steel slag has not been used so far in concrete construction. The locally produced steel slag was stored in the open atmosphere and subsequently crushed, washed and graded. It is noted that chemical analysis of the slag used in this investigation was encouraging since it did not detect the presence of free lime or any other unstable elements, capable of causing swelling effects. In this study, strength and shrinkage properties for concrete using slag as coarse aggregate were evaluated for up to one year and compared to a control mix using crushed gravel as coarse aggregate.

Preliminary Investigation

Preliminary tests were conducted on the effects of steelmaking slag on the strength of concrete. Slag was investigated for use as coarse aggregate in concrete mix. A standard concrete mix using crushed gravel as coarse aggregate was used as a reference. The specific gravity, unit weight and absorption capacity of both the gravel and slag aggregates used in the investigation were determined and are given in Table 4. The results showed the slag to have a higher specific gravity and higher unit weight compared to the gravel aggregate, while water absorption of the slag was substantially lower than the gravel aggregate. An important property of the slag used is its shape and surface texture. Following the classification of the British standard BS 812: Part 1 [11], its particle shape can be classified as angular, and its surface texture as honeycombed. The effects of the physical properties mentioned on the properties of concrete will be discussed where relevant to the study.

For the trial mixes, the crushed gravel concrete mix was modified to account for the higher specific gravity of the slag. Gravel was blended to come up with a gradation meeting ASTM C33 [12]. The Slag was also blended to create similar gradation to that of the crushed gravel (Table 5).

Table 4. Physical properties of slag and crushed gravel aggregates

Aggregate types and size		Absolute specific gravity	Bulk specific gravity		Unit weight kg/m3	Absorption capacity %
			O.D.basis	SSD basis		
Gravel	10 mm	2.66	2.54	2.59	1535	1.74
	20 mm	2.66	2.54	2.59	1533	1.67
Slag	10 mm	3.81	3.75	3.77	2148	0.35
	20 mm	3.64	3.57	3.59	2054	0.54

Table 5. Gradation of coarse aggregate used in concrete mixes

	Per cent passing		
Sieve #	Crushed gravel	Slag	ASTM limits
20 mm	98	96	90 - 100
10 mm	37	36	20 - 55
No. 4	4	4	0 - 10

Table 6. Proportions of concrete mixes using crushed gravel and slag as coarse aggregate per cubic meter of concrete.

	Crushed gravel		Slag	
	M-1A	M-2A	M-1S	M-2S
Cement	350 kg	350 kg	350 kg	350 kg
20 mm aggregate	730 kg	730 kg	931 kg	931 kg
10 mm aggregate	390 kg	390 kg	652 kg	652 kg
Fine aggregate	715 kg	715 kg	715 kg	715 kg
W/C	0.62	0.42	0.62	0.42

In this preliminary investigation, four trial mixes were cast. The mix proportions used for the trial mixes are shown in Table 6. Mix M-1A is the reference mix using crushed gravel as coarse aggregate and M-1S refers to the mix with slag as coarse aggregate. The slumps for the two mixes were similar ranging between 50 to 65 mm. The results for the compressive strengths at 7-days were similar as shown in Table 7. Trial mixes M-2 were the same as the M-1 except that the w/c ratio was reduced to 0.42 from 0.62 through the use of high range water reducer (HRWR) or superplasticizer. A dosage of 7.0 l/m^3 was used to reduce the w/c ratio and obtain a slump of around 100 mm. As expected, the 7-day strength improved markedly as a result of the lower w/c ratio. However, there was no marked difference in strength between gravel and slag concrete. The results of the 7-day compressive strengths for both mixes are shown in Fig. 1. The use of slag resulted in a significant increase in the density of concrete as can be seen from Table 7. The increase is due to the higher specific gravity of the slag compared to gravel.

Table 7. Preliminary investigation test results

Mix #	Slump (mm)	Density (Kg/m^{3}2)	7-day strength (MPa)
M-1A	65	2329	20.9
M-1S	50	2775	20.1
M-2A	100	2385	36.1
M-2S	100	2852	34.8

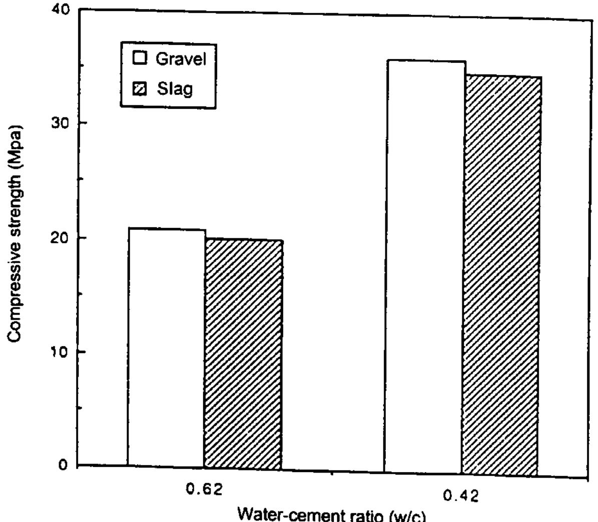

Fig. 1. Compressive strength of gravel versus slag concrete as affected by w/c ratio.

The results of the preliminary trial mixes were encouraging as it showed that using the slag from Hadeed steel factory as coarse aggregate could produce concrete with compressive strength comparable to that of concrete using crushed gravel. It should be pointed out that the higher strength of the slag concrete reported by Akinmusuru [8] over concrete using crushed rock was not corroborated by our investigation.

Comprehensive Testing Program

A comprehensive testing program was conducted using the mix proportions given in Table 6 for mixes M-1A and M-1S for gravel and slag concrete, respectively. The full scale testing was designed to study the development of compressive strength with time and the flexural strength and splitting tensile strength at 28 days under three different curing environments. Also, the modulus of elasticity at 28 days and drying shrinkage strain were measured. The test results will show if the slag can be used without negative effects on short term properties of hardened concrete. Such findings will be significant in assessing the potential of using steelmaking slag in concrete manufacturing and therefore essential before conducting long term durability and corrosion properties of concrete with steel slag.

Type I ordinary portland cement and surface dry aggregates were used. Mixing was carried out in 0.4 m^3 capacity counter-current mixer in accordance with ASTM C192 [12]. After castings, all specimens were covered with wet burlap and polyethylene sheets, and left in the casting room for 24 hours. After this initial moist curing, all specimens were demolded and cured in one of the following three curing conditions:

1. C1; immersion in a water tank (T = 21 ± 2°C)
2. C2; moderate temperature and humidity (T = 28 ± 2°C and RH = 45 ± 5%)
3. C3; high temperature/low humidity room (T = 55 ± 2°C and RH = 10 ± 5%)

Compressive strength

To study the effect of using slag as coarse aggregate on compressive strength, 45 standard 152 x 305 mm cylinders were cast for each mix. Specimens were moist cured using burlap and polyethylene covers for 24 hours after casting. After initial moist curing, fifteen specimens from each mix were cured under the three curing conditions. Three identical cylinders from each mix and for each curing conditions were tested in compression at 3, 7, 28, 90 and 210 days. The compression test was carried out in accordance with ASTM C39 [12].

Young's modulus of elasticity

For this test, 3 standard 152 x 305 mm cylinders were cast from each mix and cured under condition C1 for 28 days. At the end of the curing period, two 60-mm long strain gauges were glued longitudinally to the cleaned concrete surface and the cylinders were tested in compression in accordance with ASTM C39 [12]. The stress and strain were recorded automatically using a data-acquisition system.

Flexural strength (Modulus of rupture - MOR)

Nine standard 152 x 152 x 600 mm prisms were cast from each mix. Three specimens from each mix were cured for 28 days in the three curing conditions. At the end of curing period, the modulus of rupture test was carried out in accordance with ASTM C78 [12].

Splitting-tensile strength

For this test, 9 standard 152 x 305 mm cylinders were cast from each mix. Three specimens from each mix were cured in the specified curing conditions for 28 days. At the end of the curing period, splitting tensile strength test was carried out in accordance with ASTM C496 [12].

Shrinkage measurements

For shrinkage measurements, 75 x 75 x 285 mm concrete prisms were cast and cured according to ASTM C157 [12]. For each mix, three prisms were cast and cured using burlaps and polyethylene covers for 24 hours. After 24 hours, the specimens were demolded and then placed in lime saturated water for 30 minutes before recording the initial comparator reading. At the end of curing period a second comparator reading was made and the specimens were left to dry under condition C2.

Weekly comparator readings of each specimen were made. Each reading was an average of two measurements (second measurement is made by reversing the specimen).

Experimental Results

The compressive strength, modulus of elasticity, modulus of rupture, splitting-tensile strength, and shrinkage results of all test series conducted in this study are given below. The results are averages of three specimens kept under the same curing condition and tested at the prescribed age.

Compressive strength

Three identical cylinders from each mix and for each curing condition were tested in compression at 3, 7, 28, 90 and 210 days. The results obtained are summarized in Table 8. A comparison of compressive strengths of Mix A and Mix S at various ages and for each curing condition is given in Figs. 2 - 4. From these figures it is evident that the compressive strength of slag concrete is similar to that of gravel concrete. This holds true at all ages of curing and for all curing conditions under study.

Table 8. Summary of compressive strength test results

Age of curing (days)		Compressive strength, MPa					
		Curing condition C1		Curing condition C2		Curing condition C3	
		Mix 1A	Mix 1S	Mix 1A	Mix 1S	Mix 1A	Mix 1S
3	Mean	15.6	14.2	15.4	15.0	15.9	16.0
	Std. deviation	0.53	0.57	0.20	0.52	0.38	0.51
7	Mean	19.8	20.8	19.0	19.6	17.3	17.7
	Std. deviation	0.87	0.41	0.46	0.35	2.15	0.95
28	Mean	25.3	26.1	21.8	20.7	17.4	16.7
	Std. deviation	0.99	1.50	2.40	2.31	0.79	0.30
90	Mean	30.2	31.6	24.2	25.6	16.6	18.4
	Std. deviation	0.93	1.49	0.45	2.27	1.24	1.42
210	Mean	30.7	29.4	22.9	27.6	18.3	17.3
	Std. deviation	1.81	2.12	1.12	2.69	1.15	1.31

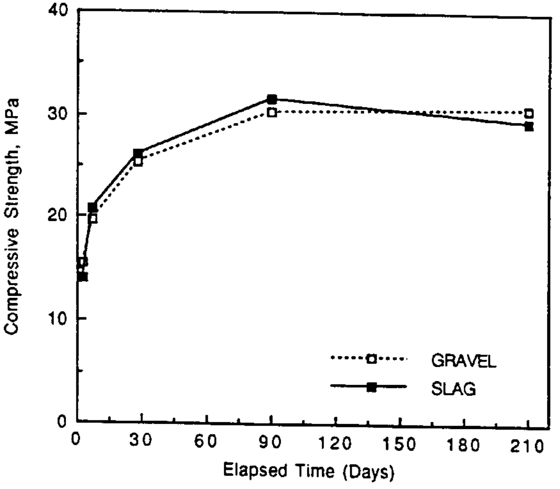

Fig. 2. Comparison of compressive strengths for gravel and slag concretes at different ages of moist curing (C1).

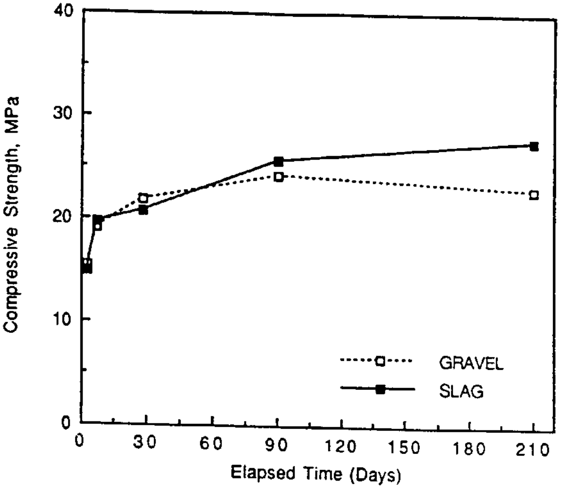

Fig. 3. Comparison of compressive strengths for gravel and slag concretes at different ages of moderate temperature and humidity curing (C2).

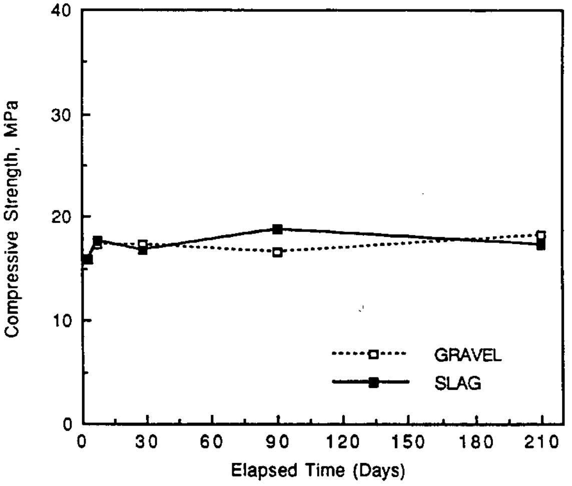

Fig. 4. Comparison of compressive strengths for gravel and slag concretes at different ages of moist curing (C1).

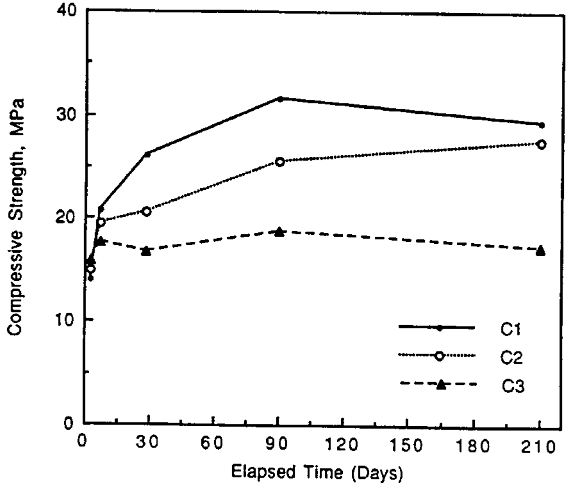

Fig. 5. Comparison of the compressive strengths for slag concrete at different ages under curing conditions C1, C2 and C3.

The effect of the curing environment on the compressive strength is very significant as can be seen in Fig. 5 for slag concrete. The strength values at 3 days are close with C3 being the highest followed by C2 with C1 given the lowest. However, at 7 days, the standard curing condition, C1, gives the highest values followed by C2 with C3 given the lowest. The same trend is maintained at 28, 90 and 210 days with the differences being more substantial. These observations are also true for gravel concrete. It is noticed that the strength at 210 days is less than that at 90 days for conditions C1 and C3. For C3, the strength drop is not substantial and could be attributed to statistical variation; however, for C1 the drop in strength may be caused by microcracks resulting from expansive elements still present in the steel slag.

Young's modulus of elasticity

The moduli of elasticity E of concrete from Mix - 1S and Mix - 1A at 28 days are compared in Fig.6. The computed modulus of elasticity E of the slag concrete at 28 days was 34.3 GPa as compared to 27.9 GPa for the gravel concrete with an increase of 22.9%. Typical stress-strain diagrams for concrete from Mix - 1A and Mix -1S are illustrated in Fig. 7. The stress-strain diagrams clearly show the increased stiffness of slag concrete as compared to gravel concrete.

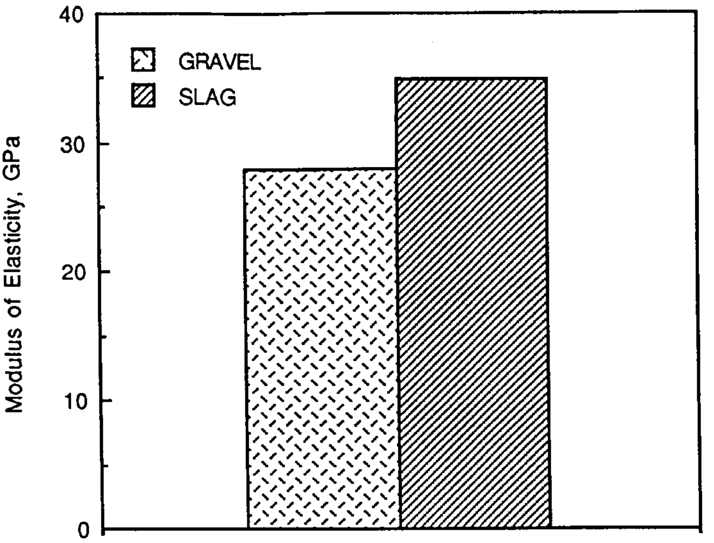

Fig. 6. Young's modulus of slag versus gravel concrete after 28 days of moist curing (C1).

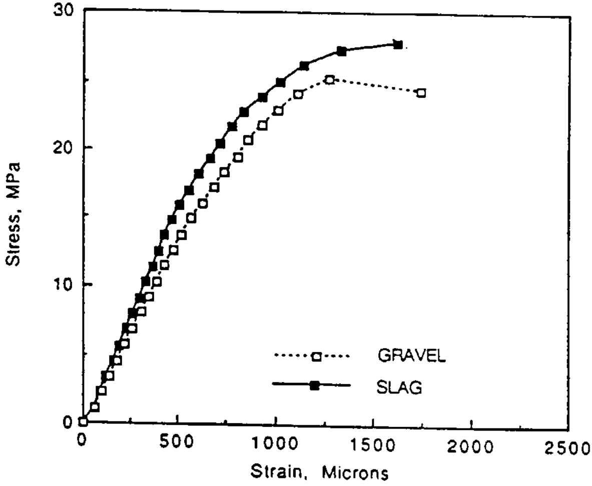

Fig. 7. Typical streee-strain diagrams of slag and gravel concretes.

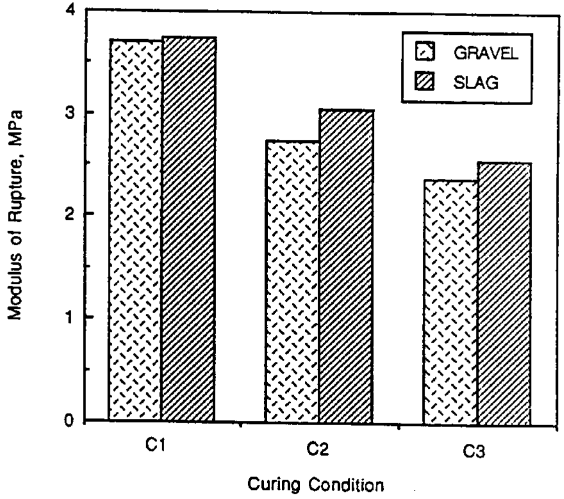

Fig. 8. Flexural strength (MOR) of slag and gravel concretes testted after 28 days of curing in environments C1, C2 and C3.

It is important to mention here that the modulus of elasticity of concrete is often correlated with its weight. According to ACI-318 [13], heavier concrete should have a larger modulus. This explains the increase in modulus for slag concrete which is about 20% heavier than gravel concrete as given in Table 7.

Flexural stregnth

The flexural strength (MOR) of slag concrete is compared to gravel concrete at 28 days in Fig. 8. The slag concrete gave slightly higher values for all three curing condiltions. The effect of the curing conditions on the flexural strength is more pronounced.

Splitting-tensile strength

The splitting-tensile strength of slag concrete as compared to gravel concrete at 28 days is illustrated in Fig. 9. The slag concrete gave higher values for all three curing conditions with the increase being more pronounced for drying conditions C2 and C3. The effect of the curing conditions on the splitting-tensile strength is significant and similar to that observed for the compressive and flexural strengths.

Drying shrinkage strain

Shrinkage strains were computed for specimens from Mix - 1S and Mix - 1A for drying condition C2 (Fig. 10). The results show that mix - 1S has substantially lower

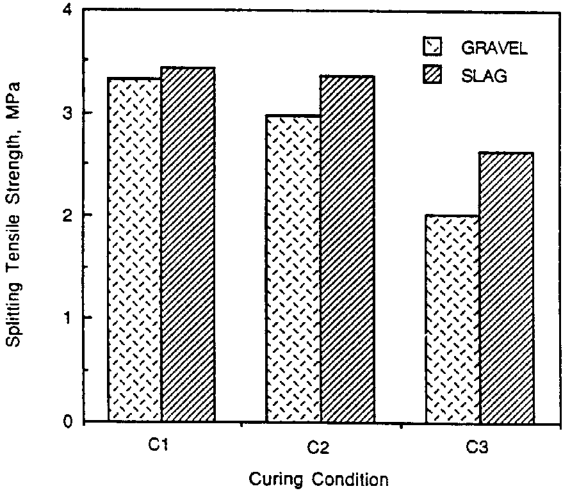

Fig. 9. Splitting tensile strength of slag and gravel concretes tested after 28 days of curing in environments C1, C2 and C3.

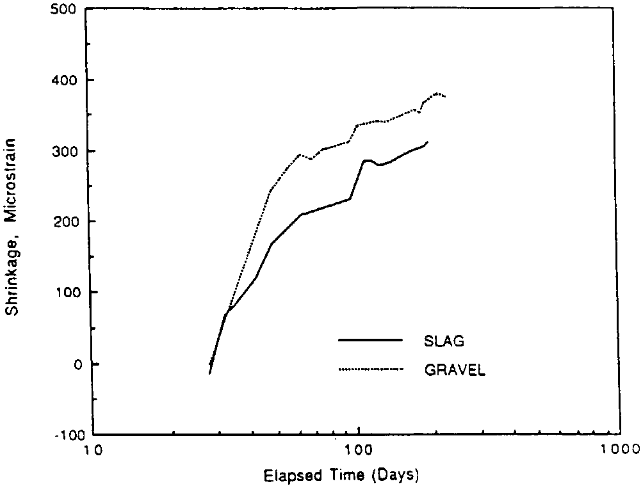

Fig. 10. Comparisons of shrinkage strains of slag and gravel concretes in drying environment (C2).

drying shrinkage strain as compared to Mix - 1A. The lower shrinkage of slag concrete as compared to gravel concrete may be the result of higher modulus of elasticity of the slag as a coarse aggregate. In addition, it can be argued that the angular particle shape and the honeycomb surface texture of the slag restrains the concrete more than the irregular shape and smooth surface of the gravel used.

Summary and Conclusions

In this paper, the results of an experimental program on the use of steelmaking slag as a coarse aggregate in concrete were reported. A comparison was made between concrete made with crushed wadi gravel of reasonable quality which is mainly found in the central region of Saudi Arabia, and concrete made with crushed and washed steel slag as coarse aggregate. The slag used was obtained from Hadeed steel factory in Jubail which utilizes and DR-EAF process for steelmaking.

The results of the test program are summarized as follows:

1) Compressive and flexural strengths for slag concrete were similar or slightly higher than gravel concrete. The compressive strength for slag concrete cured under water may adversely be affected with time and requires further investigation.
2) Splitting tensile strength for slag concrete was higher than gravel concrete.

3) Modulus of elasticity of slag concrete was higher than gravel concrete.
4) Drying shrinkage for slag concrete was lower than that of gravel concrete.

These results show that using slag as coarse aggregate in concrete has not negative effects on short term properties of hardened concrete. The slight improvement in strength properties of slag concrete can be attributed to the particle shape and surface texture of the slag, which provide for better adhesion or bond between the particles and the cement matrix. In addition, the larger surface area of a more angular aggregate provides a greater bond [14,15].

The slag concrete may be used for certain applications where its extra weight (about 20% more than gravel concrete) is advantageous. These applications include radiation shielding, gravity dams, abutments, slabs on grade and concrete pavements. However, before such use of slag in concrete can be recommended, durability and corrosion properties of slag concrete need to be investigated. Such investigation is underway and the results will be reported in future publications.

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استخدام خبث صناعة الصلب المحلي في صناعة الخرسانة

عبدالعزيز النغيمش، فيصل الصقير وراجح الزيد

قسم الهندسة المدنية، كلية الهندسة، جامعة الملك سعود، ص. ب ٨٠٠،
الرياض ١١٤٢١، المملكة العربية السعودية

(استُلم في ١٥/ ٨/ ١٩٩٥م؛ قبل للنشر في ٣/ ٦/ ١٩٩٦م)

ملخص البحث. تم في هذه الدراسة بحث استخدام خبث الصلب الناتج من مصهر القوس الكهربي في صنع الخرسانة كركام خشن وذلك لكونه قاس ولا يحتوي على مركبات كيميائية حارة مثل الجير والتي قد يكون لها تأثيرات سلبية على الخرسانة. ولغرض المقارنة، تم استخدام البحص المكسور في عمل مواز للخبث حيث تم قياس الخواص الميكانيكية إضافة إلى الانكماش الجاف لكل من خرسانة الخبث والبحص وقد أظهرت النتائج أن خرسانة الخبث تعطي ضغطا وانحناء مساويين أو أعلى بقليل من خرسانة البحص، كما أن معامل الانتشار والمرونة أعلى والانكماش الجاف أقل.

تبدو النتائج التي تم التوصل إليها مشجعة، حيث أظهرت أن استخدام الخبث ليس له تأثيرات سلبية على خواص الخرسانة في المدى القصير ولكن يلزم القيام بدراسة تأثيرات الخبث على الخرسانة على المدى الطويل قبل إعطاء توصيات باستخدامه كركام خشن في الخرسانة.