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Characterization and evaluation of Giad Arc furnace slag as partial replacement for cement in mortar mixes

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ABSTRACT

The main objective of the research presented in this paper is to conduct a physical and chemical characterization of the locally produced Electric Arc Furnace Slag (EAFS) that produced by Giad Company for Industries, and to determine the degree of its Pozzolanicity. Also the aim of the study is to explore the possibility and feasibility of using this industrial waste as a cement replacement in mortar mixes. Different percentages of cement replacement with the slag had been studied (namely 20%, 30%, 40% and 50% with the slag had been studied respectively). Chemical and physical properties of the slag were studied in accordance to the international standards (ASTM and BS) specially the American Society for Testing and Materials (ASTM C311). Chemical analysis showed that locally produced steel slag contains high amount of iron due to purification process in steel manufacturing comparing the results with standard (ACI 233). Also testing of raw materials such as fineness, loss on ignition and X-ray diffraction test (XRD) were carried out. After that the required tests on cement mortar were carried out namely; consistency test, initial and final setting times and strength test according to the standard. XRD analysis results showed presence of both crystalline and non-crystalline silica (Amorphous) which indicated good pozzolanicity of the slag. A degree of pozzolanicity of 83.4% at 28 days indicates a good quality electric arc furnace slag and a promising pozzolanic supplementary material in concrete. Compressive strength test of mortar samples in 2, 7, 14 and 28 days with different percentages of electric arc furnace slag (0%), 20%, 30%, 40% and 50% had been conducted. Finally, the study proved the efficiency and

feasibility of using one of the industrial wastes as a cement replacement in concrete industry in Sudan.

المستخلص

الغرض الأساسى من هذه الورقة العلمية هودراسة الخواص الفيزيائية و الكيميائية لخبث أفران القوس الكهربائي المنتج بواسطة شركة جياد للصناعات وتحديد درجة البوزولانية له. أيضاً تهدف لمعرفة إمكانية وجدوى إستخدام هذه المخلفات الصناعية كبديل للأسمنت في الخلطات الخرسانية وتحديد ما إذا كان هذا الخبث صالحاً للخلطات الإسمنتيّة. تم استبدال الأسمنت في عينات المونة الإسمنتيّة بنسب معينة من خبث الحديد وهي (20%، 30%، 40% و 50%) علي التوالي. تمت دراسة الخواص الفيزيائية والكيميائية لخبث الحديد المنتج محلياً وذلك وفقاً للمعاييرالعالمية وعلى وجه الخصوص معايير الجمعية الأمريكية للإختبارات والمواد. كذلك تم إجراء الإختبارات الأولية للمواد، مثل إختبار درجة النعومة ، متبقي الإحتراق، التركيب الكيميائى، حيود الأشعة السينية. بعد ذلك تم إجراء الإختبارات علي المونه الأسمنتية والتي تتمثل في إختبار القوام، إختبار زمن الشك الإبتدائي و زمن الشك النهائي وذلك تبعاً للمواصفات الأمريكية. من نتائج التحليل الكيميائي وجد أن الخبث يحتوي علي نسبة عالية من الحديد ويرجع ذلك إلي عدم الدقة في عملية التنقية في المصنع. أظهرت نتائج حيود الأشعة السينية وجود سيليكا غير متبلوره وهذا يدل مبدئياً علي أن هذا الخبث جيد. بالمقابل تم الحصول على درجة عالية من المقاومة والبوزولانية عند إجراء إختبار المقاومة والبوزولانية، فقد كانت نتيجة درجة البوزولانية 83,4% الأمر الذي يدلّ على جودة عالية لخبث أفران القوس الكهربائيّ واستخدام واعد في الخلطات الخرسانيّة. تم بعد ذلك إختبار مقاومة الإنضغاط للمونه الأسمنتية وذلك في 2، 7،14 و28 يوماً وذلك لكل نسب الإحلال بدء بالعينة التي لاتحتوي علي خبث الحديد (0%)، 20%، 30% ، 40% و 50%. أخيرا، أثبتت الدراسة كفاءة وجدوى إستخدام واحدة من المخلفات الصناعية كبديل للأسمنت في صناعة الخرسانة في السودان.

Keywords: Electric arc furnace slag, Chemical analysis, X-ray diffraction, Compressive strength, Pozzolanicity.

1. INTRODUCTION

In recent years in Sudan, different industrial plants had started mass manufacturing and mass production of structural steel such as steel reinforcement, steel beams and other structural steel sections. Some of these plants uses raw material (scrap) to manufacture steel products. So, Sudanese Electric Arc Furnace Slag (EAFS) is produced as an industry by product. This locally produced (EAFS) has been an environmental hazard and it could be investigated for the potential of been used as an artificial pozzolanic or aggregate material in the construction Industry.

The American Society for Testing Materials (ASTM C898) defines Steel Slag as "The non-metallic product consisting essentially of calcium silicates and ferrites combined with fused oxides of iron, aluminum, manganese, calcium and magnesium that is developed in a molten condition simultaneously with iron steel in basic oxygen, electric, or open hearth furnaces".

Electric arc furnace slag is produced during the manufacture of crude steel by the electric arc furnace (EAF) process. In this process steel scrap with additions of fluxes (e.g., lime stone and/or dolomite) are heated to a liquid state by means of an electric current. During the melting process the fluxes combine with non-metallic scrap components and steel incompatible elements to form the liquid slag. As the slag has a lower density than steel, it floats on top of the molten bath of steel. The liquid slag is tapped at temperatures around 1600 °C and allowed to slowly air-cool forming crystalline slag. [1]

Since the difference between electric arc furnace slag and blast furnace slag is in the technology of production rather than the chemical composition and behavior in mortar mixes, same international standards are used for both types. According to ASTM C989, Slag is classified into three grades according to its performance in the “slag activity test”. The three grades are: Grade 80, Grade 100 and Grade 120.

The basic components of Slag comprise generally CaO (30%-48%), MgO (28%-45%), Al2O3 (5%-18%) and SiO2 (1%-18%), which are in principle the same as that of Portland cement [2]. Other minor components including Fe2O3, MnO and SO3 are also present in slag. The compositions do not change very much so long as the sources of iron ore, coke and flux are consistent [3].

Between 1955 and 1995, about 1.1 billion tonnes of cement was produced in Germany, about 150 million tonnes of which consisted of blast furnace slag. GGBS has been widely used as a partial replacement of Portland cement in construction projects [2].

1.1 BENEFITS OF USING STEEL SLAG IN CONCRETE

Some of the benefits of using steel slag in concrete are:

- Reduce the cost of production of Portland cement.
- Reduce the consumption of the raw materials.
- Protect the environment.
- Enhance the quality of cement.
- Environmentally friendly energy by product [4].
- Improve the durability of a concrete structure by reducing the water permeability such as increasing the corrosion resistance and increasing the sulphate resistance and reduction in expansion due alkali reactive aggregates [4].
- Reduction of heat of hydration [5].
- Can be used in general concreting purpose [6].
- Helps to improve the properties of concrete like compressive strength, workability etc.
- Low cost and easily available [7].

1.2 PROCESS DESCRIPTION OF EAFS

Electric Arc Furnace Slag (EAFS) is a by-product of the steel making process. Steel and molten slag is produced during the melting and refining of recycled steel using electrical energy and fluxes. Lime is used as a flux to remove silicates and phosphorus from the molten steel to form slag. Energy is supplied by an electric arc, melting the steel and fluxes. During the refining or superheating stage (of the slag process), slag is poured out of the slag door. On tapping, steel is drained from the furnace via a submerged taphole and the furnace is back tilted to prevent slag entering the steel ladle, (see Fig.1).

Directed into pits adjacent to the process, molten slag (and residual molten steel) flows out the slag door of the furnace. The molten slag then begins to solidify fairly quickly into a rock-like product. EAFS solidifies in a similar manner to lava from a volcano. Its cooled structure is best described as a solid solution of oxides. Since the molten slag is accompanied by residual solidified steel (metallics), the solidified material is excavated by a front-end loader from the bays when cooled, and transported by road to a metallic separation, crushing and screening plant. Metallics are removed and recycled as ferrous feed or scrap to the iron and steel making processes of the steelworks [8].

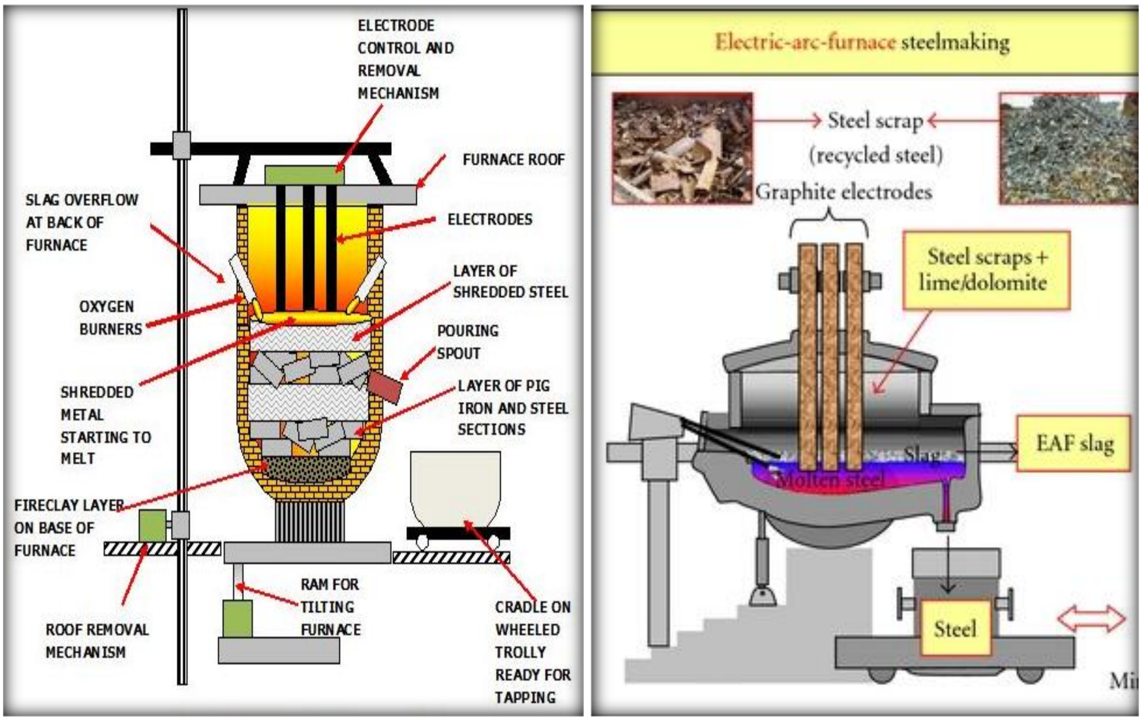

Fig. 1: Basic Layout of Electric Arc Furnace [8]

2. LITERATURE REVIEW

The compressive strength characteristics of mortar and concrete made with partial replacement of cement or fine aggregate using induction furnace slag was considered by different researchers all over the world [5], [9], [10], [11]. For the experimental investigation, mixes were prepared with fine aggregate replacement using 20 percent, 30 percent, 40 percent, mortar and concrete strength tests were conducted and the results indicated that fine aggregate 50 percent and 60 percent induction furnace slag. Compressive strength test of replacement using 30 percent induction furnace showed a better performance compared to control mix [11].

According to a research done by Nwaubani and Muntasser, EAFS is capable of reacting to form hydration products at normal temperatures.

Moreover at early ages, the weight loss recorded for the OPC-EAFS paste was lower than that of the OPC [12].

The use of finely ground granulated blast furnace slag as a substitute for cement is a standard practice from the technological, economic and ecological point of view. It improves the mechanical properties of concrete and enhances its resistance to weak by acids and salts [10].

EAFS from one of the steel plants in Western India has been characterised in detail. Its effectiveness as hydraulic material is examined before and after heat treatment in an induction furnace. The study shows that while there is a marginal reduction in the early age strength of the Portland Slag Cement mortar, the later age strength does not suffer by replacing up to 20% of Ground Granulated Blast Furnace Slag (GGBFS) by EAFS [9].

The high cost of slag disposal beside their negative impact on environment and the lack of natural aggregate resources in many regions led the reutilization of steel slag in various applications. There are also few researches that have been performed regarding the utilization of steel slag in concrete. Shekarchi et al carried out comprehensive researches on the utilization of steel slag as aggregate in concrete. The results indicated that utilization of steel slag as aggregate advantageous when compared with normal aggregates mixes [13].

3. EXPERIMENTAL WORK

3.1 MATERIALS

1) Cement:

Ordinary Portland cement (Sakhar El-Sudan) was used throughout the experimental program. Its physical properties were determined according to BS-12-1996; sufficient cement was reserved to avoid changing reference cement. The results were presented in Table 1.

2) Electric Arc Furnace Slag (EAFS):

Sudanese electric arc furnace slag produced from Giad Industrial city was used in this investigation. Six samples were collected for the work of the tests required. Chemical compositions of the used slag are given in Table (5). Below results of consistency and setting time tests of all percentage replacement of cement according to ASTM C 191 as shown in Table 2.

3) Standard Sand:

The sand used for making test specimens is natural silica sand conforming to the requirements for graded standard sand in specification C 778. The sand was prepared according to ASTM C 778, Sieved and washed then it was dried at normal condition.

4) Water:

Tap water suitable for drinking is usually good enough for concrete. The water should be free of all organic matter and certain chemicals such as alkaline and sulfate salts.

Table 1: Physical properties of cement

Item	Test conducted	Results	BS-12-1996 Requirements
1	Consistency	29.25%	(26 – 33)%
2	Setting Times		
	- Initial	2:36 hrs	Should not be less than 60 min
	- Final	4:07 hrs	Should not be more than 10 hrs
3	Compressive Strength (N/mm^2)		
	- 2 day	21.88	Should not be less than 10 N/mm^2
	- 7 day	40.63	
	- 14 day	42.71	
	- 28 day	50.42	Should not be less than 42.5 N/mm^2

Table 2: Consistency, Setting Time Tests of % of Slag Add to Cement

% of Slag Add to Cement	Consistency (%)	Setting Time (hrs)	
		Initial	Final
20%	26.75	2:40	4:12
30%	24.50	2:58	4:19
40%	21.75	3:00	4:22
50%	20.25	3:30	4:36

3.2 Testing of raw materials and mortar:

a) Fineness:

The Fineness of cement or any other alternative has an important bearing on the rate of hydration and hence on the rate of strength gain and also on the rate of evolution of heat.

The fineness of cement was tested in accordance with the standard method ASTM C430. The sample was sieved on mesh No 425 (the smallest available sieve in lab) and the retained amount was weighed and calculated as percentage of the total sample, so the result was not compared with standard specifications (no. 325 mesh)

For fineness of slag, the amount retained when wet-screened on a 45 µm (No. 325) sieve shall not exceed 20 percent. Results of fineness for cement and slag are shown in Table (3) below:

Table 3: Results of Fineness for Cement and Slag

Sample	Fineness (%)	ASTM C430 Standard Requirement
Cement	9	Not more than 10
Slag	13.5	Not more than 20

b) Chemical analysis

Chemical analysis was carried out according to the standard methods ASTM C114: 2003 technical methods of analysis. Chemical analysis is used to determine SiO_2, Fe_2O_3, Al_2O_3, CaO, MgO, Sulphate as percentage age by mass, loss on ignition at 1000°C, and Insoluble residue.

c) X - Ray Diffraction (XRD)

X- ray diffraction technique was used to determine whether the siliceous compounds of the slag are amorphous or not and determined by Bragg's law.

$$\mathbf{2d(\sin\theta) = \lambda}$$

Where d is the spacing between diffracting planes, $\boldsymbol{\theta}$ is the incident angle and λ is the wavelength of the beam.

d) Strength activity index test

According to ASTM C989-99 Slag activity shall be evaluated by determining the compressive strength of both Portland- cement mortars and corresponding mortars made with the mass combinations of slag and Portland cement.

The activity index shall be expressed as percentage of the strength of the control sample. It follows that the activity index at 28 days shall be not less than 70%. The compressive strength was determined for the test and control samples as specified in ASTM C109.

Mortar cubes were mixed in order to determine the strength activity index of EAFS. Cement was replaced by steel slag with the percentages of 20%, 30%, 40% and 50%. Control sample (0% steel slag) was mixed for the purpose of compression and for the calculation requirements. Mix design was performed according to the BS4550. The mortar samples were first mixed then they were molded in (50*50*50) mm3 cubes. Then they were cured and crushed at different ages. The water to cement ratio was taken (w/c = 0.5).

Table 4 explained quantities of component in mix design of mortar. In order to calculate the strength activity index. Strength activity index was determined in as follows:

$$\text{Strength activity index} = (SP/ P)*100\%$$

Where, SP: Average compressive strength of test mixture in cubes

P: Average compressive strength of control mix cubes

Table 4: Quantities of component in mix design of mortar

Sample	Cement (g)	Slag (g)	Sand (g)	Water (ml)
Control (0%)	450	0	1350	225
20%	360	90	1350	225
30%	315	135	1350	225
40%	270	180	1350	225
50%	225	225	1350	225

20% replacement sample at age of 28 days was used in this calculation according to ASTM C109. Results of strength activity index explained in Table 4.

4. Analysis and discussion of results

4.1 Chemical analysis

Chemical analysis was carried out at the Industrial Research and Consultancy Centre, Ministry of Industry, Khartoum north. The chemical composition of steel slag was tested in accordance to (ASTM C 311&ACI 233) and the results are shown in Table 5 below.

Table 5: Results of Chemical Composition Analysis of EAFS

Test	Results % age by mass					
	1	2	3	4	5	6
Loss on ignition	NIL	NIL	NIL	NIL	NIL	NIL
Silica, as SiO_2	21.86	17.47	14.83	18.19	19.50	22.77
Ferric Oxide, as Fe_2O_3	31.77	24.11	21.47	27.96	13.45	15.87
Aluminum Oxide, as Al_2O_3	8.39	19.90	24.04	18.20	28.34	22.45
Calcium Oxide, as CaO	34.66	33.47	31.23	33.25	35.86	33.93
Magnesium Oxide as MgO	2.81	2.73	2.19	1.12	0.33	3.26
Sulphate	2.10	0.13	2.55	1.88	1.52	0.72

For limiting values according to ACI 233 – R classifies the range of chemical composition of steel slag in United States and Canada. For all samples of steel slag of this study the following notes could be stated:

It is clear from the above Table 5 that for SiO_2 of all samples lower values than the standard, Al_2O_3 for sample 1 lies in range of standard, all values of MgO do not satisfy , sulphate acceptable and high proportion of iron due to the iron purification process of Giad.

The limiting values according to BS 6699: 1992 are: maximum insoluble residue of 1.5 percent, maximum magnesia content of 14 per cent, maximum loss on ignition of 3 per cent, manganese content of 2 per cent.

In addition, the maximum lime/silica ratio is 1.4 and minimum chemical modulus [(CaO) + (MgO)]/ (SiO_2), is 1.0.

Where each symbol in brackets refers to the percentage by the mass in the total slag of the particular oxides as determined according to BS EN 196 part 2 1992.

According to BS 146:1991 and BS 4246:1991, at least two- third of the total mass of slag must consist of the sum of CaO, MgO, and SiO_2. Also the ratio of the mass of CaO plus MgO to the mass of SiO_2 must exceed 1.0, this ratio assures a high alkalinity, without which the slag would be hydraulically inactive.

Thus according to the first criterion, the CaO content (34.66, 33,47, 31.23, 33.25, 35.86 and 33.93) for sample 1,2,3,4,5 and 6) respectively don't satisfy the requirements (40-45%) , the silica content (21.86, 17.47, 14.83, 18.19, 19.5 and 22.77) is less than the lower limit of (30-40%).As stated in the BS 146:1991 and BS 4246:1991, lower amount of CaO and SiO_2 can be used.

However, when taking into account the second and the third criterion (BS 146:1991,BS 4246:1991 and BS 6699:1992) we find that the sum of CaO, MgO, and SiO_2 is approximately (50-60) for all samples less than the minimum for samples, whereas the ratios of [(CaO) + (MgO)]/ (SiO_2) for sample 6 near the minimum, In addition the lime/ silica ratio for sample 1and 6 close to the standard, sample 4 and 5 slightly to the BS and sample 2 and 3 outer of range with standard.

LOI Nill for all samples <3%, SO^3 <4% for all samples. It could not seen that LOI and SO_3 content for all samples satisfy the requirements of BS 6699:1992.

It is well known that chemical analysis alone does not give conclusive evidence about the pozzolanicity of the materials concerned, however, it has to be substantiated with both XRD and compressive strength test to correlate between the chemical analysis and pozzolanicity of the material.

4.2 XRD test

From the analysis of X-ray diffraction of mostly samples observed these samples combines both pozzolanity and hydraulic properties that indicates assign of non-crystalline silica, which indicates a sign of good pozzolana.

XRD Results:

X-ray diffraction test was performed on steel slag specimens and the results are shown in figures (2), (3) and (4) respectively.

XRD Results interpretation:

XRD analysis was performed between angles ranges of (4-60) for 3 samples of electric arc furnace slag (S_1, S_2 and S_3). The results are shown in Fig. 2, Fig. 3 and Fig. 4.

- **The schema of XRD for (S_1)** shows many peaks as shown in Fig. 2. The most intensive one (100%intensity) has a d-value of 3.2^0 A (Angstrom) which is the d- value of quartz. There were other small peaks observed at $(5.06, 3.65, 4.22, 2.3and 2.08)^0$ A. this is conclusive proof of the presence of an amorphous or non-crystalline silica. The peak at 2.61 is a signed to very strong Tri calcium silicate (Ca_3SiO_5). The peak at 2.794^0 A is a signed to very strong Dicalcium silicate (Ca_2SiO_4). The presence of these indicates show that this sample of combines both pozolanity and hydraulic properties that indicates a sign of non-crystalline silica, which indicates a sign of good pozolana.

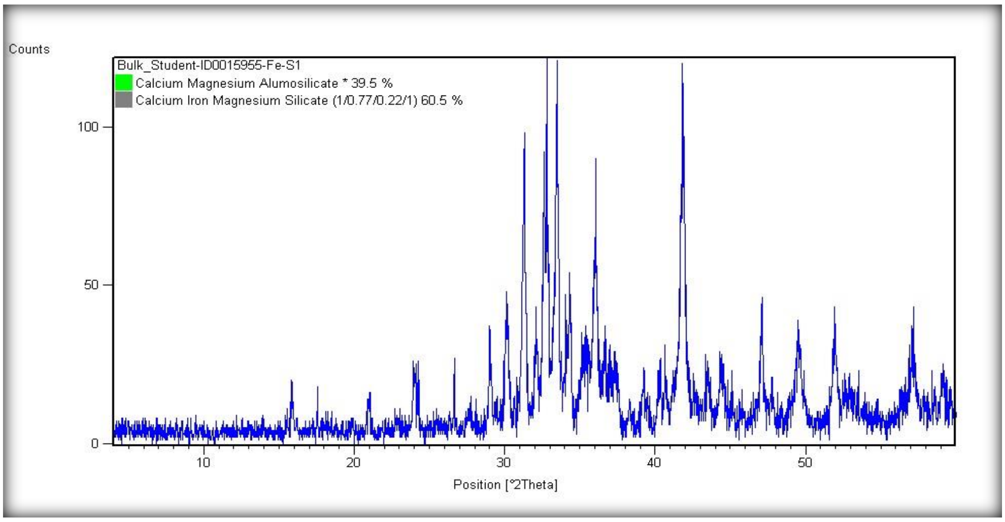

Fig. 2: XRD test results for sample (1)

- **The schema of XRD for (S_2)** shows any peaks as shown in Fig. 3. The most intensive one (100%intensity) has a d-value of 2.15^0 A (Angstrom). The peak at 2.77^0 A is a signed to very strong Tri calcium silicate (Ca_3SiO_5). The peak at 2.794^0 A is a signed to very strong Dicalcium silicate (Ca_2SiO_4). There were other small peaks observed at $(8.03, 6.8, 5.56, 4.9, 4.22, 1.8, \text{and } 1.89)^0$ A. this is conclusive proof of the presence of a non-crystalline silica. The presence of these guides indicates a sign of non-crystalline silica, which indicates a sign of a good pozzolana.

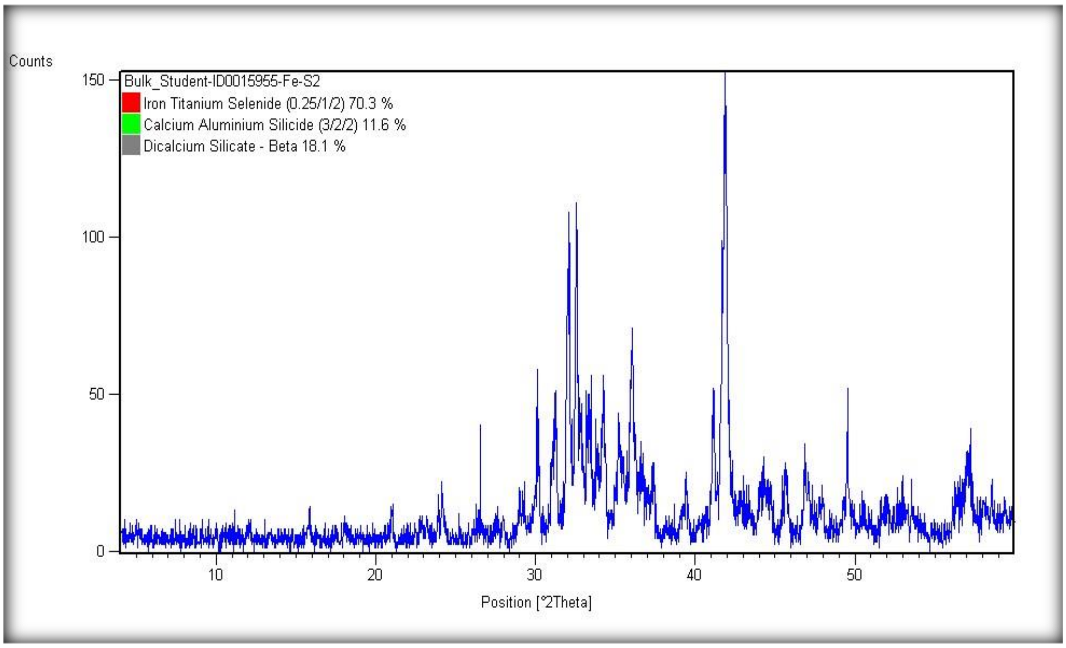

Fig. 3: XRD test results for sample (2)

- **The schema of XRD for (S_3)** shows many peaks as shown in Fig.4. The most intensive one (100%intensity) has a d-value of 2.149^0 A (Angstrom).There were very small silica peak in this planner. There were other peaks observed at $(3.06, 2.28, 2.03, 1.98, 1.927, 1.757 \text{ and } 1.738)^0$ A. The peak at 2.73^0 A is a signed to strong and very strong Tri calcium silicate (Ca_3SiO_5). The peak at 2.794^0 A is a signed to very strong Dicalcium silicate (Ca_2SiO_4). The presence of these guides indicates a sign of non-crystalline silica, which indicates a sign of a good pozzolana.

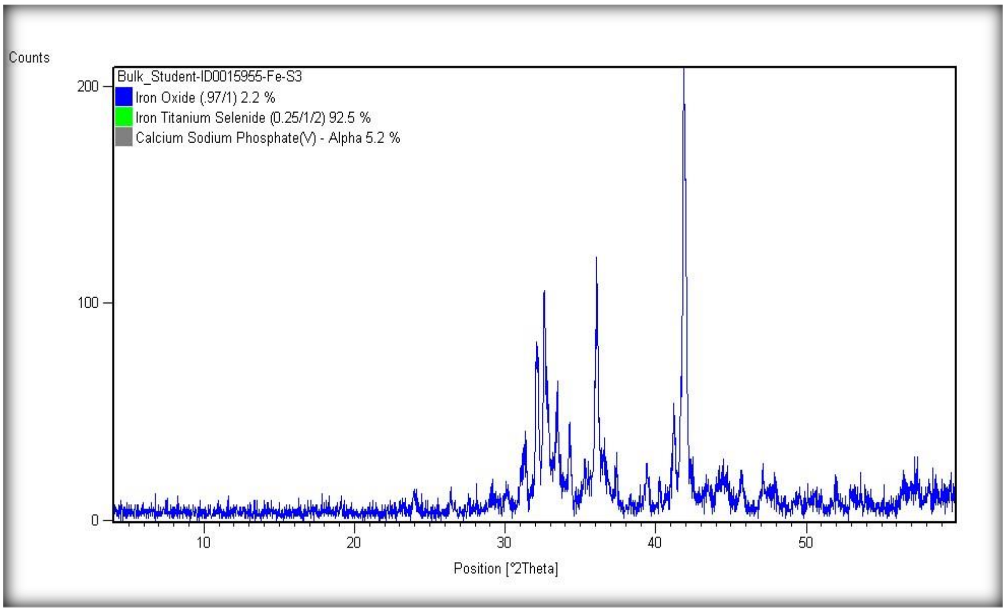

Fig. 4: XRD test results for sample (3)

4.3 Strength activity index test:

Strength Activity Index is calculated as follows:

Strength Activity Index % = (Strength of 20% replacement at 28 Days/ Strength of control sample at 28 Days)*100%

(20%) Strength Activity Index of 28 Days = (42.09/50.42)*100% = 83.4%

ASTM C 989, 75% as minimum of strength activity index, hence the locally produced arc furnace slag has higher strength activity index than the minimum required by ASTM C 989.

The pozzolanic activity of Giad slag was also evaluated by determining its strength activity index with Portland cement at 2,7,14 and 28 days as shown in Table 6. The result obtained, i.e. 83.4% (classified as grade 80 with standard).

Table 6: Mortar compressive strength results for different replacement percentages at different ages

% of Slag Add to Cement	**Average Strength (N/mm^2)**			
	2 Days	7 Days	14 Days	28 Days
0%	21.88	40.63	42.71	50.42
20%	13.13	24.58	28.96	42.09
30%	10.64	21.25	23.75	38.75
40%	7.29	14.38	18.13	28.34
50%	3.54	7.09	10.00	18.54

The two graphs below as illustrated in Fig. 5 and Fig. 6 show the strength obtained from the control sample and the blast furnace slag replacement samples with different percentages at different ages.

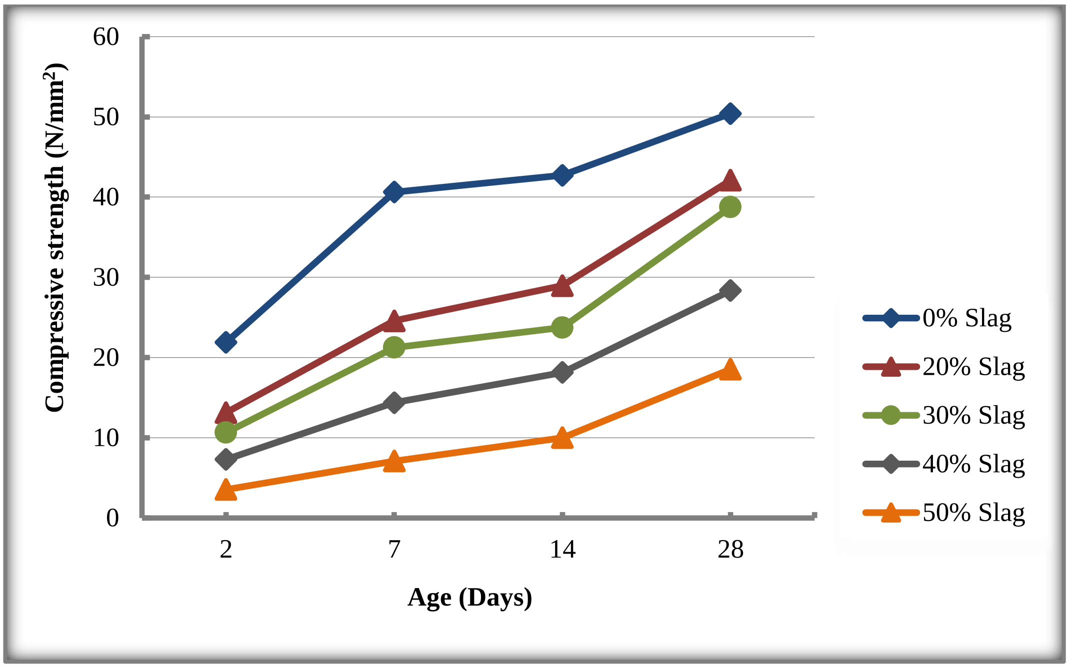

Fig. 5: Comparison between strength of different slag replacement ratios at different ages for mortar

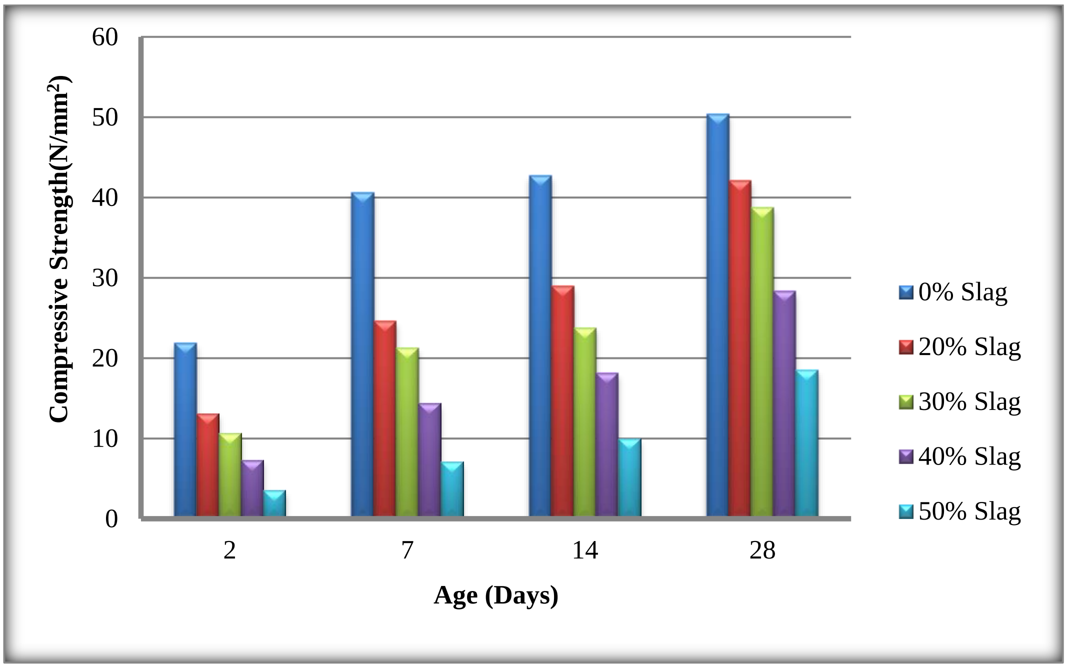

Fig. 6: Histogram of compressive strength of different slag replacement ratios at different ages for mortar

5. Conclusions:

On the basis of the experimental investigations carried out the following conclusions could be drawn:

- According to the physical and chemical analysis for locally produced electric arc furnace slag, it was found that it has acceptable chemical and physical qualities when compared with the standard.
- Comparing the results of chemical analysis obtained in this study with the standard method ACI 233, the locally produced steel slag contains high proportion of iron, due to the iron purification process.
- From the analysis of X-ray diffraction of most of the samples it was observed that these samples combines both pozzolanity and hydraulic properties which indicates assign of non crystalline silica and a sign of good pozzolana, but in some samples there were presence of crystalline silica.
- The strength test results showed that the locally produced steel slag from Giad Company is a good pozzolan and its strength activity index was 83.4% which is greater than the minimum target of 75% set by the American Society for Testing and Material.
- Based on the results of the characterization (chemical, physical, XRD and mortar tests) and using American Society of Testing and Material Standard (ASTM C 989 and ASTM C311) the steel slag product by Giad Company in Sudan was classified as a pozzolan of grade 80.
- The rate of strength gain in slag replaced concrete is slow at early stages but with proper curing the strength goes on increasing tremendously.
- From the results of compressive strength it could be seen that the compressive strength increases remarkably with increasing curing time. Also, the compressive strength is decreases with increase the slag content, as mentioned before this may be due to chemical composition of slag.

6. Recommendations:

Based on the results, finding and conclusions of this study, the following recommendations could be stated:

- To get the best result there should be a complete control during the process of iron purification plants in order to take advantages of these residues optimize.
- In Giad industrial city there is huge quantities waste of steel industry so if it is utilized optimally; it can form a good additive to the cement when it is used in concrete structures.
- For structural concrete, it recommended not to increase the steel slag in the mix more than 25%.
- In this study, steel slag test until the age of 90 days, so it is recommended that further studies for longer period of time in order to get a better understanding of the long term strength development.
- Take steel slag as material should be included in courses of building material in civil engineering departments in civil engineering studies in Sudan.
- Further studies are to be carried out to take advantage of steel slag in the production of bricks, blocks and other cement production units.
- For a better utilization of electric arc furnace slag with high quality, there must be rapid quenching in air or water so as the slag to contain a larger amount an amorphous silica. Also the slag must be finely crushed.

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- ASTM C778-02, ''*Standard Specification for Standard Sand''*, American Society for Testing and Materials.
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