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EVALUATION OF THE USE OF STEELMAKING SLAG AS AN AGGREGATE IN CONCRETE MIX: A FACTORIAL DESIGN APPROACH

Article Highlights

- A factorial design methodology was applied to evaluate concrete mix production
- Steel slag was evaluated as an aggregate in concrete mix production
- Influential factors on the compressive strength were proposed
- Possible factor-interaction effects were examined

Abstract

Slag is investigated towards its potential use as an aggregate in concrete mix production. Full factorial design methodology is applied to study the effect of two process input variables, namely: slag as coarse aggregate and slag as medium aggregate on the properties of concrete mix. Additionally, the interaction between input variables is also examined. Incorporating steel slag aggregate in the concrete mix affected its compressive strength. Enhanced compressive strength concrete mix was obtained with 70 wt.% coarse slag aggregate and 70 wt.% medium slag aggregate. Under these proportions, the 28-days compressive strength was higher than the 28-days compressive strength of a concrete mix prepared from normal aggregate. Strong interaction effect exists between slag aggregate size on the compressive strength at 7-days curing. Lower compressive strength for the concrete mix might be obtained if improper proportions of mixed medium and coarse slag aggregate were employed.

Keywords: steelmaking slag; concrete; factorial design; compressive strength.

The aggregates typically account for about 75% of the concrete volume and play a substantial role in different concrete properties such as workability, strength, dimensional stability and durability. Conventional concrete consists of sand as fine aggregate and gravel, limestone or granite in various sizes and shapes as coarse aggregate. There is a growing interest in using waste materials as alternative aggregate materials and significant research is made on the use of many different materials as aggregate substitutes such as coal ash, blast furnace slag, and steel slag aggregate. This type of use of a waste material can solve problems of lack of aggregate in various construction sites and reduce environmental problems related to aggregate mining and waste disposal. The use of waste aggregates can also reduce the cost of the concrete production [1].

Jordan's steel and iron industry began with the establishment of the first local steel manufacturer, Jordan Iron and Steel in 1965. Due to continuous and rising need for steel, twelve local steel mills are now established in Jordan with a total annual production capacity of 1.2 million t [2]. Some of these factories utilize imported semi processed iron in the form of plates to be melted and processed in a later stage to produce reinforced bars. The other type of factories utilizes iron scrap for the production of reinforced bars. It is estimated that the annual production of slag from these factories is around 100-200 thousand tons. Inventing new ways to reuse this accumulated waste is the most pressing and daunting challenge that face Jordan's industrial sector.

The primary components of iron and steel slag are limestone and some other materials in oxide form.

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In the case of steelmaking slag, the slag contains metallic elements such as iron in oxide form; however, because refining time is short and the amount of limestone contained is large, a portion of the limestone auxiliary material may remain un-dissolved as free CaO [3]. In general, several factors are affecting physical and chemical properties of steel slag. These factors include type of steel furnace in the steelmaking plant and the method of steel slag processing. Various approaches can be followed for the utilization of steel slag in cement and concrete applications. One may think about using steel slag in the production of cement. In this approach, the steel slag is mixed with limestone and clay as a raw material feed to cement kiln. In this case, the slag must be clinkered [4]. Another approach is the incorporation of steel slag in cement and composite cements [5]. In addition steel slag can be utilized as an aggregate material. Several advantages of using slag aggregates in concrete mixes are gained such as: reliable quality, increased strength and does not generate alkali-aggregate reactions. In addition, blast furnace slag fine aggregate does not contain materials that may affect the strength and durability of concrete, such as chlorides, organic impurities clay and shells [5,6].

Extensive research has been conducted for the application of steel slag in broad areas of construction. It is vital to quantify the benefits of using such cheap material in concrete technology and concrete asphalt pavement [6-14]. In this study, we evaluate the beneficial use of steel slag obtained from Jordan's steel industry as an aggregate in concrete mix production. Our investigation involves studying the effect of using steel slag of different grades when combined with normal aggregates by different ratios on improving the mechanical properties of hardened concrete. The effect of medium slag aggregate and coarse slag aggregate and the combination between them on the mechanical quality of concrete mix is investigated by applying a 2^2 full factorial design methodology. The main objectives of this study are to identify the most influential process operating conditions on the production of concrete mix and the interaction effects among variables on the compressive strength of the produced concrete.

EXPERIMENTAL

Preparation of the steel slag-based aggregate

Steel slag was provided by local Jordanian factory in the form of boulders (size < 100 mm). The factory produces steel products made from scrap metal, recycled from used automobiles, plant equipment, machinery, or byproducts of the manufacturing and construction sectors by utilizing an electric arc furnace (EAF) for scrap melting and a ladle furnace for the precision control of chemistry and the purification of the liquid steel.

The majority of the steel slag contains free CaO and MgO. Experiments must be performed to investigate the content of free CaO and MgO in the slag. In general, the content of free CaO and MgO in EAF--slag is significantly lower than in basic oxygen furnace steel slag (BOF slag) [1]. Slag pretreatment is necessary to reduce the content of free CaO and MgO in the slag. The ageing or weathering method was followed to reduce the content of free CaO and MgO in the EAF slag. It has been reported that that a proper treatment aimed to stabilize slag by exposing them to outdoor weather and regular spraying for at least 90 days, may eliminate any subsequent expansive phenomenon, allowing a safe use of such slag as aggregate in concrete production [15]. Prior to use, the EAF slag was aged for a period of 6 months. The air aging method was applied by leaving the EAF slag out in an open area to enable weathering. The presence of free CaO and MgO in the slag does not seem to represent a limit for the durability of concrete, due to their stabilization in crystalline lattice [16].

The aged EAF slag aggregate was prepared by crushing the boulders, followed by sorting the ground slag by sieving. In this study, medium and coarse EAF slag was used. The medium EAF slag aggregate was obtained from the sieved material which passed through the 12.5 mm sieve and retained on the 4.75 mm sieve. The coarse EAF slag aggregate was obtained from the sieved material which passed through the 19 mm sieve and retained on the 12.5 mm sieve. Physical and chemical properties of the EAF slag aggregates are given in Table 1. The mechanical properties of the EAF slag aggregates were conducted according to (ASTM C 33, 2003; ASTM C 138/C 138M, 2001; ASTM C 150, 2005).

Table 1. Mechanical properties of aggregate used in this study

Parameter	Steel slag aggregate	Natural aggregate
Saturated density, kg/m^3	2323	2020-2100
Apparent specific gravity	3.2	-
Abrasion value, %	19.4	20-24
Flakiness index	10.98	20-30
Elongation index	9.89	10
Crushing value, %	26.1	-

Preparation of normal aggregate

The normal coarse, medium and fine aggregate source for all mix designs was obtained from gravel pits. The gravel was obtained from local area known in Jordan as "Al-Ghoor". The gravel was crushed then sieved to obtain the desired size fraction. The fine aggregate was obtained from sieved material which passed through the 4.75 mm. The medium aggregate was obtained from the sieved material which passed through the 12.5 mm sieve and retained on the 4.75 mm sieve. The coarse aggregate was obtained from the sieved material which passed through the 19 mm sieve and retained on the 12.5 mm sieve.

Preparation of concrete mix

All concrete mixes were prepared by keeping the water-to-cement ratio and fine aggregate-to-total aggregate ratio constant at 0.6 and 0.35, respectively. No additives were used for the preparation of concrete mix. The high water-to-cement ratio was applied to ensure good workability conditions since no additives were used for concrete mix preparation and to account for water absorption by aggregates. Cement used in this study was Ordinary Portland Cement produced by a local Jordanian factory. The cement is classified as CEM-1 42.50 N. The chemical composition of cement is as follows: 19.94% SiO_3, 5.37% Al_2O_3, 3.18% Fe_2O_3, 63.65% CaO, 2.59% MgO, 2.88% SO_3, 0.82% K_2O and 0.1% Na_2O [17].

The materials were added to the concrete mixture in the following order: coarse aggregate, medium aggregate, fine aggregate and cement. The mixture was mixed under dry condition for about 1 min, then 80 % of water was added. After 1.5 min of mixing, the rest of water was added. Every batch of concrete mix was mixed for a total time of 3 min. The concrete mixes were cast in steel molds (150 mm×150 mm×150 mm) and compacted using a tamping rod. One day after casting, the concrete samples were removed from the mold and cured in a tank of water at a temperature of 20 °C for 3, 7 and 28 days. All concrete mix are prepared by keeping the cement content as 425 kg/m^3, medium-to-total aggregate ratio of 0.38 and coarse-to-total aggregate ratio of 0.6. Table 2 shows the mix proportions for the mixes applied in this study.

Characterization of samples

Sample characterization was carried out by examining the compressive strength. The compressive strength of concrete was determined according to ASTM C-39.

Experimental factorial design and analysis

Design of experiment is a powerful tool that can be used in a wide spectrum of experimental situations. Design of experiments allows for multiple input factors to be studied and to determine their effect on a desired process/design/quality output. When studying multiple inputs at the same time, design of experiment can identify important interactions that may missed when experimenting with one variable at a time (OVAT approach). All possible combinations between process input variables can be investigated by conducting full factorial design. The factorial design methodology can be utilized to confirm possible input/ /output relationships and to develop a predictive equation suitable for performing design simulations with minimum time and cost.

In this research, EAF slag is incorporated as aggregate during the production of concrete mix. Most of studies concerning concrete containing slag aggregate are conducted by adopting the OVAT approach. In these studies, a given grade of conventional aggregate are replaced partially or totally by its counterpart slag aggregate with the remaining factor held constants. The effect of such replacement of either fine, medium or coarse aggregate is then solely evaluated. This approach provides an estimate of the effect of a single variable at a selected fixed condition of the other variables. However, for such an estimate to have general relevance it is necessary to check whether the effect would be the same at other settings of the other variables or not. Nevertheless, studies on the effect of combined replacement of

Table 2. Mix design parameters for concrete mixes applied in this study (kg/m^3)

Component	Run-1	Run-2	Run-3	Run-4	Run-5
Cement	425	425	425	425	425
Water	255	255	255	255	255
Fine aggregate	510	510	510	510	510
Medium slag aggregate	138	415	138	415	0
Medium normal aggregate	415	138	415	138	553
Coarse slag aggregate	223	223	668	668	0
Coarse normal aggregate	668	668	223	223	891

mixed grade of aggregate on the mechanical properties of concrete at the same time are rarely conducted.

To achieve this goal, a full factorial design methodology was followed to identify the main effects of two processing factors on the mechanical properties of concrete. The two factors studied were replacement percentage of medium conventional aggregate by medium EAF slag aggregate (X_1), and replacement percentage of coarse conventional aggregate by coarse EAF slag aggregate (X_2). Each of the two factors was studied at two levels (Table 3). Therefore, the arrangement and number of experiments is considered to be 2x2 or 2^2 factorial design. The four formulations are shown in Table 4 with variable levels coded with plus and minus signs. The prepared concrete mixes were subjected to the following tests (response output variables): 3-days compressive strength (Y_1), 7-days compressive strength (Y_2), and 28-days compressive strength (Y_3). In addition, one concrete mix that contained 100% normal aggregate was prepared and tested for its 3, 7 and 28-days compressive strength.

Table 3. Process input variables and levels of variables

Input variable	Slag as medium aggregate, wt.% (X_1)		Slag as a coarse aggregate, wt.% (X_2)	
Level	Low (-)	High (+)	Low (-)	High (+)
Condition	30	70	30	70

The main effect of each variable is computed using the following equation [18]:

$$E = Y_{+1} - Y_{-1}$$

where Y_{+1} is average response for the high level of the variable and Y_{-1} is average response for the low level of the variable.

The interaction ($I_{A,B}$) between two process parameters (say, A and B) can be computed using the following equation [18,19]:

$$I_{A,B} = \frac{1}{2}\left(E_{A,B(+1)} - E_{A,B(-1)}\right)$$

where $E_{A,B(+1)}$ is the effect of factor "*A*" at high level of factor "*B*" while $E_{A,B(-1)}$ is the effect of factor "*A*" at low level of factor "*B*".

RESULTS AND DISCUSSION

Main and interaction effects of process input variables on compressive strength

The main effects of process variables on the 3, 7 and 28 day compressive strength have been studied. Table 5 shows the calculated main effects based on all experimental observations. Figure 1 shows the main effect plots for the studied process variables.

The absolute value of the effect of EAF slag aggregate grade on the 3-days compressive strength was the same. Very slight effect was noticed for both aggregate grades at any proportion on the 3-days compressive strength. Concrete mix made of either 30 or 70 wt.% coarse EAF slag aggregate and concrete mix made of either 30 or 70 wt.% medium EAF slag aggregate exhibited almost the same (21.9-23.4 MPa) 3-days compressive strength. In addition, concrete mix made from normal aggregate without incorporating any of the steel slag aggregate possessed nearly the same 3-days compressive strength of 22.8 MPa. It seems that three days of curing was not sufficient enough to produce strong adhesion between the cement paste and the aggregate, thereby, giving close value of compressive strength. To assess the viability of effect of parameters and confirm the existence or absence of interaction effects between parameters, we constructed the interaction plot shown in Figure 2.

Table 5. Full 2^2 factorial design analysis of process response

Term	Response		
	Y_1	Y_1	Y_3
Main Effect of X_1	-1.6	-2.2	4.6
Main Effect of X_2	-1.6	3.7	6.3
Interaction effect X_1X_2	0.5	3.7	-1.9

Figure 2 shows that there is week interaction effect between parameters, that is, the main effect of

Table 4. Experimental design matrix and response of output variables

Run	In put variables		Output variables			
	X_1	X_2	Y_1 / MPa	Y_2 / MPa	Y_3 / MPa	Slump, cm
1	-	-	24.4	31.1	34.6	0
2	+	-	22.4	25.3	41.1	2
3	-	+	22.4	31.1	42.8	1
4	+	+	21.3	32.6	45.5	2
5	0%	0%	22.8	31.1	40.9	0

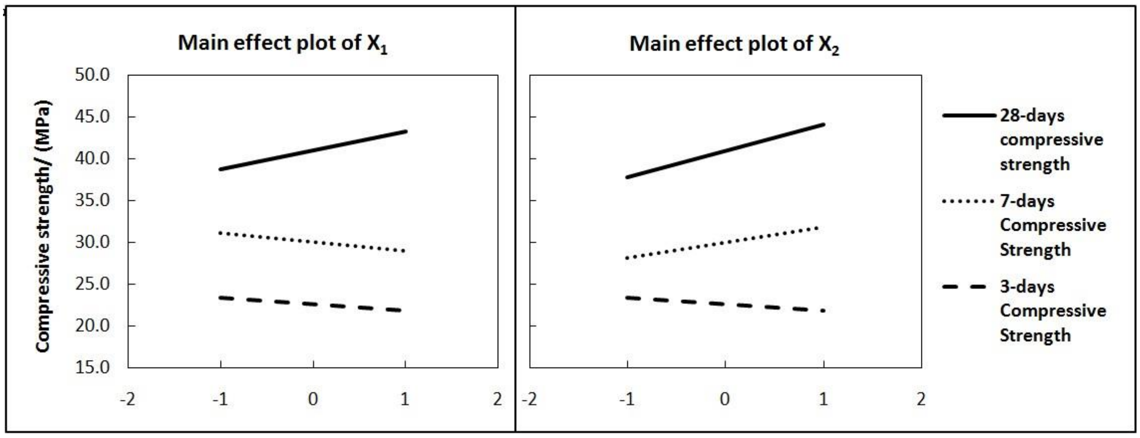

Figure 1. Main effect plots for process input variables (coarse and medium slag aggregate) on compressive strength.

coarse EAF slag aggregate proportion in the concrete mix on the 3-days compressive strength is independent on the proportion of medium EAF slag aggregate in the same mix. Similarly, the main effect of medium EAF slag aggregate proportion in the concrete mix on the 3-days compressive strength is independent on the proportion of coarse EAF slag aggregate in the same mix.

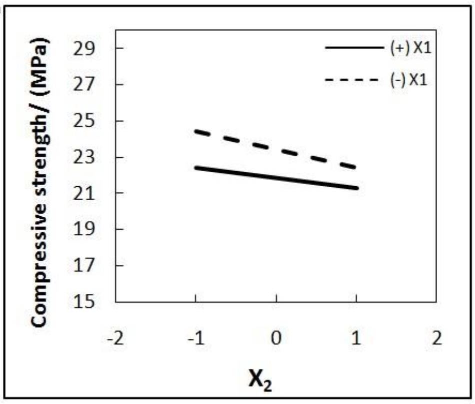

Figure 2. Interaction effect plot for coarse and medium slag aggregate on 3-days compressive strength.

The 7-days curing enhanced the compressive strength of concrete mixes. The 7-days compressive strength of concrete mixes containing EAF slag aggregate was larger than 3-days compressive strength by at least 30%. The same results was noticed for concrete mix made from normal aggregate without incorporating any of the EAF slag aggregates. The effect of medium EAF slag aggregate on the 7-days compressive strength was slightly higher at 30 wt.% replacement compared to 70 wt.% replacement. On the other hand, the effect of coarse EAF slag aggregate on the 7-days compressive strength was slightly higher at 70 wt.% replacement compared to 30 wt.% replacement. This trend in results must also be judged by confirming existence or absence of interaction effect between EAF slag aggregate grades. This is shown in the interaction plot given in Figure 3.

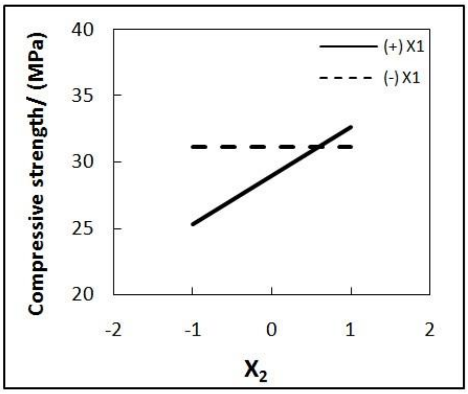

Figure 3. Interaction effect plot for coarse and medium slag aggregate on 7-days compressive strength.

The interaction between the process input variables on the 7-days of compressive strength represents an antagonistic-type interaction [19]. At 75 wt.% medium slag proportion, increasing the coarse EAF slag aggregate proportion in the concrete mix from 30 to 70 wt.% substantially increased the 7-days compressive strength from 25.3 to 32.6 MPa. However, at 30 wt.% medium EAF slag proportion increasing the coarse EAF slag aggregate proportion in the concrete mix from 30 to 70 wt.% kept the 7-days compressive strength unchanged at ~31 MPa. This interaction effect between parameters can hardly be observed by following the OVAT approach of experimentation. The interaction effect shown in Figure 3 shows that local maximum of 7-days compressive strength could be obtained at 70 wt.% medium EAF slag aggregate proportions and 70 wt.% coarse EAF slag aggregate proportions in the concrete mix.

The 28-days curing enhanced the compressive strength of concrete mixes. The 28-days compressive strength of concrete mixes containing EAF slag aggregates was larger than 3-days compressive strength by at least 62%. Concrete mix made from normal aggregate exhibited 40.9 MPa of 28-days compressive strength with an enhancement by approximately 80% in reference to the 3-days compressive strength of the concrete mix made from normal aggregate. The effect of medium EAF slag aggregate on the 28-days compressive strength was higher at 70 wt.% replacement compared to 30 wt.% replacement. Similarly, the effect of coarse EAF slag aggregate on the 28-days compressive strength was noticeably higher at 70 wt.% replacement compared to 30 wt.% replacement. This trend in results must also be judged by confirming existence or absence of interaction effect between slag aggregate grades. This is shown in the interaction plot given in Figure 4.

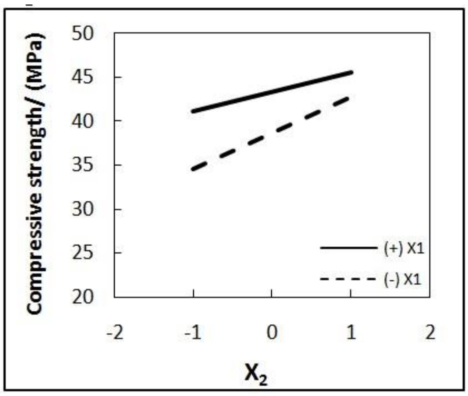

Figure 4. Interaction effect plot for coarse and medium slag aggregate on 28-days compressive strength.

Small interaction between the process input variables on the 28-days of compressive strength was noticed within the concrete mix proportions selected in this study. At 70 wt.% medium EAF slag proportion, increasing the coarse EAF slag aggregate proportion in the concrete mix from 30 to 70 wt.% increased the 28-days compressive strength from 41.1 to 45.5 MPa. In the same manner, at 30 wt.% medium EAF slag proportion increasing the coarse EAF slag aggregate proportion in the concrete mix from 30 to 70 wt.% increased the 28-days compressive strength from 34.6 to 42.8 MPa. The interaction effect shown in Figure 4 shows that local maximum of 28-days compressive strength could be obtained at 70 wt.% medium EAF slag aggregate proportion and 70 wt.% coarse EAF slag aggregate proportion in the concrete mix.

CONCLUSION

Concrete mixes were successfully prepared by utilizing slag generated from the steelmaking industry. A full factorial design analysis was effectively performed to assess the most influential process operating conditions on the compressive strength of concrete mixes made from different mixed proportions of EAF slag aggregates. The proportions of the course and medium size EAF slag aggregate were prominent process variables found to be affecting the 7-days and 28-days compressive strength of a concrete mix.

Under 3-days curing, there was no appreciable enhancement on the compressive strength of concrete mixes prepared from EAF slag aggregate at any proportion in comparison with concrete mixes prepared from normal aggregates. Both type of mixes possessed almost the same 3-days compressive strength.

Under 7-days curing, strong interaction effect for the proportion of EAF slag aggregates was noticed on the compressive strength. Concrete mixes comprising lower coarse slag aggregate content and higher medium EAF slag content exhibited lower compressive strength compared with concrete mix prepared from normal aggregate. Nevertheless, concrete mixes comprising higher coarse slag aggregate content and any proportion of medium EAF slag content exhibited almost the same compressive strength of concrete mix prepared from normal aggregate.

Under 28-days curing, there was noticeable enhancement on the compressive strength of concrete mixes prepared from high proportions of EAF slag aggregate in comparison with concrete mixes prepared from normal aggregates.

The mechanical properties of concrete mixes prepared in this study are satisfactory. However, it is recommended that other important properties such as durability and corrosion of EAF slag concrete are to be investigated before mass use.

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NAUČNI RAD

PROCENA UPOTREBE ŠLJAKE IZ PROIZVODNJE ČELIKA KAO AGREGATA U CEMENTNIM MEŠAVINAMA POMOĆU PUNOG FAKTORIJALNOG PLANA

U radu je analizirana upotreba šljake kao potencijalnog agregata u proizvodnji cementa. Primenjen je pun faktorijalni plan radi proučavanja uticaja dve ulazne procesne promenljive, i to šljaka kao krupni agregat i šljaka kao srednji agregat na osobine cementne mešavine. Pored toga, ispitivana je interakcija između ulaznih promeljivih. Ubacivanje agregata šljake iz proizvodnje čelika u cementnu mešavinu uticalo je na njenu pritisnu čvrstoću. Povećana pritisne čvrstoće cementne mešavine sa 70 mas.% krupne šljake i sa 70 mas.% srednje šljake. Pri ovim proporcijama, 28-dnevna pritisna čvrstoća dobijene cementne mešavine je jača od 28-dnevne pritisne čvrstoće cementne mešavine pripremljene od normalnih agregata. Postoji jaka interakcija između veličine agregata šljake i pritisne čvrstoće posle sedmodnevnog očvršćavanja. Manja pritisna čvrstoća cementne mešavine mogla bi biti dobijena ako bi se koristile agregati srednje i krupne šljake pomešani u neodgovarajućim proporcijama.

Ključne reči: bioetanol, pamuk, lignoceluloza, predtretman, hidroliza, fermentacija.