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Experimental investigation of surface modified EOF steel slag as coarse aggregate in concrete

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Abstract An experimental work was carried out to study the effect of Energy Optimizing Furnace (EOF) steel slag as coarse aggregate replacement in concrete. Surface modification of slag was carried out to seal the surface voids of raw slag aggregates. Quarry dust obtained as an extractive waste from the granite stone quarries has been used as a blending material in this work. After several trials, it was found that a mix proportion of 1:6:14 (cement:quarry dust:slag aggregate) was the most suitable mix ratio for the surface modification of the slag aggregates. Various mixes of concrete were prepared with different proportions of modified slag (ranging from 0% to 100%) as replacements for aggregates. Three grades of concrete (20 MPa, 30 MPa and 40 MPa) were used in the investigation and the concrete mixes were evaluated for compressive strength and splitting tensile strength. It was found that the compressive strength improved for 25 percent replacement of natural coarse aggregates. The splitting tensile strength was found to peak at 25 percent replacement of natural aggregates.

1. Introduction

Presently, there are various methods for production of steel and the EOF is relatively a recent technique employed to manufacture steel from iron ore. The produced steel slags contain EOF slag. Earlier researchers have utilized other types of steel slag as both fine and coarse aggregate replacement successfully in concrete. Brand and Roesler (2015) have utilized different basic steel slags as aggregates and also carried out tests to evaluate the chemical and mineralogical properties. Adegoloye et al. (2015) have successfully utilized Electric Arc Furnace (EAF) slag and Argon Oxygen Decarbonization (AOD) slag as aggregates. Numerous studies were carried out with EAF slag as replacement for coarse aggregates (Muhumood et al., 2009; Abu-Eishah et al., 2012; Alizadeh et al., 2003; Manso et al., 2006). The instant chilled steel slags were experimented to be a suitable replacement for natural coarse aggregates in concrete (Montgomery and Wang, 1991). The study majorly

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Table 1 Composition of EOF slag and EAF slag.

Compound	EOF slag (%)	EAF slag (%)
CaO	36.96	20–40
FeO	28.93	20.40
SiO_2	13.81	6–23
MgO	7.46	3–15
Al_2O_3	2.53	3–14
MnO	3.00	1.5–15
P_2O_5	1.58	–
TiO_2	0.60	–
Na_2O	0.057	–
K_2O	0.032	–
Loss on ignition	3.70	–

focused on the strength properties of concrete with steel slag aggregates. Wang (2010) studied the feasibility of adopting steel slag coarse aggregate in concrete by determining the expansive force of the steel slag aggregates. Durability properties were also studied extensively to evaluate the performance of steel slags in concrete (Manso et al., 2006; Luxan et al., 2000).

It was found that the steel slag is volumetrically unstable as compared to the blast furnace slag due to the presence of expansive oxides (CaO/MgO) (Wang, 2010). The chemical composition of EOF steel slag was observed and it was found that the properties vary from other steel slag properties. The chemical properties of EOF slag are listed in Table 1. It was observed that it contains 36.96% of Calcium Oxide (CaO) which in the presence of water undergoes hydration to calcium hydroxide ($Ca(OH)_2$) resulting in volume expansion leading to cracking. Surface modification of slag can seal the passage to the inner core of slag aggregate and can reduce the hydration considerably.

As natural resources are fast being depleted to satisfy the ever increasing demand for them, much emphasis has been laid on utilization of extractive wastes in construction practices. Since the EOF steel slag is a recent technique adopted in the steel manufacturing industry, research is required to be carried out to study the feasibility of its adoption as aggregates in concrete. This work focuses on the study of compressive and splitting tensile strength of concrete for three different grades of concrete (20 MPa, 30 MPa and 40 MPa) with EOF slag aggregate as replacement to stone aggregates in concrete. The EOF slag aggregates were blended with slurry of cement and very finely sieved quarry dust.

2. Materials

2.1. Cement and aggregate

Ordinary Portland Cement (OPC) conforming to IS: 12269-(1987) with a specific gravity of 3.15 and potable water was used for production of concrete. The fine and coarse aggre-

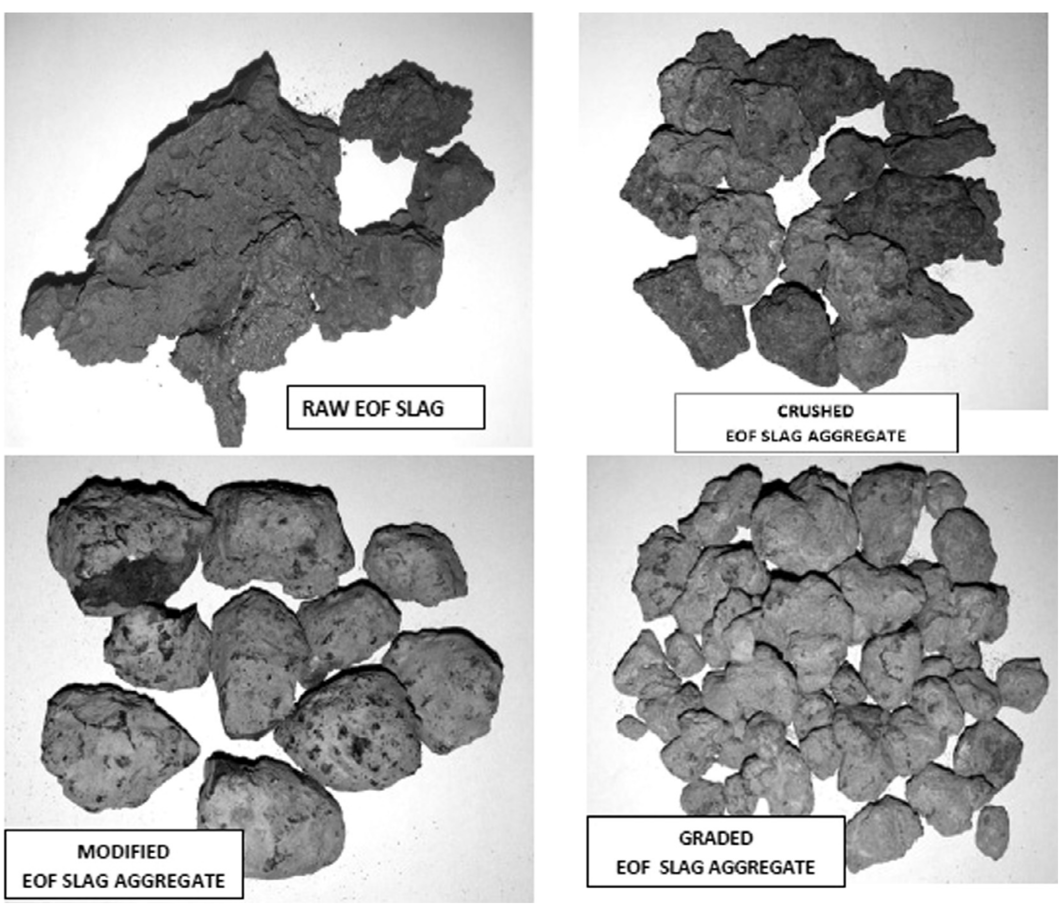


Figure 1 Raw and modified EOF slag.

Table 2 Sieve analysis results.

Sieve size mm	Cumulative passing	
	Test results	IS standard limits
40	100	100
20	100	95–100
16	100	–
12.5	90	–
10	55	25–55
4.75	0	0–10
2.36	0	–

gates were graded as per IS: 383-(1970). The fine aggregates and coarse aggregates utilized in this study conform to Zone II as per IS: 383-(1970) with a specific gravity of 2.6 and fineness modulus of 0.9. 20 mm natural aggregate with a specific gravity of 2.7 and fineness modulus of 3.5 respectively. No superplasticizer was used in this study in order to maintain a low slump value.

2.2. Energy Optimizing Furnace (EOF) slag

The EOF steel slag was obtained locally from Jindal Steel Limited - Salem Works. It was observed that the surface of the slag was highly porous. The chemical composition of the EOF steel slag is listed in Table 1. It was reported that the chemical composition of slag vary depending on its origin (Rojas and Rojas, 2004). EAF steel slag composition range as reported by earlier researchers (Abu-Eishah et al., 2012) was also listed in Table 1. The water absorption and specific gravity of EOF slag was found to be 2.4% and 3.1, respectively.

2.3. Surface modification of slag aggregate

The slag aggregate obtained from slag waste needs to be modified for the reasons of volume expansion and high porosity. Surface Modification is done to fill the internal voids of the slag using a slurry mixture of finely graded quarry dust and cement. The mixing of above slurry with the slag aggregate is done using a standard mixture machine. Several trials were carried out to find the most optimum use of quarry dust and cement slurry to completely fill the surface voids of the slag aggregate and the most optimum ratio was found to be 1:6:14. After thoroughly mixing the slag aggregate, the aggregates were dried for about 7 days. Fig. 1 shows the surface modified slag aggregate used in this study. It was observed that some slag aggregates were in clustered form and were thoroughly separated out. The specific gravity of the surface modified slag was found to be 3.21 and the water absorption was found to be 1.55%.

Sieve analysis was carried out to determine the feasibility of adopting the slag aggregate in concrete mix. The results of the sieve analysis and the IS standard limits for 20 mm aggregates are listed in Table 2. From the table it could be observed that the grading of aggregates were within the prescribed limit of the IS recommendation.

To examine the chemical composition and voids of raw and surface modified slags aggregates, the aggregate specimens were subjected to investigation using Scanning Electron

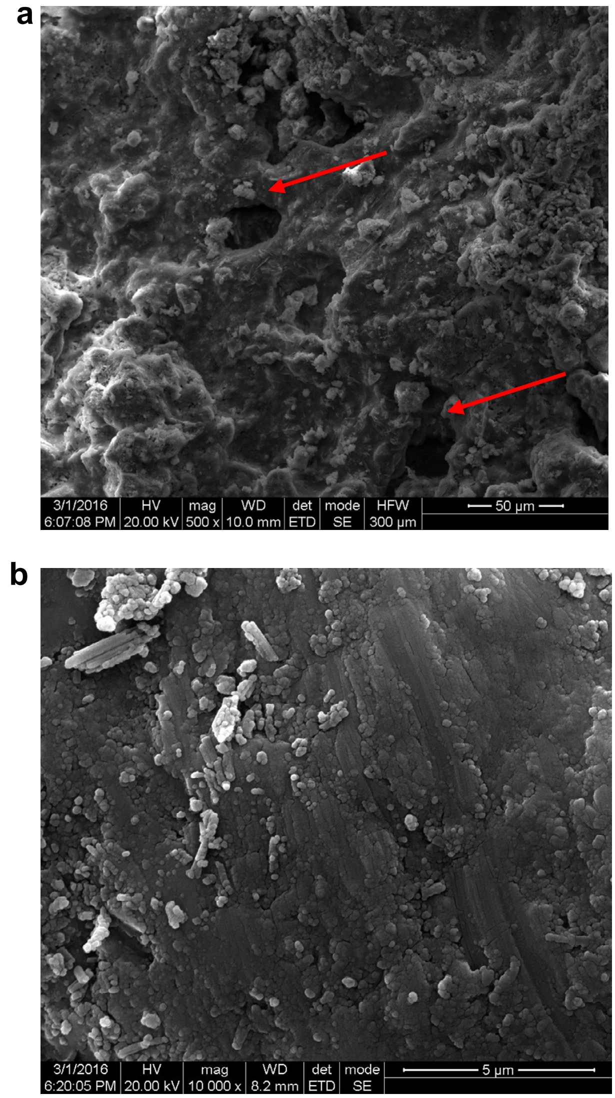


Figure 2 (a) SEM image of raw slag, (b) SEM image of modified slag.

Micrographs (SEM). The SEM images show that the voids were effectively filled as shown in Fig. 2(a) and (b). The arrow marks in Fig. 2(a) show the presence of voids in raw slag. The Voids were absent in Modified slag as observed in Fig. 2(b).

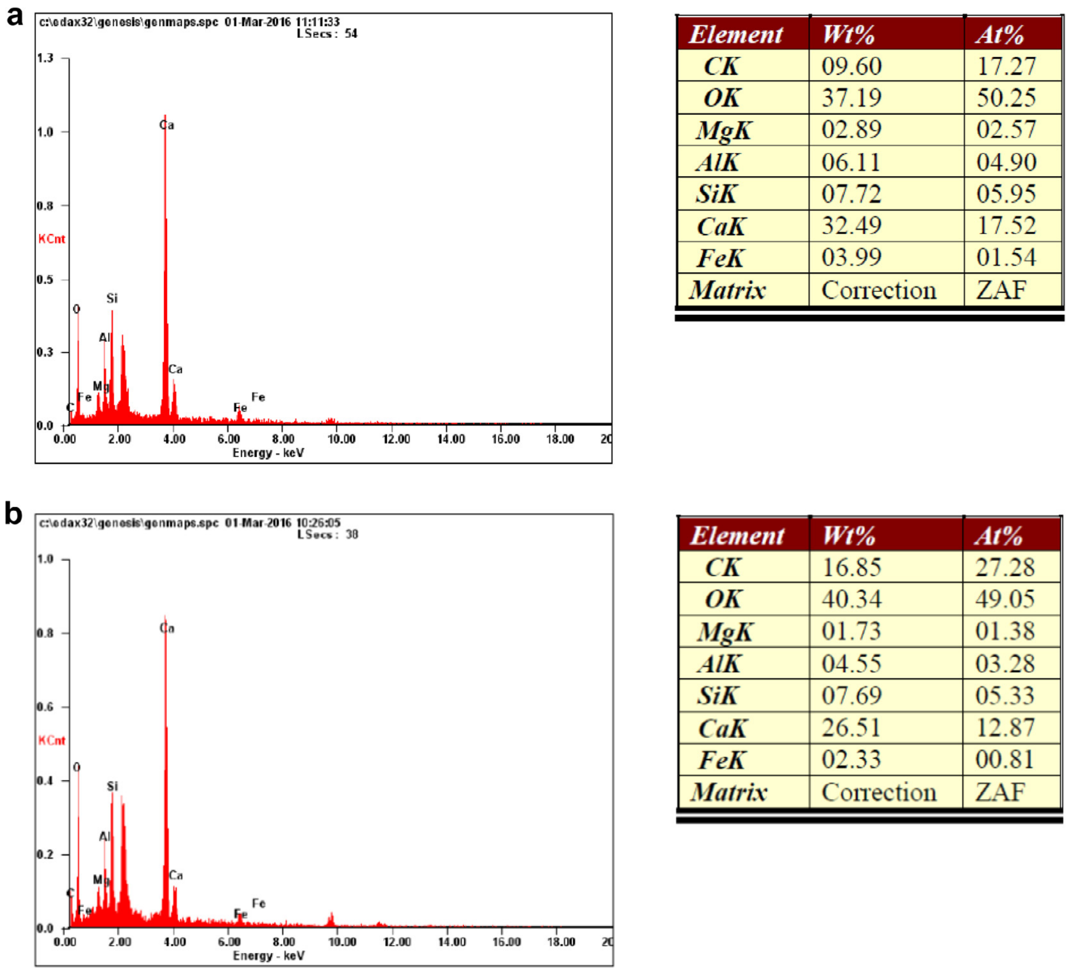
To compare the chemical composition of the raw and modified slag the EDX spectrum was obtained. The EDX spectrum of the slag specimens is shown in Fig. 3(a) and (b).

2.4. Mix proportions

The mix proportions for different grades of concrete was tabulated and given in Table 3. The cement content in the table includes the cement used in modification of the aggregate.

3. Experimental procedure

In this work, standard cubes of dimension 150 × 150 × 150 mm and cylinders of 150 × 300 mm were cast and tested. Tests were carried out to evaluate the compressive strengths



(a)

Element	Wt%	At%
CK	09.60	17.27
OK	37.19	50.25
MgK	02.89	02.57
AlK	06.11	04.90
SiK	07.72	05.95
CaK	32.49	17.52
FeK	03.99	01.54
Matrix	Correction	ZAF

(b)

Element	Wt%	At%
CK	16.85	27.28
OK	40.34	49.05
MgK	01.73	01.38
AlK	04.55	03.28
SiK	07.69	05.33
CaK	26.51	12.87
FeK	02.33	00.81
Matrix	Correction	ZAF

Figure 3 (a) EDAX spectrum of raw slag, (b) EDAX spectrum of modified slag.

Table 3 Mix proportion for different grades of concrete.

Mix	% slag aggregate	Cement kg/m^3	Fine aggregate kg/m^3	Coarse aggregate kg/m^3	Slag aggregate kg/m^3	Water Lts
20 MPa	0	342.89	711.62	1136.03	0.00	210.06
	25	342.89	711.62	852.02	322.16	213.70
	50	342.89	711.62	568.01	644.31	217.35
	75	342.89	711.62	284.01	966.47	220.99
	100	342.89	711.62	0.00	1288.63	224.64
30 MPa	0	428.61	643.12	1131.60	0.00	209.34
	25	428.61	643.12	848.70	320.90	212.97
	50	428.61	643.12	565.80	641.80	216.60
	75	428.61	643.12	282.90	962.71	220.23
	100	428.61	643.12	0.00	1283.61	223.87
40 MPa	0	555.38	569.06	1096.67	0.00	208.42
	25	555.38	569.06	822.50	311.00	211.94
	50	555.38	569.06	548.34	621.99	215.46
	75	555.38	569.06	274.17	932.99	218.97
	100	555.38	569.06	0.00	1243.99	222.49

and splitting tensile strengths at the end of 7 days and 28 days of curing for three grades of concrete (20 MPa, 30 MPa and 40 MPa). In each grade of concrete, 15 cubes and 15 cylinders were cast in 5 batches by partially replacing stone aggregates by slag aggregates from 0% to 100% in increment of 25%. The test specimens were tested for its 7 and 28 day strength to evaluate the compressive and splitting tensile strengths using a 2000 kN capacity Compressive Testing Machine.

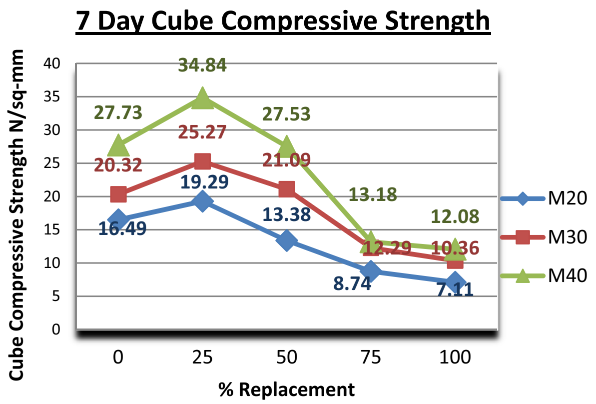


Figure 4 7-Day compressive strength graph.

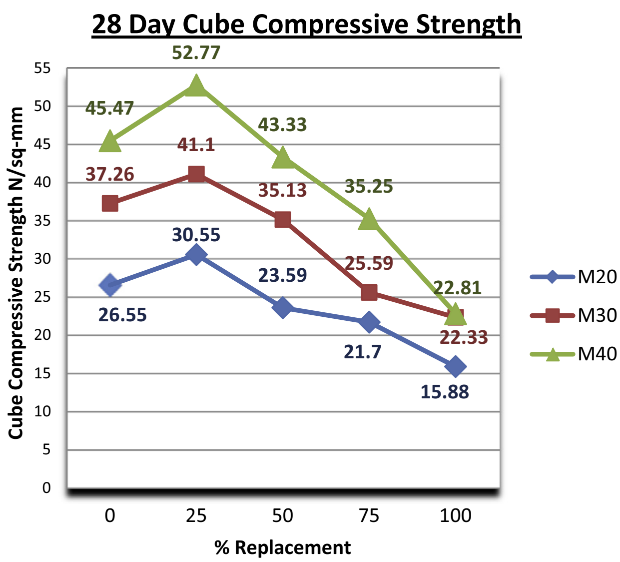


Figure 5 28-Day compressive strength graph.

4. Interpretation of test results

4.1. Compressive strength

Tests were carried out to evaluate the compressive strength which is a very important property of concrete. The Average compressive strengths at the end of 7 days of curing for the three grades of concrete (20 MPa, 30 MPa and 40 MPa) for different percentage replacements of slag aggregate namely 0%, 25%, 40%, 75% and 100% are shown in Fig. 4. Similarly, the average 28 day compressive strength for the different grades was also found and the results are depicted in Fig. 5. From Figs. 4 and 5 it can be observed that the maximum compressive strength increases as the grade of concrete increases till 25% replacement of slag. Subsequently, the compressive strength beyond 25% replacement of slag aggregate was found to decline drastically. In all the three grades of concrete the compressive strength for 75% and 100% replacement was found to be lower than the compressive strength values without slag aggregates indicating that the replacement will not be effective for higher replacement percentage. The lower angular shape and low sharpness edge of surface modified

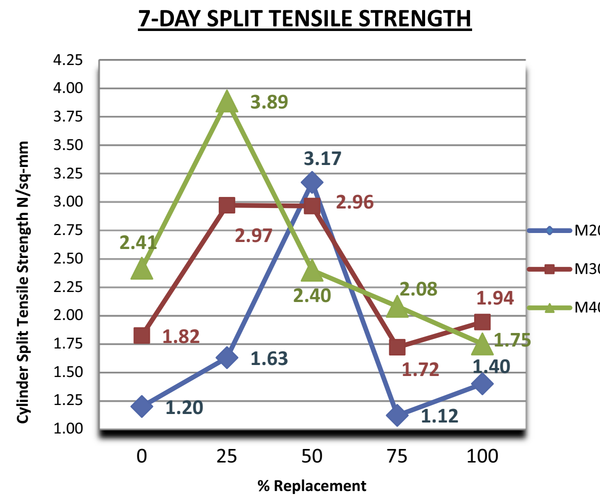


Figure 6 7-Day split tensile strength graph.

EOF slag decreased the compressive strength for a higher replacement ratio beyond 25%. This may be attributed to the reason that there is a possibility of low binding between aggregate and cement mortar for a higher replacement ratio of modified EOF slag aggregate similar to that of EAF slag (Etxeberria et al. (2010)).

4.2. Split tensile strength

The results of the 7-day split tensile strength are shown in Fig. 6 and the results of 28-day splitting tensile strength are presented in Fig. 7. From the results obtained it is observed that the split tensile strength values at the end of 7 days increase initially and decrease on further increase in percentage replacement of slag. This indicates that the influence of slag aggregate in resisting tensile strength is significant at only lower values of replacement beyond which the tensile strength deteriorates. Almost similar behavior is observed from the 28 day results. It can be inferred that the peak split tensile strength can be achieved when the stone aggregates are replaced by 25% slag aggregates. The decrease in splitting tensile strength beyond a 25% replacement is due to the high

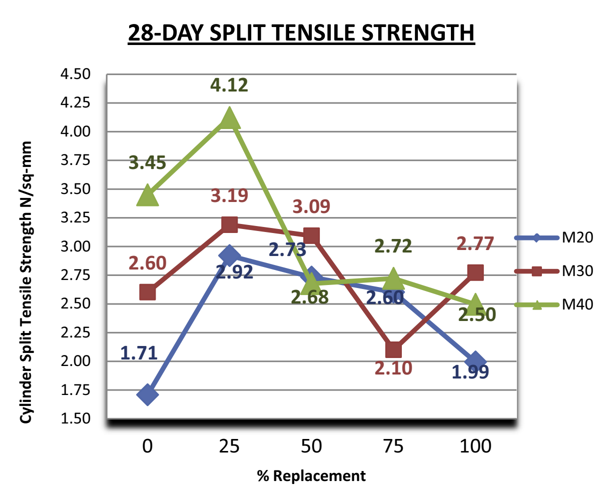


Figure 7 28-Day split tensile strength.

porosity of concrete caused by the increasing volume of modified EOF slag aggregates. Another reason for reduction in tensile strength is due to higher w/c ratio values. Both the factors have reduced the bonding between aggregate and cement mortar paste beyond 25% slag replacement.

5. Conclusions

- The increase in compressive strength of concrete for higher percentage replacement of slag aggregate was found to be less significant.
- The partial replacement of natural stone aggregate by modified slag aggregate was found to be most optimal for 25% replacement in terms of compressive strength for the grades of concrete tested in this study.
- Splitting tensile results indicate that 25% replacement by slag aggregates is found to be greater for all the grades of concrete.
- Surface modified slag aggregate obtained by blending slag aggregate with quarry dust was found to be an effective solution in overcoming the volume expansion problem of the slag aggregate.

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