Strength Behaviour of Geopolymer Concrete by Partial Replacement of Coarse Aggregate with Steel Slag

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Abstract—The development of sustainable and environment friendly construction materials has gained major attention recently because of depletion of natural resources. Attempts were made to develop materials that can partially or fully eliminate the use of cement in concrete due to the high emissions of greenhouse gases during their production. An experimental study was conducted to investigate the influence of steel slag by partially replacing coarse aggregate in flyash based geopolymer concrete. The mechanical and flexural properties were tested with steel slag in proportions of 10%, 20%, 30% and 40% in geopolymer concrete after 3, 7 and 28 days of curing. A total of 45 specimens were cast and compressive strength, split tensile strength and modulus of rupture were tested. It was observed that, the optimum amount of steel slag that can be used in geopolymer concrete as coarse aggregate is 30%. The results showed that the geopolymer concrete with steel slag as coarse aggregate offered higher strength in compression and flexure, when compared with the geopolymer concrete without adding steel slag.

Index Terms—concrete, flyash, geopolymer, loading, frame, steel, slag

1 Introduction

Concrete is one of the most widely used construction materials in which Portland cement is used as binding material. On the other hand, there are environmental issues like climate change due to global warming during last decades. The emission of greenhouse gases like CO_2 is the main cause of global warming. The cement industry is responsible for contributing to major portion of CO_2 emission. According to Department of Industrial Policy and Promotion, annual cement production in India is around 400 million tons, per capita consumption is around 225 kg. One way of mitigating the emissions factor is by way of adopting geopolymer technology.

Geopolymers consists of networks or chains of molecules of inorganic substances. Normally ordinary portland cement (OPC) paste gains strength by the calcium-silicate-hydrate (CSH) gel formation. Whereas the geopolymer gains the strength by the process named poly condensation. Some of the by-product materials from various industries like flyash, silica fume etc. are rich in silica and alumina.

Flyash is a by-product from coal powered thermal power plants which is rich in silica. The main chemical components of flyash are silicon dioxide, aluminium oxide and iron oxide etc. The most available type is low calcium flyash which is obtained as a by-product of burning bituminous coal or anthracite. According to Central Electricity Authority, the annual production of flyash in India is more than 180 million tons. Out of this, only about 55% flyash is utilised in the production of pozzolana cement, workability improving admixtures and in stabilisation of soil.

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Slag is the term which includes all non metallic by-products from the steel industries. The commercially available ferrous slag products are basic oxygen furnace steel slag (BOF) and electric arc furnace steel slag (EAF). BOF slag is produced when scrap metals are oxidised by injecting large quantity of oxygen into the molten iron mix to create molten steel. After cooling, the molten slag becomes a dense material. EAF slag is formed when scrap metals are oxidised by the electric current and the molten slag is generally placed into ground bays for cooling. In the present study BOF slag was used.

2 Literature review

Geopolymer is an inorganic polymer that contains silicon-oxygen-aluminium (Si-O-Al) frame-work. The geopolymerisation requires presence of an alkali and alkali metal salt for dissolution of silica and alumina. In the presence of alkali hydroxide and silicate solution, polymerisation takes place when alumino silicates dissolves and free SiO_4 and AlO_4 compounds are formed in solution. These compounds are alternatively connected, which gives geopolymers [1].

The effect of ambient curing on the early and final compressive strengths were investigated on flyash based geopolymer concrete [2]. The long term mechanical properties of flyash based geopolymer concrete were carried up to 1 year of age [3].

Both the fine aggregate and coarse aggregate in concrete can be replaced with steel slag. The geopolymer mix can be designed as per IS 10262:1982 and cast specimens and investigated experimentally [4].

3 Experimental Programme

The materials used were flyash, fine aggregate, coarse aggregate, steel slag, sodium hydroxide, sodium silicate and thermo mechanically treated (TMT) bars.

3.1 Fine Aggregate

The river sand passing through 4.75 mm IS sieve, confirming to zone II of IS 383: 1970 was used. The specific gravity and the fineness modulus of fine aggregate were 2.6 and 3.6 respectively. The uniformity coefficient was 3.33.

3.2 Coarse Aggregate

Crushed natural stone of maximum size 20 mm, with a specific gravity and water absorption of 2.7 and 0.1% respectively, were used as coarse aggregate for the study. Coarse aggregate used in this study conforms to IS 383:1970 specifications.

3.3 Flyash

Low calcium (class F) flyash was used as the geopolymer binder. Particles retained on 45 micron IS sieve in percent was obtained as 19.5. According to Table 2 of IS 3812 (Part 1): 2013, maximum value for this is 34. Standard consistency of flyash was 28%. The initial setting time of the flyash obtained was 3 hrs.

3.4 Steel Slag

The type of steel slag used was angular shaped basic oxygen furnace (BOF) steel slag and its specific gravity and water absorption were 3.1and 1.9 % respectively.

4 Casting of Specimens

The test specimens were prepared by using flyash, river sand, coarse aggregate, sodium silicate solution and sodium hydroxide solution. The sodium hydroxide was available in the form of pellets which mixed with required amount of water forms the 14M solution. According to Shaikh (2016), conventional mixing was used to prepare the geopolymer concrete. The fresh mix was poured in three layers into standard cubes of size 150 × 150 × 150 mm for compressive strength test, 150 × 300 mm cylinders for split tensile strength test and 1000 × 150 × 150 mm for flexural strength test. The reinforcement detailing of the beam is shown in Fig. 1. TMT steel bars of grade Fe 500 was used. Two numbers of 12 mm diameter and 10 mm diameter bars were provided as the bottom and top reinforcement respectively. Stirrups of diameter 6 mm with a spacing of 90 mm also provided. The top surface was levelled by using a smooth trowel after compaction. The specimens were demoulded after 24 hours. Since the use of steam curing limits the application of geopolymer concrete, ambient curing was provided [6]. Similarly geopolymer concrete specimens were cast by replacing the coarse aggregate by using steel slag with varying percentages such as 10, 20, 30 and 40.

5 Testing of Specimens

Five concrete mixes with different proportions of steel slag ranging from 0% to 40% were considered for the tests.

5.1 Compressive Strength Test

Cube specimens of size 150 × 150 × 150 mm were tested in compression testing machine of 3000 kN capacity with a loading rate of 14 N/mm² per minute. The test was conducted according to IS 516: 1959. Three samples of each mix were tested. The maximum load taken by the specimen was noted and compressive strength was calculated at the end of 3, 7 and 28 days curing.

5.2 Split tensile Strength Test

The specimens were tested as per IS 5816: 1999. Three geopolymer concrete cylinders of diameter 150 mm and height 300 mm were tested in a compressive testing machine. The test was carried out by placing the cylinder specimen horizontally between the loading surfaces of the machine. Split tensile strength was computed with the equation,

$$\sigma_t = \frac{2P}{\pi DL}$$

Where,
P = applied load (N)
D = diameter of the specimen (mm)
L = length of the specimen (mm)

5.3 Flexural Strength Test

The geopolymer concrete beam specimens with partially replaced coarse aggregate by steel slag percentages such as 0%, 10, 20, 30 and 40 were designated as D0, D10, D20, D30 and D40 respectively. The size of beam specimens was 1000 ×150 × 150 mm. The beams were designed as per IS 456: 2000 with clear cover of 20 mm. Two numbers of 12 mm diameter and 10 mm diameter bars were provided as the bottom and top reinforcement respectively. Stirrups of diameter 6 mm with a spacing of 90 mm also provided. Five numbers of beam specimens were cast using the same reinforcement.

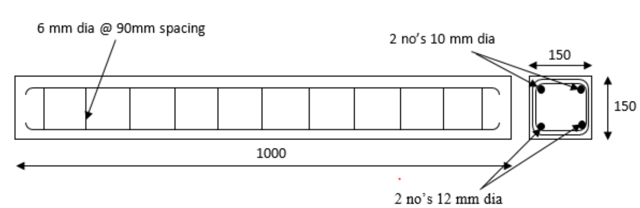
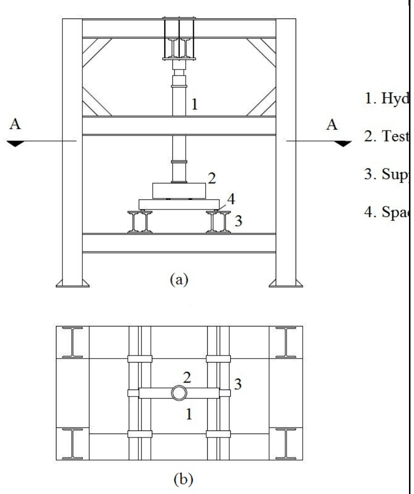


Fig. 1. Reinforcement detailing of the beam

Test setup: The specimens were tested by using loading frame of 750 kN capacity shown in Fig. 2 (a) and (b). Compression type load cells were used to measure the load applied on the test specimen, in which it was fixed to the ram of the hydraulic jack, which will be pressing the specimen under the given load. Two numbers of linear variable differential transducers (LVDTs) of 100mm were placed at the centre bottom of the beams. The measured displacement was captured using a Data Acquisition system. The Fig. 3 shows the experimental setup.



. Fig. 3 Experimental setup

6 Results and Discussion

6.1 Compressive Strength Test

The compressive strength tests has conducted on different samples of geopolymer concrete with partially replaced coarse aggregate by steel slag. The results of compressive strength test are given in Table 1 and depicted in Fig. 4.

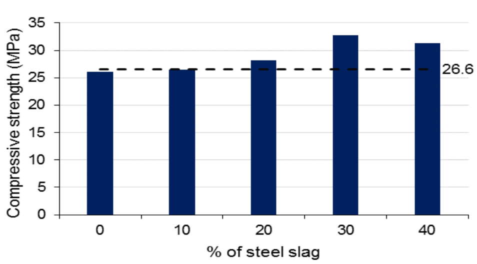


Fig. 4. Variation of compressive strength of geopolymer concrete with % of steel slag

TABLE 2
Compressive Strength Results

Percentage of steel slag	Average Compressive Strength (N/mm²) 3 day	7 day	28 day
0	19.48	21.63	26.07
10	20.22	23.18	26.52
20	21.26	24.37	28.15
30	22.07	25.78	32.74
40	20.67	25.55	31.26

The compressive strength of the concrete was found to increase up to 25.6%. Further the compressive strength was found to be reduced. The optimum percentage of steel slag in geopolymer concrete was found to be 30%.

6.2 Tensile Strength Test

The results of split tensile strength tests are given in Table 2

TABLE 2
Tensile Strength Results

Percentage of steel slag	Average Split Tensile Strength (N/mm²) 7 day	28 day
0	2.07	2.43
10	2.29	2.59
20	2.45	2.90
30	2.85	3.70
40	2.71	3.04

and depicted in Fig. 5.

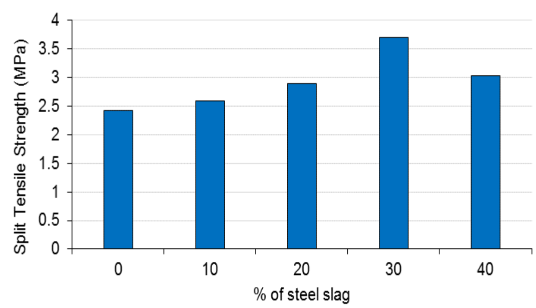


Fig. 5. Variation of tensile strength of geopolymer concrete with % of steel slag

The tensile strength of the concrete was found to increase up to 52.3%. Further the compressive strength was found to be reduced. The optimum percentage of steel slag in geopolymer concrete was found to be 30%.

6.3 Flexural Strength Test

This section analyses (i) load–displacement relations (ii) flexural strength (iii) moment carrying capacity (iv) crack propagation and failure mode and (v) deflection ductility index.

Load – deflection curves of the different beams are shown in Fig. 6. At the initial zone of curves up to the first cracking point, linear behaviour was observed and the beams stiffness shows almost identical values, as this stage is controlled mainly by the tensile strength of geopolymer concrete. In the post cracking zone, a non-linear behaviour with significant stiffness reduction up to yielding of tensile steel in the different beams were observed. In the post yielding, the beams showed ability to withstand higher load and to gain more deformability until failure with the increase in percentage of replacement of coarse aggregate with steel slag. From Fig. 6, it is observed that the beam D30 is having maximum load carrying capacity compared to that of the other specimens and it is about 41.77% more than the control specimen. It is clear that, as the percentage of steel slag increases the initial cracking load and maximum deflection of the flyash based geopolymer concrete beams increases.

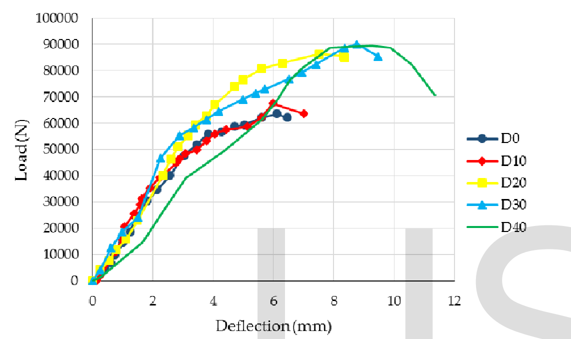


Fig. 6. Load vs. deflection graph

During testing, the load corresponding to the first crack point was noted as well. The failure load and the corresponding deflection for each specimen was noted down from the data recorded by the data acquisition system and is shown in Table 3.

TABLE 3
TEST RESULTS

Beam designation	First cracking load (kN)	Ultimate load (kN)	Maximum deflection (mm)
D0	12.5	63.581	6.460
D10	22.5	67.627	7.025
D20	23	86.329	8.366
D30	30.5	90.140	9.456
D40	31.5	89.580	11.362

Flexural strength was determined using the following stress equation,

$$\sigma = \frac{WL}{bh^2}$$

Where,
W = first cracking load (N)
L = length of beam (mm)
b = width of beam (mm)
h = depth of beam (mm)

The flexural strength of the beams with different percentages of steel slag is shown in Table 4 and depicted in Fig. 7.

TABLE 4
FLEXURAL STRENGTH OF BEAMS

Beam designation	First Cracking load (kN)	Flexural strength (MPa)
D0	12.5	2.96
D10	22.5	5.33
D20	23	5.45
D30	30.5	7.23
D40	28.5	6.75

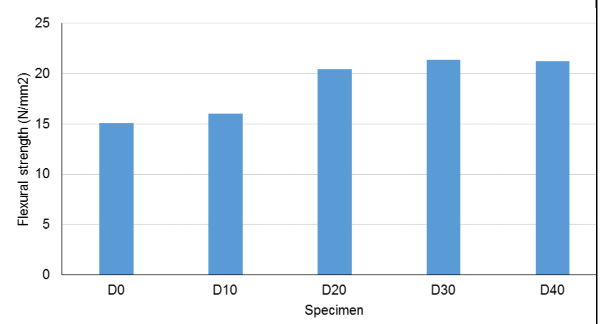


Fig. 7. Variation of flexural strength of geopolymer concrete with % of steel slag

The maximum flexural strength were observed for specimen D30 and it is about 41.8% more than the control specimen. The improvement in strength was due to the bonding of angular steel slag aggregate with geopolymer matrix.

Moment carrying capacity and corresponding deflection for beam specimens with different percentage of steel slag is shown in Table 5. Cracking moment (M_{cr}) was taken as the moment corresponding to the initial cracking load. Yield moment (M_y) was identified as the point at which deflection starts increasing rapidly with a small increment in load. Ultimate moment (M_u) was considered as the point of maximum moment on load – deflection plot. Δ_{cr}, Δ_y and Δ_u are deflections corresponding to M_{cr}, M_y and M_u respectively. It was observed that, with the increase in percentage of replacement of coarse aggregate with steel slag in geopolymer concrete, the moment carrying capacity of the beam increased, up to 30% replacement.

TABLE 5
TEST RESULTS ON FLEXURE BEHAVIOUR OF BEAM

Specimen	Moment (kNm)			Deflection (mm)		
	M_{cr}	M_y	M_u	Δ_{cr}	Δ_y	Δ_u
D0	1.67	7.47	8.48	0.889	3.824	6.118
D10	3.00	7.68	9.02	1.173	4.443	5.977
D20	3.07	11.05	11.51	1.487	6.307	7.523
D30	4.07	11.81	12.02	1.725	8.359	8.780
D40	4.20	11.81	11.94	2.640	7.884	9.254

Crack propagation and failure mode Fig. 8 shows the crack patterns of the beams.

The crack patterns shows that the beams failed by flexure–shear failure. For this type of failure, the cracks generally initiates in the vertical direction. As the load increases, it moves in an inclined direction due to the combined effect of shear and flexure. When the load was increased further, cracks propagated to top and the beam splits.

The crack spacing in all the geopolymer concrete beams was approximately same. Both the flexural and shear cracks were formed in the specimens. The inclined cracks propagated up to compression zone.

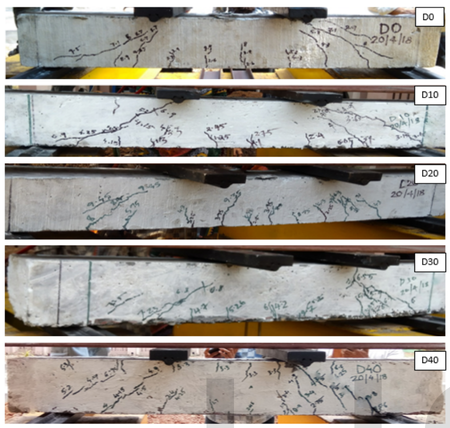


Fig. 8. Crack pattern

Deflection ductility index is the ratio of deflection at ultimate state of beam to the deflection at yielding point of steel. The deflection ductility index for beams tested in this study is presented in Table 6. From the Table 6, it is clear that the ductility index for all the beams is below 3.

A high ductility index indicates that a structural member is capable of undergoing large deformations before failure. For beams with ductility index in the range of 3 to 5 is considered imperative for adequate ductility especially in the areas of seismic design and redistribution of moments. Beams with low ductility index lacked adequate ductility and cannot redistribute moment.

TABLE 6
DUCTILITY INDEX VALUES

Specimen	Ductility ratio
D0	1.59
D10	1.34
D20	1.19
D30	1.05
D40	1.17

7 CONCLUSIONS

The rapid developments in the world has made the depletion of existing natural resources at a faster rate. The uncontrolled use of natural resources made their availability scarce impacting the environment adversely. Hence, the use of by-products from various industries are encouraged nowadays. One way of mitigating the energy crisis is by way of adopting geopolymer technology.

The current study aimed to determine the strength behaviour of flyash based geopolymer concrete in which the coarse aggregate was partially replaced with steel slag. The compressive and split tensile strength test results showed that the optimum amount of steel slag required to replace coarse aggregate by weight in geopolymer concrete is 30%.

1. The geopolymer concrete attains 75% of its strength within 3 day and 83% strength in 7 day.
2. The optimum percentage of steel slag in geopolymer concrete was found as 30% and the percentage of improvement of strength within this optimum amount of steel slag is 25.6%.
3. The split tensile strength test also showed similar trend of compressive strength test. About 52.3% improvement in strength was observed.
4. About 41.8% improvement in flexural strength was observed for 30% percentage of steel slag.
5. The initial cracking load and maximum deflection goes on increasing with the percentage of steel slag in geopolymer concrete.

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