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Flexural studies on reinforced geopolymer concrete beams under pure bending

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Abstract. The present investigation is mainly focused on studying the flexural behavior of reinforced geopolymer concrete (RGPC) beams under pure bending. In this study, copper slag (CS) was used as a partial replacement of fine aggregate. Sand and CS were blended in different proportions (100:0, 80:20, 60:40 and 40:60) (sand:CS) by weight. Fly ash and ground granulated blast furnace slag (GGBS) were used as binders and combination of sodium hydroxide (8M) and sodium silicate solution were used for activating the binders. The reinforcement of RGPC beam was designed as per guidelines given in the IS 456-2000 and tested under pure bending (two-point loading) after 28 days of ambient curing. After conducting two point load test the flexural parameters viz., moment carrying capacity, ultimate load, service load, cracking moment, cracking load, crack pattern and ultimate deflection were studied. From the results, it is concluded that RGPC beams have shown better performance up to 60% of CS replacement.

Keywords: reinforced geopolymer concrete beams; copper slag; two-point loading; flexural parameters

1. Introduction

In order to avoid the emission of carbon dioxide (CO_2) from the cement in concrete, a French scientist Davidovits proposed an alternative binder in the year 1978 for the concrete technology i.e., geopolymer technology (Abhishek *et al.* 2015). Geopolymer is an alternative binder material obtained from the polymerization of source materials under alkaline activator solution (AAS) such as combination of Na_2SiO_3 and NaOH or K_2SiO_3 and KOH. A wide range of natural and industrial by-products used as a source materials having reactive silica (Si) and alumina (Al) like fly ash (Rangan 2008, Abhishek *et al.* 2015), GGBS (Supraja and Kanta Rao 2011), rice husk ash (Detphan and Chindaprasirt 2009, He *et al.* 2013), red mud (He *et al.* 2013), metakaolin (Ekaputri *et al.* 2017) etc. But fly ash alone only used as a source material in geopolymer concrete (GPC) shows poor results under ambient room temperature curing (Guru Jawahar *et al*. 2016).

On the other hand, the utilization of natural sand as fine aggregate in concrete production is very high, and the demand of sand will be more due to increasing of infrastructural developments in the recent years, and thereby the availability of natural sand will be decreased day by day in our life. To overcome this problem some of the researchers identified some alternative fine aggregates namely slag (Singh *et al.* 2015), quarry dust (Raman *et al.* 2011), granite fines (Sreenivasulu *et al.* 2015, Sreenivasulu *et al.* 2016, Sreenivasulu *et al.* 2018, Chitrala Sreenivasulu *et al.* 2018), copper slag (Chithra *et al.* 2016, Mithun and Narasimhan 2016) etc., to minimize the cost of concrete by using the alternative materials instead of conventional materials. Mahendran and Arunachelam (2016) studied performance of fly ash based GPC incorporating CS as fine aggregate and concluded that the compressive strength of GPC showed better results with the increasing percentage of CS up to complete replacement and a nominal decrease in compressive strength gain was observed with the increasing percentage of CS. Neethu Susan and Usha (2016) also observed that the partial replacement of CS in GPC affects the mechanical and durability properties of the concrete and results indicated that the GPC up to 40% CS replacement showed better results when compared to GPC having only sand. The utilization of CS as fine aggregate in GPC may also decrease the cost of concrete and shows solution for several environmental problems (Mahendran and Arunachelam 2015, 2016).

At present, various investigations have been carried out to study the effect of CS on the strength properties of GPC, but limited studies have been done on the performance of GPC beams and slabs.

So, keeping in view of the existing issues, the present investigation is mainly focused on the flexural behavior of reinforced geopolymer concrete (RGPC) beams under pure bending (two point loading) after 28 days ambient curing. During this investigation, the flexural parameters viz., load characteristics, moment characteristics, crack pattern and ultimate deflection were studied. In this study, copper slag (CS) was used as a partial replacement of fine aggregate at

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Table 1 Mix proportions of constituent materials (kg/m^3 and lit)

Mix type	Coarse aggregate		Fine aggregate		Fly ash	GGBS	Na_2SiO_3	NaOH	Extra water	SP
	20 mm	10 mm	Sand	CS						
100:0[a]	774	516	549	0	204.5	204.5	102	41 (8M)	92.5	2.86
80:20	774	516	439.2	109.8	204.5	204.5	102	41 (8M)	92.5	2.86
60:40	774	516	329.4	219.6	204.5	204.5	102	41 (8M)	92.5	2.86
40:60	774	516	219.6	329.4	204.5	204.5	102	41 (8M)	92.5	2.86

[a]100:0: Where 100 is the percentage of sand and 0 is the percentage of CS by weight.

different replacement levels (0%, 20%, 40% and 60%) by weight.

2. Experimental study

2.1 Materials and mix proportion

In this study, fly ash (Class F) designated from ASTM C-618 (ASTM C 618-03, 2003) and GGBS whose specific gravity values respectively 2.26 and 2.84 were used as geopolymer binders for manufacturing of GPC. The black glassy granule of copper slag (CS), whose specific gravity value 3.94, was used as a partial replacement of sand in GPC. Here, fly ash was produced from Rayalaseema Thermal Power Plant (RTPP), Muddanur, A.P, GGBS and CS collected from Astrra chemicals, Chennai, India. Crushed granite stones of size 20 mm and 10 mm were used as coarse aggregate that are blended in 60:40 proportions by percentage of weight.

The combination of sodium silicate solution (Na_2SiO_3) and sodium hydroxide (NaOH) solution were used as activators. Conplast SP430 was used as a superplasticizer (SP) which acts as a High Range Water Reducer (HRWR). In this study, SP was used at 0.7% of GPC binder to get adequate workability of GPC.

Based on the limited past research on GPC (Hardjito and Wallah 2002, Hardjito and Rangan 2005); the mix design and its proportions for different mixes of GPC were selected for the constituents of the mixtures are given in Table 1.

2.2 Test setup

All the beam specimens were tested under two-point loading (four-point bending) in the structural loading frame and the test setup of RGPC beam under two-point loading as shown in Fig. 1. Each specimen was supported on roller assemblies and knife edges to allow longitudinal motion and rotation with an effective span (L) of 1000 mm. For applying loads on the beams, an I- section consisting of two additional rollers at the bottom of the section was used. The distance between these two rollers is 333.33 mm (L/3) and placed symmetrically about their centerline. The load was applied by using a hydraulic loading jack through the load cell on the specimen and the deflection values were recorded at each load increment by using data logger. During this process of incremental loading, the specimen has undergone bending and cracks were developed at the bottom of the load and at supports. The cracks were observed and the crack patterns were highlighted on the specimen surface. The linear variable displacement transducers (LVDT) were placed under the load point and at mid-span to measure the deflections.

Table 2 Compressive strength of GPC

Mix Type	Compressive strength (MPa)
100:0	45.87
80:20	53.31
60:40	60.54
40:60	66.25

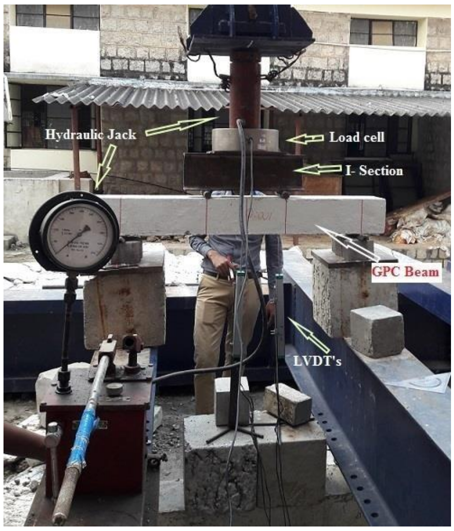


Fig. 1 Detailed test setup of RGPC beam under two-point loading

2.3 Details of tested specimens

All specimens were constructed with an effective span of 1000 mm, shear span and the distance between loads being 333.33 mm. The specimen cross section dimensions are 150 mm wide and 200 mm depth. All beams were reinforced with 2Ø 12 mm and 2Ø 10 mm deformed bars at the tension and compression zones respectively. The shear reinforcement in the specimen consisting of 6 mm diameter reinforcing bar stirrups at a center-to-center spacing of 150 mm. The effective span-to-depth and shear span-to-depth ratios were 5 and 1.67 respectively. The clear cover provided between bottom face of beam and bottom of stirrup was 20 mm. Details of the tension, compression and steel stirrup reinforcements are presented in Fig. 2.

3. Results and discussions

3.1 Compressive strength

Table 2 shows the compressive strength values of GPC

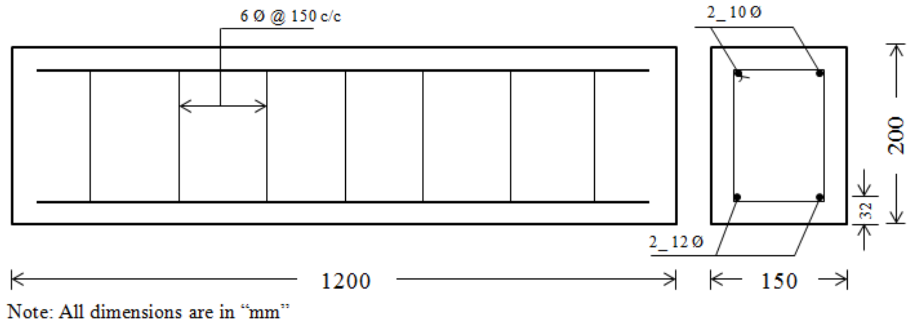


Fig. 2 Geometry and cross section of tested beam

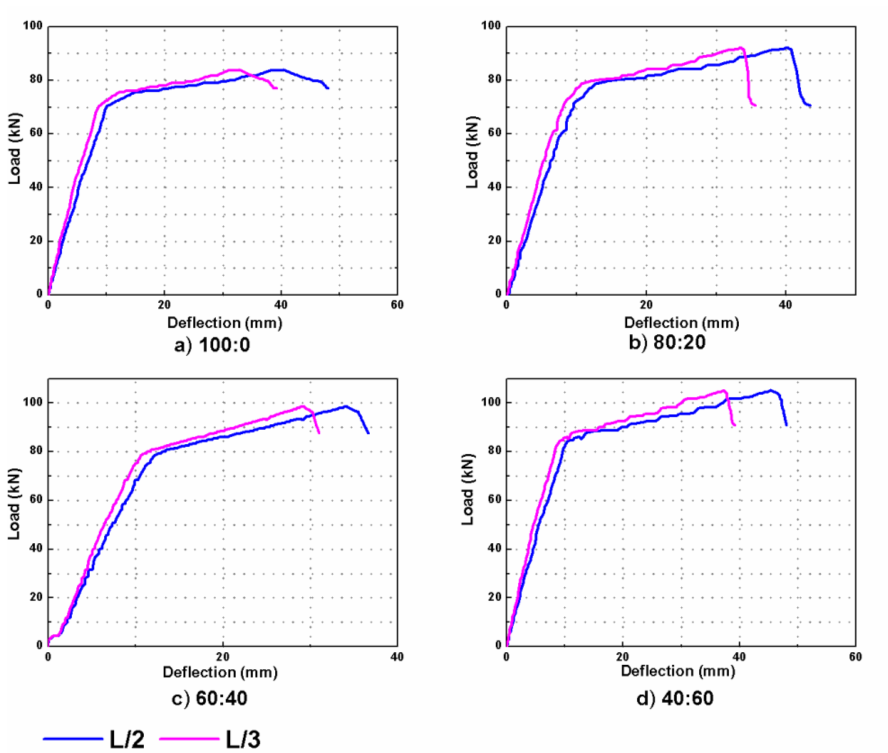


Fig. 3 Load-deflection curves

mixes at 28 days of curing period using copper slag as fine aggregate replacement.

From Table 2, it is observed that the compressive strength values ranges from 45.87 MPa (100:0) to 66.25 MPa (40:60). After 28 days of curing, the compressive strength values of GPC mixes (80:20, 60:40 and 40:60) were respectively 16.26%, 31.98% and 44.43% higher than that of GPC mix (100:0) i.e., without CS replacement.

3.2 Load-deflection behavior of RGPC

The experimental load-deflection curves of GPC mixes (100:0, 80:20, 60:40 and 40:60) at 28 days of ambient curing are depicted in Fig. 3. In this study, the deflections were measured at mid span (L/2) and under point load (L/3) of RGPC beam. The results showed that the deflections at L/2 were higher than those of L/3 deflection values, which is in line with the concept of pure bending theory. From Fig. 3, it can be observed that each load-deflection curve shows two types of behaviors i.e., linear and nonlinear behavior of RGPC beam. The linear part of the curve represents the un-cracked behavior of the beam up to the first crack load, whereas the nonlinear part shows the behavior of cracked beam after the first crack load up to the failure of specimen.

From Fig. 3, it is also noticed that the load-deflection curves of RGPC beams have two turning points which indicate the behavior of beam specimens used in this study. The portion in between starting (initial) point to first turning point reflects the elastic behavior, whereas the portion in between first turning point to second turning point represents the ductility (plastic) behavior of RGPC beam. The load at second turning point represents ultimate load. The portion after second turning point reveals the fracture behavior of specimen.

From Fig. 3, the ultimate deflection was observed at mid span and under point load for the RGPC mixes. After 28 days of curing, 100:0 mix exhibited a mid span deflection of 40.38 mm at an ultimate load of 83.9 kN, whereas 80:20, 60:40 and 40: 60 mixes exhibited the mid span deflections of 40.2 mm, 33.84 mm and 45.42 mm respectively at the

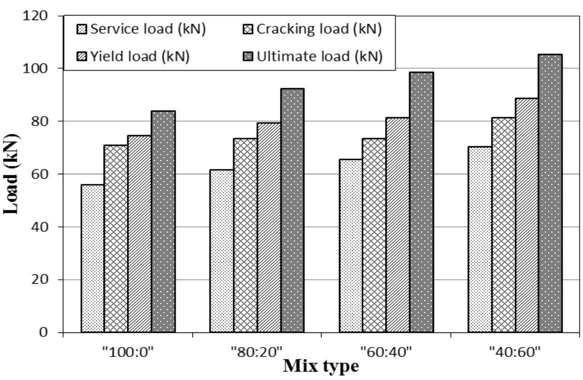


Fig. 4 Load characteristics

ultimate loads of 92.46 kN, 98.45 kN and 105.34 kN. Similar type of deflection trend also observed in the under point load of the beams.

3.3 Load characteristics

The load characteristics viz., first crack load, service load, yield load and ultimate load of RGPC beams are shown in Fig. 4. The serviceable load has been calculated by using factor of safety 1.5, taken from IS code (IS 456, 2000). From Fig. 4, it can be easily noticed that the first crack load increases from 70.75 kN to 81.36 kN, while the service load increases from 55.95 kN to 70.22 kN for the mixes from 100:0 to 40:60 respectively.

On the other side, yield load and ultimate load also showed similar type of trend and obtained maximum load values of 88.70 kN and 105.33 kN respectively for the mix 40:60. This is due to better bonding behavior and interlocking of binder matrices with aggregate and reinforcement in RGPC beams. The another reason behind this type of phenomena was mainly due to presence of reactive oxides like SiO_2 and Al_2O_3 in CS apart from binder materials such as fly ash and GGBS. The reactive oxides present in CS react with AAS (Na_2SiO_3+NaOH) contribute additional formation of Na-(-Si-O-Al-O-) (geoploymeric) chain bonds in the geopolymer matrix and leads to enhancement of load carrying capacity results.

3.4 Moment characteristics

The moment characteristics (moment carrying capacity and cracking moment) values of RGPC beams under two point loading for different mix proportions are listed in the Table 3. In this study, in accordance with IS code (IS 456 2000), the ultimate moment of resistance (M_u) was computed as 12.43 kN-m and the limiting moment of resistance ($M_{u,lim}$) was obtained as 23.36 kN-m. Hence, the design section was under-reinforced and satisfied the design criteria. The moment carrying capacity obtained from the experimental and analytical results were compared and illustrated in Table 3.

From Table 3, it can be easily noticed that the experimental moment carrying capacity values of RGPC mixes (80:20, 60:40 and 40:60) were respectively 10.16%, 17.31% and 25.51% higher than that of RGPC mix (100:0). The experimental cracking moment values of CS replaced RGPC mixes were 3.69%, 3.93% and 14.99% higher than the mix 100:0. Table 3 shows the experimental cracking moment values when the cracks are developed. In accordance with IS code (IS 456 2000), the analytical cracking moment values (M_{cr}) were computed and represented in Table 3. From the cracking moment results, it is observed that the experimental values were higher than the analytical values due to better elastic behaviour of RGPC beams under pure bending.

In order to assess the type of failure (flexural or shear) in the RGPC beams, the formation of crack patterns were observed and it mainly dependent on the grade of concrete, bond behaviour, interlocking of binder matrices with aggregate and reinforcement in the beam (Hassan, Hossain and Lachemi 2010).

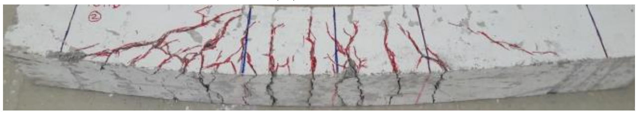
In present study, after conducting flexural test on all beams, it is noticed that wider cracks were observed in the beam (100:0) under pure bending. The crack widths were gradually decreased for the beams with the subsequent increased replacement of CS. The crack pattern of RGPC beams were noticed in the flexure zone under pure bending which are depicted in Fig. 5.

Table 3 Moment characteristics

Mix Type	Moment carrying capacity (kN-m) (Experimental)	Moment carrying Capacity (kN-m) (Analytical)	Cracking moment (kN-m) (Experimental)	Cracking moment (kN-m) (Analytical)
100:0	13.99	12.60	11.79	4.74
80:20	15.41	12.75	12.23	5.11
60:40	16.41	12.86	12.26	5.45
40:60	17.56	12.94	13.56	5.70

(a) 100:0

(b) 80:20



(c) 60:40

(d) 40:60

Fig. 5 Crack pattern of RGPC beams

4. Conclusions

The following conclusions are drawn based on the present investigation.

1. The complete load-deflection behaviour of RGPC beams were studied at different CS replacements.
2. The increase of CS replacement increased the ultimate load carrying capacity and decreased the deflections up to 40%, whereas the beam (mix 40:60) attained a deflection of 45.42 mm at an ultimate load of 105.34 kN.
3. The load characteristics viz. cracking load, service load, yield load and ultimate load of RGPC beams increased with the increased replacement levels of CS (0% to 60%).
4. The moment characteristics viz. moment carrying capacity and cracking moment values of RGPC beams increased with the increased replacement levels of CS (0% to 60%).
5. The presence of reactive oxides (SiO_2 and Al_2O_3) in CS was contributed to the better performance of RGPC beam.

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