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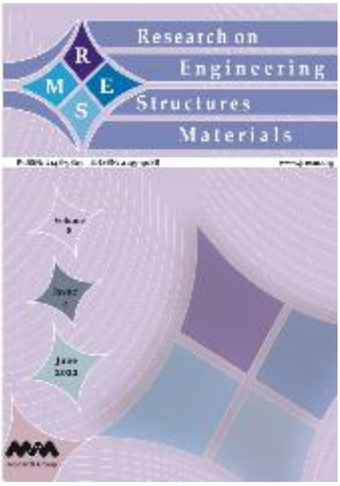

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Research Article

Short-term mechanical performance and flexural behavior of reinforced slag-fly ash-based geopolymer concrete beams in comparison to OPC-based concrete beams

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Abstract

The study presents experimental investigation on short term mechanical properties and flexural behaviour of conventional Ordinary Portland Cement (OPC) based concrete and slag-fly ash based geopolymer concrete. Conventional and geopolymer concrete mixes were designed to achieve compressive strength equivalent to M40 and M70 grade as per Indian standard code. Mechanical properties of concrete mixes such as compressive strength, split tensile strength, flexural strength, modulus of elasticity and Poisson's ratio were evaluated and compared. The flexural behaviour of reinforced concrete beams for both conventional and geopolymer concrete has been studied using 4-point bend test. The findings suggest that geopolymer concrete shows comparable mechanical properties in terms of split tensile strength, flexural strength and Poisson's ratio. However, modulus of elasticity of geopolymer concrete is lower than the conventional concrete of equivalent strength. Studies on flexure behaviour of reinforced concrete beams shows that both geopolymer and conventional concrete exhibit comparable flexural behavior in terms of load-deflection curves, yield load and yield moment. The amount of energy dissipated in flexure is marginally higher for high strength conventional concrete. Based on the visible cracks developed in flexure, it was concluded that the reinforced conventional concrete and reinforced geopolymer concrete show similar number and type of cracks in flexure.

1. Introduction

Usage of conventional Ordinary Portland Cement (OPC) based concrete has many adverse environmental impacts. OPC production is an energy-intensive process and is a significant source of CO_2 emissions in the environment. With the growth of construction sector, the production of OPC is expected to rise exponentially, especially in developing countries. Many researchers have tried to find alternate ways to find environment friendly alternative cementitious systems, including attempts to create eco-friendly cement-free concrete to solve the issue [1, 2, 3]. As a result, geopolymer concrete has emerged as one of the widely accepted replacement for OPC based concrete. The geopolymer concrete has shown excellent structural performance [4], durability [5], better resistance to acid attack [6], good mechanical properties under chemical attack [7] and better chemical stability than conventional concrete [8]. The mechanical performance of geopolymer concrete in terms of split tensile strength and compressive strength, is also comparable to that of OPC concrete [9]. Some further advantages of geopolymer concrete include high early strength

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[10] and good temperature resistance [11]. Geopolymer is amorphous rather than crystalline, as compared to other natural zeolitic materials [12]. Geopolymer concrete differs from conventional concrete as it does not use conventional Portland cement as a cementitious material. It uses industrial waste like fly-ash and Ground Granulated Blast Furnace Slag (GGBS). These materials act as precursors and are activated using alkaline solutions like Sodium hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3). The hydration product of geopolymer concrete does not involve water; instead, as geopolymerisation reaction occur, water added to the mix gets expelled out during the subsequent drying and curing process. Activation of precursors in geopolymers is different from the hydration reactions when Portland cement is mixed with water, which produces the primary hydration products. i.e., calcium silicate hydrate (C-S-H) gel and calcium hydroxide in conventional concrete. The difference causes variations in these two concrete systems' mechanical, durability, and chemical properties [13].

Studies on conventional concrete are extensively available in literature [14]–[17] for both normal and high strength concrete. Some past studies have highlighted the mechanical properties of geopolymer concrete to establish it as a suitable replacement for conventional concrete as construction material. Numerous experiments on the fresh and hardened properties of geopolymer concrete utilizing various precursors and activators have been done by researchers across the world. It is known that the major ingredients in the geopolymerization reaction—alumina (Al_2O_3) and silica (SiO_2)—present in the precursors dissolve in water and react with alkali from the activators to form an aluminosilicate gel, which gives the geopolymer concrete mix its mechanical strength [18]. According to Ojha et al [1]. , the workability of geopolymer concrete depends on the proportion of precursors to alkaline solution as well as the ratio of Na_2SiO_3/NaOH. Due to the viscous nature of sodium silicate, an increase in the aforementioned ratios results in a larger water requirement for the creation of a workable geopolymer concrete mix.

Hutagi and Khadiranaikar [19]studied the flexural behavior of reinforced geopolymer concrete beams cured under ambient temperature. The study involved twelve reinforced concrete beams tested using four-point bend test. The authors reported geopolymer beams' behavior to be similar to the conventional concrete beams in flexure. In a similar study, El-Sayed and Algash [20] evaluated the flexural behavior of ultra-high performance geopolymer concrete reinforced with Glass Fiber Reinforced Polymer (GFRP) bars. The study reported a higher crack width in Geopolymer concrete beams reinforced with GFRP bars than the steel reinforcement control beam. GFRP bars as reinforcement improve mechanical behavior like deflection, crack pattern, number of cracks, and mode of failure. Mo et al., [21] have reviewed past investigations on the structural performance of geopolymer concrete. The structural elements considered in the study included the reinforced concrete beams, columns, slabs, and panels. Based on the review, the authors found no negative effect of geopolymer beams on the structural performance of the elements considered. Study conducted earlier [14] using four-point bend test on reinforced geopolymer concrete beams the behavior of the beam was studied based on the ultimate load values. The results have shown similar performance for both geopolymers as well as conventional concrete beams. Saranya et al. [13] studied application of binary geopolymer beam with GGBS and dolomite as source material. Ten beams were cast and tested. Experimental and numerical simulations of beams were conducted under monotonic loading and has been found to have superior properties. Mohammed et al., [22] performed a similar review and data analysis on the mechanical properties of the Geopolymer concrete. The study attempted to establish a correlation between various mechanical properties and the compressive strength of the Geopolymer concrete.

Under reinforced fly ash based (low calcium) geopolymer concrete beams as seen in past [13, 19, 20, 21] have indicated similar first cracking load, crack width, load–deflection relationship, flexural stiffness, ultimate load and failure mode compared to conventional reinforced concrete beams subjected to flexural loading. In few cases, it was seen that the reinforced geopolymer concrete beams gave higher first crack load, ultimate load, mid deflection and smaller crack width when compared to conventional concrete beams. Studies done on flexural behavior of reinforced geopolymer concrete with combination of different constituents of geopolymers with fly ash to compare with conventional concrete that has indicated capability to take more flexural load, decrease of deflection and increase of first cracking load, ultimate load carrying capacity and higher ductility but a greater number of narrow cracks.

Study conducted by past researchers on flexural behaviour of reinforced geopolymer concrete beams are with fly ash-based system mostly. Studies conducted by Saranya et al. [13] was on application of binary geopolymer beam with GGBS and dolomite as source material. Past studies done by researchers such as Mo et al. [21] evaluated structural performance of geopolymer concrete after being subjected to elevated temperature and indicated that flexural behaviour was influenced by multiple factors, and the material demonstrated some defects; which was inconsistent to the behaviour of the ambient beams. Hutagi and Khadiranaikar [19] conducted the study with low calcium geopolymer concrete with fly ash instead of GGBS.

Research Significance: The literature on combined slag and fly ash based geopolymer concrete which is high calcium system is limited when it comes to study on flexural behaviour of reinforced slag and flyash based geopolymer concrete. Before putting any new building materials into practice, its structural performance in terms of flexure, shear and compression in very essential and present study covers mechanical and flexural behaviour of reinforced geopolymer concrete having combined slag: fly ash based high calcium system wherein ratio of GGBS and fly ash is kept at 70:30 respectively by weight, the activator modulus is maintained as 1 and curing regime is kept as ambient. Majority of the previous studies conducted in the area of alkali activated (geopolymer) concrete were primarily focused on normal strength concrete mix and present study deals with the comparison of mechanical and flexural behaviour of both normal and high strength reinforced high calcium geopolymer concrete with conventional concrete.

The present study gives an experimental analysis of the flexural behavior and short-term mechanical characteristics of OPC concrete and slag and fly ash based geopolymer concrete. Two separate mixtures—one for M40 grade and the other for M70 grade, are used to make geopolymer and conventional concrete. Cube compressive strength, split tensile strength, flexural strength, elastic modulus, and Poisson's ratio are among the mechanical parameters that were examined. Further, using a 4-point bend test on beams with dimensions of 200 mm x 200 mm x 2400 mm, the flexural behavior of concrete has been investigated. Energy dissipation performance of conventional beams and geopolymer beams has been also evaluated.

2. Materials and methods

2.1 Materials

In conventional concrete mix OPC-53, fly ash and silica fume were used as cementitious materials. In the geopolymer mix fly ash, and GGBS are used. The properties of OPC complies with IS 269: 2015[23]. Fly ash and silica fume are used as per IS 3812: 2013[24] and 15388: 2003[25] respectively. GGBS confirms the requirement of IS 16714: 2018[26]. The physical characteristics of OPC, silica fume, fly ash and GGBS have been evaluated as per test procedure laid down in relevant parts of IS 4031. The chemical characteristics of OPC, silica fume, fly ash and GGBS have been evaluated as per IS 4032: 1985 [27]. Coarse aggregate had the maximum nominal size of 20mm and the fine aggregate confirms to the

Table 1. Physical characteristics of GGBS, fly ash, OPC and silica fume

Properties	Indian Standard for Testing	OPC -53 Grade	Silica Fume	Fly Ash	GGBS
Fineness Blaine's (m^2/kg)	IS 4031 (Pt-2): 1999	320	22000	403	335
Soundness Autoclave (%)	IS 4031 (Pt-3): 1988	0.05	-	-	-
Soundness Le Chatelier (mm)	IS 4031 (Pt-3): 1988	1	-	-	-
Setting Time Initial (min.) & (max.)	IS 4031 (Pt-5): 1988	170.00 & 220.00	-	-	-
Specific gravity	IS 4031 (Pt-11): 1988	3.16	2.24	2.2	2.9

Table 2. Chemical characteristics of GGBS, fly ash, OPC and silica fume

Chemical Name	GGBS	Fly ash	OPC	Silica Fume
Calcium Oxide (CaO), %	37.66	5.80	60.73	-
Silica (SiO_2), %	34.60	48.66	20.38	95.02
Reactive Silica, %	33.96	23.52	-	-
Alumina (Al_2O_3), %	18.38	26.72	4.95	-
Iron Oxide (Fe_2O_3), %	0.98	8.87	3.96	0.80
Magnesium Oxide (MgO), %	5.15	1.43	4.78	-
Na_2O_{eq} (%)	0.60	0.74	0.52	-
Loss on Ingnition, %	0.40	4.76	1.50	1.16
Total Sulphur as SO_3 ,%	0.05	0.75	2.07	-
Sulphide sulphur (%)	0.39	0.56	-	-
Chloride (Cl), %	0.024	0.026	0.04	-
Manganese Oxide (MnO), %	1.32	0.13	-	-

Table 3. Properties of coarse and fine aggregates

Parameter		Indian Standard for Testing	Coarse Aggregate 20 mm	Coarse Aggregate 10 mm	Fine Aggregate
Specific gravity		IS 2386 (Pt-3): 1963	2.83	2.83	2.65
Water absorption (%)		IS 2386 (Pt-3): 1963	0.3	0.3	0.59
Sieve Analysis Cumulative Percentage Passing (%)	20mm	IS 2386 (Pt-1): 1963	98	100	100
	10 mm	IS 2386 (Pt-1): 1963	1	68	100
	4.75 mm	IS 2386 (Pt-1): 1963	0	2	99
	2.36 mm	IS 2386 (Pt-1): 1963	0	0	89
	1.18 mm	IS 2386 (Pt-1): 1963	0	0	64
	600 µ	IS 2386 (Pt-1): 1963	0	0	43
	300 µ	IS 2386 (Pt-1): 1963	0	0	26
	150 µ	IS 2386 (Pt-1): 1963	0	0	14
	Pan	IS 2386 (Pt-1): 1963	0	0	0
Abrasion, Crushing & Impact Value (%)			19,19,13	-	-
Flakiness % & Elongation %			29, 25	-	-

Zone II as per IS 383:2016[28]. The physical characteristics of coarse and fine aggregates have been evaluated as per test procedure laid down in relevant parts of IS 2386. Table 1 to Table 3 gives the physical and chemical properties of the materials used in the preparation of the mixes.

2.2 Concrete mix design

The mix design details for Reinforced Conventional Concrete (RCC) and Reinforced Geopolymer Concrete (RGC) for normal and high strength concrete are as shown in table 4A. The cost comparison of both normal & high strength geopolymer concrete and conventional concrete has been given in Table 4b and 4c. The conventional concrete has designed as per IS 10262: 2009 [29] . The ratio of coarse to fine aggregates has been kept as 60:40 for normal strength conventional concrete mix and 35:65 for high strength RCC mix. Slump for all the concrete mixes was kept in the range of 75-100 mm. Superplasticizer have been used in conventional concrete mixes to achieve the required slump between 75-100 mm.

Table 4A. Mix design Details

Parameter		Mix RGC M40	Mix RGC M70	Mix RCC M40	Mix RCC M70
Total cementitious/ precursor content (kg/m^3)		350	380	362	525
Individual cementitious materials / precursors (kg/m^3)	OPC	-	-	290	400
	Silica Fume	-	-	-	50
	GGBS	245	266	-	-
	Fly ash	105	114	72	75
Ratio of water to total cementitious material / precursor		0.50	0.40	0.47	0.27
Na_2O (% by weight of total precursor)		7	8	-	-
Activator Modulus (SiO_2/Na_2O)		1	1	-	-
NaOH (kg/m^3)		17.24	21.39	-	-
Na_2SiO_3 gel (kg/m^3)		74.20	92.12	-	-
Fine Aggregate (kg/m^3)		690	660.80	650	692
Coarse Aggregate – 10 mm (kg/m^3)		514.50	540	777	754
Coarse Aggregate – 20 mm (kg/m^3)		631	662	518	406
Water (kg/m^3)		132.48	107.58	170	140
Superplasticizer (%)		Nil	Nil	0.70	1.00

The effects of varying constituents of concrete in conventional concrete mix on mechanical and durability properties is a well-established fact, but this is not the case with geopolymer concrete, the hydration, chemical reaction and microstructural properties are more complex for geopolymer concrete. Various factors that can affect its strength can be said to be temperature, activator modulus, type, quality and proportions of slag and fly ash, water content etc. Hence, to obtain optimized mix trial and error method is being used and based on strength results of various mixes the mix is finalized as shown in table 4. The ratio of GGBS and fly ash is kept at 70:30 respectively by weight, the activator modulus is maintained as 1. The ratio of coarser to fine aggregates is kept at 55:45 percent for all geopolymer mixes and percentage by weight of total precursor content for Na_2O is fixed at 7 and 8 percent for M40 and M70 mix respectively. The alkaline activator solution used in geopolymer concrete is the combination of Sodium Silicate solution (SiO_2/Na_2O), potable water and Sodium Hydroxide (NaOH), for this study the value Activator Modulus (SiO_2/Na_2O) is kept constant as 1. The activator needs to dissolve the reactive part Si and Al present in the GGBS and Fly-Ash and provide a highly alkaline medium for condensation-polymerization reaction. The sodium silicate and sodium hydroxide solutions were prepared separately and mixed at the time of casting. NaOH solution is prepared one day before casting as it generates a lot of heat, and then it is used to obtain a required amount of workability here water doesn't participate in hydration reaction but is required for maintaining the workability of geopolymer mix. Mixes were prepared in a big pan type mixer (capable of preparing 120 litres of concrete mix in a single batch. For a particular concrete mix, concrete was prepared in three batches. From each of the first and second batch, one reinforced concrete beam and one set (i.e. total 6 cubes) of concrete cubes were cast. From third batch, specimen for evaluation of split tensile strength, flexural strength, MOE, Poisson's ratio were cast along one set (i.e. total 6 cubes) of concrete cubes were cast to ascertain the compressive strength of concrete from each batch. Total 6 specimens were cast for evaluation of each parameter i.e. compressive strength, split tensile strength, flexural strength, MOE and Poisson's ratio. Average result of 6 specimen has been reported in the manuscript. As mentioned above one set (i.e. total 6 cubes) of concrete cubes were cast from each batch to ascertain the compressive strength of concrete from each batch.

Table 4B. Cost comparison for M40 grade of geopolymer & conventional concrete (per m^3)

		Geopolymer concrete			**Conventional Concrete**			
	Material	**Rate**	**Quantity (per m^3)**	**Cost (Rs.), Approx.**	**Material**	**Rate**	**Quantity per m^3**	**Cost (Rs.) Approx.**
Dry Binder	GGBFS	2.00 Rs per kg (Indian Rate)	245 kg	490	Cement	6.5 Rs per Kg (Indian Rate)	290 kg	1885
	Fly Ash	1.00 Rs per kg (Indian Rate)	105 Kg	105	Fly Ash	1.00 Rs per kg (Indian Rate)	72	72
Activator	Caustic soda	30 Rs per kg (Indian Rate)	17 kg	510	Not applicable			
	Sodium Silicate solution	12 Rs per kg (Indian Rate)	74 kg	890	Not applicable			
	Total cost of precursor and activator in Geopolymer concrete			**Rs 1995 per m^3**	**Total cost of cementitious material in conventional concrete**			**Rs 1957 per m^3**
Aggregates almost same in similar in both cases								

Table 4C. Cost comparison for M70 grade of geopolymer & conventional concrete (per m^3)

	Geopolymer concrete				Conventional Concrete			
	Material	Rate	Quantity (per m^3)	Cost (Rs.), Approx.	Material	Rate	Quantity per m^3	Cost (Rs.) Approx.
Dry Binder	GGBFS	2.00 Rs per kg (Indian Rate)	266 kg	532	Cement	6.5 Rs per Kg (Indian Rate)	400 kg	2600
	Fly Ash	1.00 Rs per kg (Indian Rate)	114 Kg	114	Fly Ash	1.00 Rs per kg (Indian Rate)	75 kg	75
	-	-	-	-	Silica Fume	20.00 Rs per kg (Indian Rate)	50 kg	1000
Activator	Caustic soda	30 Rs per kg (Indian Rate)	21 kg	630	Not applicable			
	Sodium Silicate solution	12 Rs per kg (Indian Rate)	92 kg	1104	Not applicable			
	Total cost of precursor and activator in Geopolymer concrete			**Rs 2380 per m^3**	**Total cost of cementitious material in conventional concrete**			**Rs 3675 per m^3**
	Aggregates almost same in similar in both cases							

2.3 Methods for evaluation of mechanical properties of conventional and geopolymer mixes

Compressive strength test of concrete mixes was evaluated on concrete cubes of size 150 mm as per IS: 516 (Part 1/Sec 1): 2021 [36]. Flexural strength test of concrete mixes was determined as per IS 516 on concrete beam (size 100 × 100 × 500 mm) at the age of 28 days as per IS: 516 (Part 1/Sec 1): 2021. Split tensile strength and modulus of elasticity of concrete mixes were determined as per as per IS: 516 (Part 1/Sec 1): 2021 and IS: 516 (Part 8/Sec1): 2020 [37] respectively on concrete cylinder (150 mm diameter and 300 mm height).

2.4 Reinforced concrete beam detailing

The beam specimens were designed with an aim to obtain pure flexure failure. The cross-sectional dimensions of beams were fixed as 200 mm wide and 200 mm depth, and the beam length is kept as 2400 mm. The clear cover provided is 25 mm. The cross-sectional area and side view are as shown in figure 1(a), 1(b) and 1(c). The steel bars used in beams are 16mm, 20mm and 8mm. The reinforcement design of beam in flexure and shear is being done as per IS-456, for M40 grade beams 2 bars of 16 mm diameter and one bar of 20 mm diameter is used. Whereas, for M70 grade beams, 20 mm diameter high yield steel bars are used.

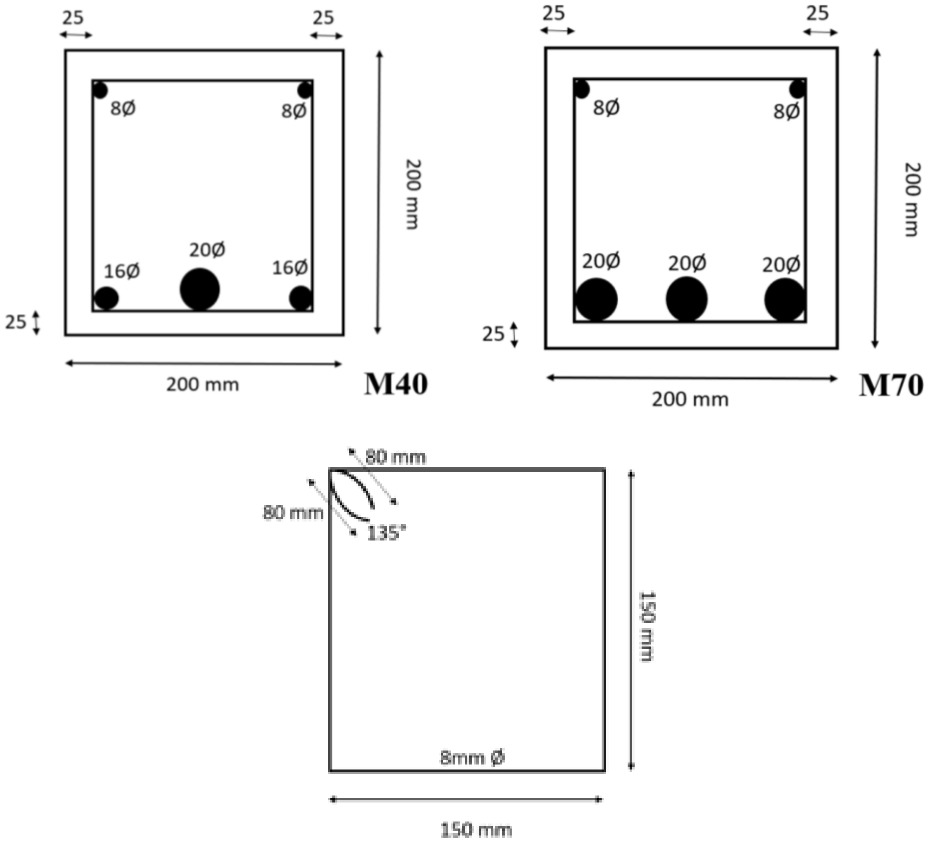
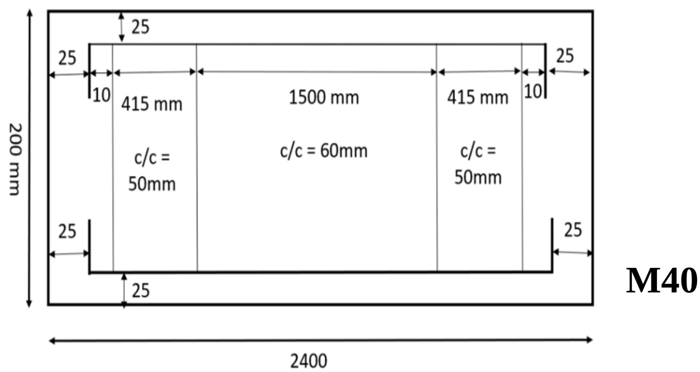


Fig. 1(a) Design details for M40 and M70 reinforced beam (Sectional View) and (b) Details of shear reinforcement



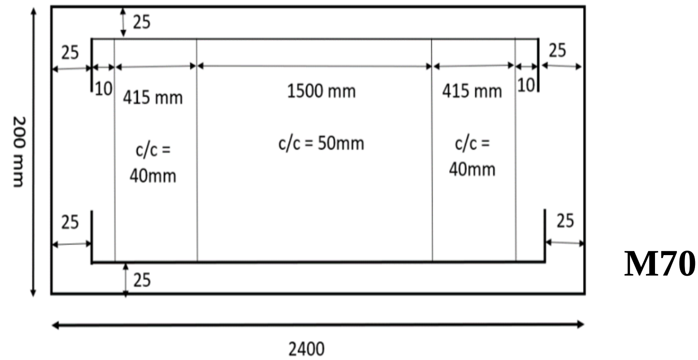


Fig. 1(c) Design details for M40 and M70 reinforced beam (Lateral View)

To make the beam extra safe in shear the shear reinforcement are provided on slightly higher side the stirrups are provided at a spacing of 60 mm c\c and 50 mm c\c for M40 and M70 grade for both RCC and RGC beams. The spacing of stirrups is reduced further to 40 mm c\c at ends where the possibility of occurrence of shear failure is slightly higher. Nominal amount of compressive reinforcement is provided in both the M40 and M70 grade beams. The reinforcement details of all beams are provided in Table 5.

Table 5. Reinforcement details of beam specimen

Specimen Id	Area of steel (mm^2)	
	A_{SC}	A_{ST}
M40 RCC	100.54	711.41
M40 RGC	100.54	711.41
M70 RCC	100.54	937.26
M70 RGC	100.54	937.26

2.5 Preparation of specimen

The steel molds of size 200*200 mm are used for both RGC and RCC beam, before filling of the molds the molds are coated with lubricating oils in order to prevent the adhesion of hardening concrete. The reinforcement cage is fixed in the mold after putting the cover blocks of 25 mm to obtain required arrangement. The concrete is being filled in the moulds in three layers of equal depths. After each layer the needle vibrator and tamping rods are used to ensure proper compaction. Figure 2 shows the moulds, reinforcement and freshly cast beams for testing.

Although, the polymerization reaction is generally accelerated in higher temperatures than in ambient behavior and gives higher early strength, yet the beams cured at ambient temperature gives better compressive strength in 28 days as compared to 7 days, thus the curing of beams is conducted at ambient room temperature. Three cubes of 150 mm are casted along with the beams to determine the compressive strength of concrete at the day of testing i.e., 28 days strength.

(a) (b)

Fig. 2 (a) Reinforcement and mould for preparing the specimen and (b) Casting of specimen

2.6 Loading and test setup

The four-point bend test is conducted on beams using Flexural Testing Machine of capacity 500 kN. The loading applied is the displacement controlled loading. The beam is being placed on the steel girder and out of the 2400 mm length of beam clear span of beam is maintained as 2000 mm. The distance between the point loads is kept as 666 mm, thus dividing the clear span of 2000 mm in three equal parts. The concrete cubes specimens were tested in a displacement-controlled compression testing machine of 3000 kN capacity at room temperature of 27 ± 2°C and relative humidity 65% or more. LVDT was used to get the deflection at the centre of beam. The first crack load was obtained by visual examination. The test setup for four-point bend test is been shown in figure 3(a) and 3(b).

Fig. 3 (a) Beam in 4 point bend test and (b) Test Setup

3. Results and discussions

3.1 Fresh concrete properties

Fresh concrete properties such as initial workability (in terms of initial slump) and air content after preparation of mix were evaluated for all the 4 concrete mixes and test results are given below in table 6.

Table 6. Fresh properties of geopolymeric and conventional concrete mixes

S. No.	Specimen Id	Initial workability in terms of slump	Air Content (%)	Superplasticizer (% by weight of cementitious content)
1.	M40 RCC	100 mm	1.30	0.80
2.	M40 RGC	Collapse	1.20	Nil (i.e. 0 %)
3.	M70 RCC	85 mm	1.60	1.20
4.	M70 RGC	80 mm	1.40	Nil (i.e. 0 %)

Superplasticizer was used in case of conventional concrete mixes to achieve sufficient initial workability (i.e. slump of at least 75 to 100 mm) as mentioned in Table 6. In case of geopolymer concrete mixes, superplasticizer was not required at all, as M40 RGC mix showed collapse behaviour immediately after preparation of mix. Whereas, M70 RGC mix showed initial slump of 80 mm without any superplasticizer. In case of, conventional concrete mixes, M40 RCC and M70 RCC required 0.80% and 1.2% superplasticizer to achieve an initial slump of 100 mm and 85 mm respectively. All the four concrete mixes were homogenous and did not show any signs of bleeding and segregation. Air content for conventional and geopolymer concrete mixes are observed to be in range of 1.2 to 1.6%.

3.2 Mechanical properties of mixes

Test results of different mechanical properties i.e. compressive strength, split tensile strength, flexural strength, modulus of elasticity and Poisson's ratio for all the concrete mixes have been tabulated below in table 7. The mechanical properties of conventional mix are compared with geopolymer concrete mix of equivalent strength. The conventional and geopolymer concrete mixes were designed and optimized to have almost similar and comparable compressive strength, so that other mechanical characteristics of conventional and geopolymer concrete can be compared. One of the significant difference in both the concrete system is the difference in their modulus of elasticity. Six specimens for each mix were tested for evaluation of every parameter and average value of test results have been tabulated in table 7.

Table 7. Mechanical properties of different mixes

Specimen Id	Cube Compressive strength (MPa)	Split Tensile Strength (MPa)	Flexural Strength (MPa)	Modulus of elasticity (GPa)	Poisson's Ratio
M40 RCC BEAM 1	46.11	4.04	4.42	32.64	0.16
M40 RCC BEAM 2	44.61				
M40 RGC BEAM 1	50.71	4.10	5.07	22.92	0.17
M40 RGC BEAM 2	51.46				
M70 RCC BEAM 1	82.15	5.05	8.52	43.13	0.14
M70 RCC BEAM 2	83.90				
M70 RGC BEAM 1	77.80	4.50	5.85	33.37	0.14
M70 RGC BEAM 2	79.80				

As per experimental plan, in order to compare the behaviour of hardened concrete properties of geopolymer and conventional concrete mixes, mixes were cast to obtain almost comparable compressive strength for geopolymer and conventional concrete mixes of equivalent grade. Flexural and split tensile strength of concrete mix has a direct relationship with its compressive strength. Split tensile strength of M40RGC is about 101.5 % of split tensile strength of M40RCC and split tensile strength of M70RGC is about 89.00 % of split tensile strength of M70RCC. Flexural strength of M40RGC is about 115 % of flexural strength of M40RCC and Flexural strength of M70RGC is about 69 % of flexural strength of M70RCC. For concrete mixes equivalent to M40 grade, the flexural and split tensile strength values of M40 RGC are slightly higher in comparison to M40 RCC. This observation is supported by the previous findings [30] also reported that flexural strength of alkali activated concrete is higher in comparison to flexural strengths of conventional Portland cement concrete of similar grade. However, in case of high strength concrete mixes equivalent to M70 grade, trends are opposite to the observations made for flexural and split tensile strength of mixes equivalent to M40 grade. Flexural and split tensile strength of M70 RGC mix are lower in comparison to M70 RCC of equivalent grade at 28 days. This increase in flexural and split tensile strength of high strength conventional Portland cement concrete is similar to findings of Arora et.al [16, 40, 41] wherein it was reported that flexural strength of silica fume concrete was higher by 10- 15% as compared that of Portland cement concrete for about 12-15 % silica fume addition. The addition of silica fume in concrete mix leads to reduction in the development of cracks at micro level near the interface of cement paste and unreacted cement or pozzolans [30, 42, 43, 44, 45]. Modulus of elasticity of M40RGC is about 70.00 % of modulus of elasticity of M40RCC and Modulus of elasticity of M70RGC is about 77 % of Modulus of elasticity of M70RCC. Modulus of elasticity of both M40 RGC and M70 RGC are observed to be lower than their corresponding conventional concrete mixes of similar grade. This observation is supported by observations of research studies carried out by past researchers [30, 31, 32]. The intrinsic modulus of C-A-S-H gel formed in slag-based geopolymer concrete is comparable with the C-S-H gel formed in cement. But the intrinsic modulus of N-A-S-H gel formed in low-calcium fly ash gel based geopolymer concrete is much smaller than that of the C-S-H gel formed in cement. The lower value of modulus of elasticity for geopolymer concrete than conventional concrete can be attributed to the low intrinsic modulus of N-A-S-H gel and higher initial micro-cracks formulation in geopolymer concrete [30, 31, 32].

3.3 Load- deflection behaviour

Figure 4 and 5 show the load-deflection curves for the RCC beams and reinforced geopolymer beams for the M40 and M70 grade concretes respectively. The load vs displacement curves at the mid span of the beam are as mentioned in figure 5 for M40 mixes of conventional and geopolymer concrete and in figure 6 for M70 mixes.

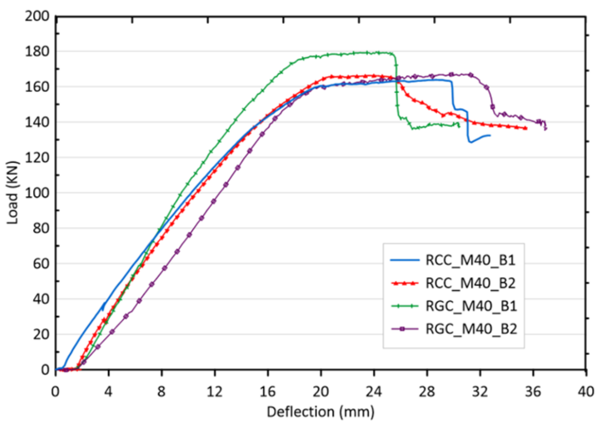


Fig 4 Load deflection curves for M40 RCC and RGC beams

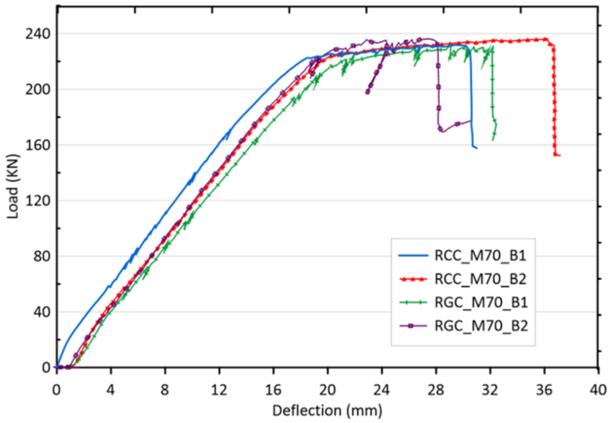


Fig 5 Load deflection curves for M70 grade RCC and RGC beams

Yield point was determined visually from load deflection curve and the yield point is stage where no significant increase in load was observed and deflection was increasing continuously. The yield points for all M40 mixes are in the displacement range of 18 to 22 mm. The drop in the curves for all mixes represents the occurrence of failure. The displacement range for ultimate or failure points of various curves of grade M40 is much higher as compared to range of yield points, it is between 26 to 33 mm. After the yield point the curves are depicting an elastic plastic behavior for all curves except for RGC M40 beam 2 where the curve slightly shows strain hardening behavior. From load displacement results it is evident that the yield points are reached at the same time for both conventional concrete and geopolymer concrete of same grade at almost similar deflection. The curves suggests that the flexural behaviour of both the conventional and geopolymer concrete are comparable. The values of experimental moment calculated from the load-deflection curve and predicted moment as per IS456 is given in Table 8.

The predicted maximum strength of beams is calculated as per the dimensions of beam and the reinforcements provided and these are calculated as per IS 456: 2000 [33]. The moment of resistance (Mp) is calculated as per IS-456. Experimental maximum value which is obtain from beam testing is obtained then from mid span moment formula for four point test the predicted maximum moment (Me) that the beam can resist is calculated. The normalized strength is calculated as given in Equation 1, whereas, the expression for normalized moments is as given in Equation 2;

$$Normalised\ Load = \frac{P}{\sigma b d} \tag{1}$$

$$Normalised\ moment = \frac{M}{\sigma b d^2} \tag{2}$$

Where, σ is the Compressive strength of the mix at 28 days, P is Load obtained from the load deflection curve, M is Moment obtained from the load deflection curve, b is Width of the beam and d is the Depth of the beam. The normalized yield strength as a percent of ultimate strength varies from 95 to 100 percent, this shows that beams are not undergoing strain hardening. Whereas, the ratio of normalized yield moment to ultimate moment varies in between. Figure 6 gives us the relationship between the normalized yield strength and normalized ultimate strength.

Table 8. Characteristics of load deflection curves of the beams

Id	Moment		Compressive Strength MPa	Normalised Moment		Predicted Moment Mp (KN-m) (as per IS 456)	Me/Mp
	Yield kN-M	Ultimate (Experimental) kN-M		Yield kN-M	Ultimate kN-M		
M40 RCC BEAM 1	53.30	54.17	46.11	0.15	0.15	44.01	1.23
M40 RCC BEAM 2	53.97	55.20	44.61	0.15	0.15	44.01	1.25
M40 RGC BEAM 1	57.03	59.57	50.72	0.15	0.15	44.01	1.35
M40 RGC BEAM 2	53.30	55.27	51.47	0.14	0.14	44.01	1.26
M75 RCC BEAM 1	74.23	75.70	82.15	0.10	0.10	67.37	1.12
M70 RCC BEAM 2	74.87	77.53	83.90	0.10	0.11	67.37	1.15
M70 RGC BEAM 1	75.70	76.47	77.80	0.11	0.11	67.37	1.14
M70 RGC BEAM 2	74.67	77.50	79.80	0.11	0.11	67.37	1.15

The findings in the study is comparable to past literatures. Hutagi and Khadiranaikar [19] studied the behavior with reference to various first crack load, service load and ultimate load. The results were found to be similar to that of conventional cement concrete reinforced beams. Kumaravel and Thirugnanasambandam [34] in their paper studied the flexural behaviour of geopolymer concrete beams and compared with control cement concrete beams. The results show that the geopolymer concrete beams exhibit increased flexural strength. The deflections at different stages including service load and peak load stage are higher for geopolymer concrete beams. Moreover the review paper by Under reinforced fly ash based (low calcium) geopolymer concrete beams as seen in past [13, 19, 20, 21] have indicated similar first cracking load, crack width, load–deflection relationship, flexural stiffness, ultimate load and failure mode compared to conventional reinforced concrete beams subjected to flexural loading. Mo et al. [21] shows that there is no detrimental effect on structural performance when geopolymer concrete is compared with the conventional concrete. For four-point bend test the theoretical maximum deflection occurs at the mid-point and is given by Equation (3);

$$\Delta max = \frac{23pl^3}{648\,EI} \quad (3)$$

Where, Δmax is the Maximum deflection at mid span, p is the Load applied on the beam, l is total length, E represents modulus of elasticity and I is the Moment of inertia of the beam cross section.

The values of normalized yield deflection to ultimate displacement is in the range between 55 to 75 percent, from this it can be said that beams follow inelastic behavior for very long time after the yield points.

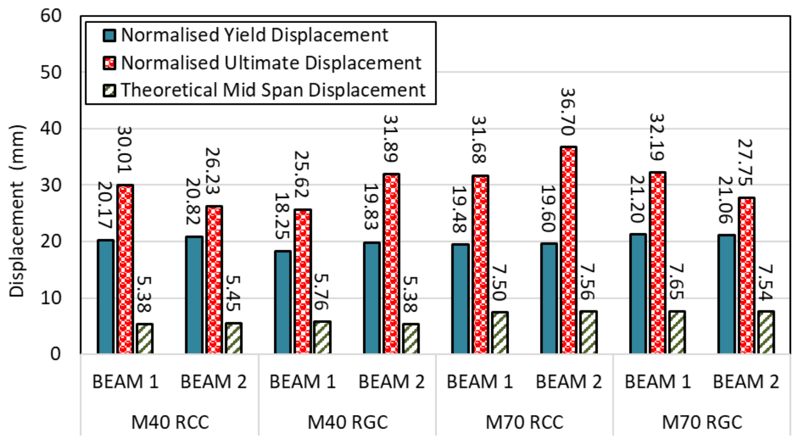


Fig. 6 Theoretical mid span displacement, normalized yield displacement and ultimate displacement for all mixes

3.4 Strength Characteristics

Table 9 and Table 10 shows the normalized yield strength and normalized ultimate moment respectively. As shown in table, the yield strength and yield moment for the comparable strength conventional and geopolymer concrete are comparable. One of the reasoning for the similarity can be attributed to the cross-linked structure in geopolymer mix which makes it capable to take similar load as conventional concrete with lower binding content. Table 9 and table 10 also confirms the action of reinforcement in OPC and the geopolymer concrete is also comparable. Figure 7 represents normalized yield strength as percentage of normalised ultimate strength. Sumajouw et al. [38] evaluated the flexural load capacity of the sixteen reinforced geopolymer concrete beams and the average experimental to prediction ratio was found to be 1.11. Considering that the beams were under-reinforced, the effect of the geopolymer concrete compressive strength was marginal. Similar trend has been observed in the study discussed in this manuscript.

Table 9. Normalized yield strength and normalized ultimate strength of the beams

Id	First Crack kN	Yield Load kN	Ultimate Load kN	Compressive Strength MPa	Normalized Yield Strength kN	Normalized Ultimate Strength kN	Py/Pu
M40 RCC BEAM 1	60.25	159.90	162.50	46.11	0.087	0.088	98.40
M40 RCC BEAM 2	64.75	161.90	165.60	44.61	0.091	0.093	97.77
M40 RGC BEAM 1	66.85	171.10	178.70	50.72	0.084	0.088	95.75
M40 RGC BEAM 2	57.90	159.90	165.80	51.47	0.078	0.081	96.44
M70 RCC BEAM 1	79.92	222.70	227.10	82.15	0.068	0.069	98.06
M70 RCC BEAM 2	82.25	224.60	232.60	83.90	0.067	0.069	96.56
M70 RGC BEAM 1	87.65	227.10	229.40	77.80	0.073	0.074	99.00
M70 RGC BEAM 2	80.75	224.00	232.50	79.80	0.070	0.073	96.34

Table 10. Normalized yield moment and normalized ultimate moment of the beams

Id	M_Y kN-M	M_U kN-M	Compressive Strength MPa	Normalized Yield Moment kN-M	Normalized Ultimate Moment kN-M	My/Mu
M40 RCC B-1	53.30	54.17	46.11	0.029	0.029	98.40
M40 RCCB-2	53.97	55.20	44.61	0.030	0.031	97.77
M40 RGC B-1	57.03	59.57	50.71	0.028	0.029	95.75
M40 RGC B-2	53.30	55.27	51.46	0.026	0.027	96.44
M70 RCC B-1	74.23	75.70	82.15	0.023	0.023	98.06
M70 RCC B-2	74.87	77.53	83.90	0.022	0.023	96.56
M70 RGC B-1	75.70	76.47	77.80	0.024	0.025	99.00
M70 RGC B-2	74.67	77.50	79.80	0.023	0.024	96.34

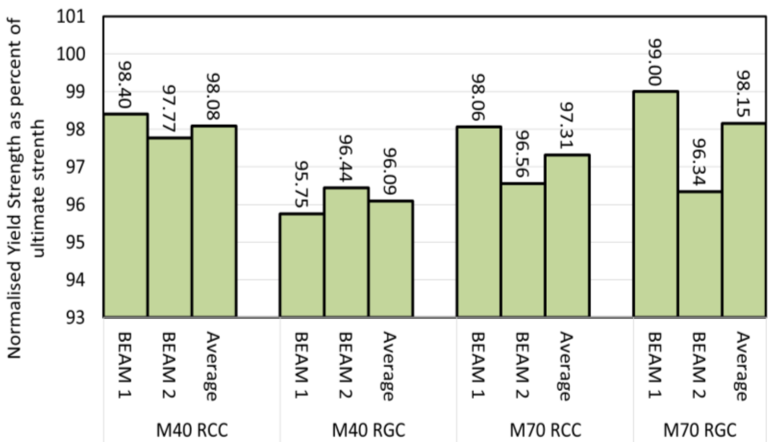


Fig. 7 Normalized yield strength as percentage of normalised ultimate strength

3.5 Energy dissipation

Figure 8 shows the values of energy dissipated by the beam during the four point bend test. It can be seen that the beams of higher grade dissipates more energy. In terms of energy dissipation, the performance of geopolymer concrete beams as compared to conventional concrete beams is almost identical. However, in high strength concrete, the energy dissipation values are found to be slightly lower in geopolymer concrete compared to conventional concrete. The observed variation in energy dissipation in higher grade concrete can be attributed to the presence of silica fume in the high strength conventional OPC concrete. The difference in the gel systems formed in these two variation of the mixes can be attributed as a possible explanation of the observed trend which is not much significant in the normal strength concrete. Findings in the literature [30] suggests that the C-S-H gel formed in OPC concrete and the N-A-S-H gel primarily found in fly ash based geopolymer have variations in their intrinsic modulus which is well reflected in high strength concrete.

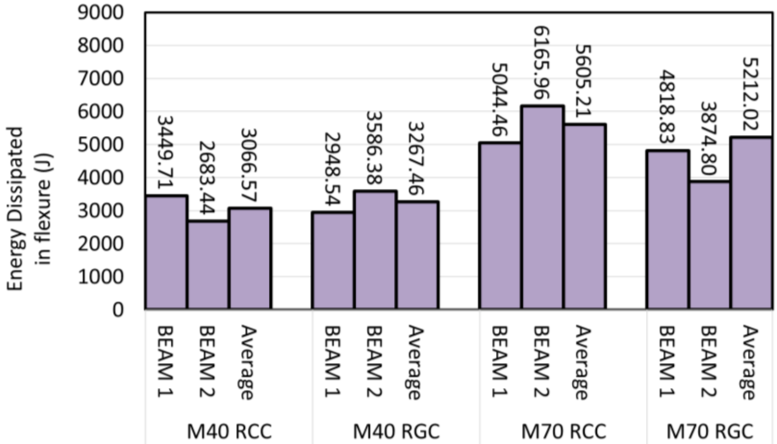
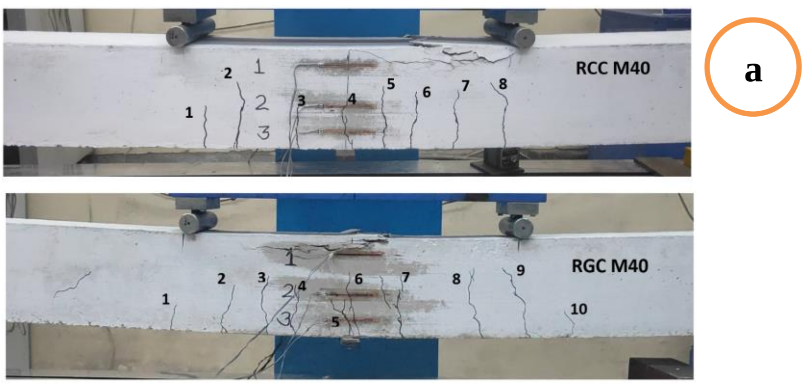


Fig. 8 Energy dissipated in flexure by beams

3.6 Crack width and pattern

Figure 9 (a) and (b) show the crack patterns observed in the beam after the completion of the test. In the test the flexural cracks were first observed at the tension zone in beam between the loading arrangements. With increase in load the cracks developed both in size and number. The patterns of cracks clearly shows that all beams have undergone pure flexure failure. It can be further depicted that the cracks patterns, crack width and number of cracks are almost identical for both reinforced as well as geopolymer concrete for both normal and high strength beams. As shown in figure 9 (a) and (b), the number of visible cracks in normal strength conventional concrete is 8 and in normal strength geopolymer beam is 10 where two cracks are smaller in size. The high strength conventional concrete bears 10 major cracks and the corresponding strength geopolymer concrete has 9 cracks of identical patterns and size. Researchers also investigated the structural behaviour of under reinforced geopolymer concrete beams containing different concrete materials. Andalib et al. [39] incorporated 30% Palm Oil Fuel Ash (POFA) into the geopolymer concrete to produce reinforced geopolymer concrete beams and they observed comparable cracking and ultimate moments as well as crack pattern as conventional reinforced concrete beams. Literature supports the findings of present study. Hutagi and Khadiranaikar [25] has also found that there is no significance difference in crack patterns of reinforced concrete beams as well as geopolymer beams



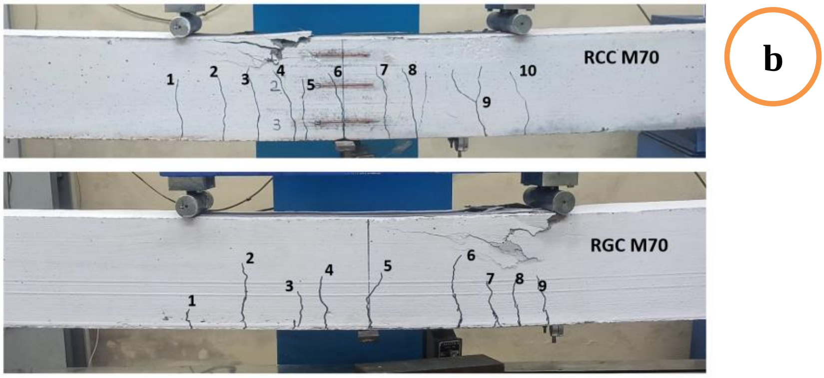


Fig. 9 (a) M40 RCC and RGC beams 9 and (b) M70 RCC and RGC

The past literature has also shown the similar trends which validates the findings of this paper. In the experimental study conducted by Ren et al. [35] geopolymer concrete beams under a flexural load resembled the mechanical performance of the OPC concrete beams.

4. Conclusions

In present study, short-term mechanical properties and flexural performance of normal and high strength reinforced conventional and geopolymer concrete were experimentally analyzed. Geopolymer and conventional concrete mixes were designed for M40 and M70 grade. The mechanical characteristics such as cube compressive Strength, split tensile strength, flexural strength, modulus of elasticity and Poisson's ratio were evaluated for all the four mixes. Further, the flexural behaviour of reinforced concrete beam was studied using 4-point bend test on reinforced concrete beams. Following conclusions can be drawn from the above study:

- Geopolymer concrete achieves similar and comparable compressive strength as in case of conventional concrete at lower precursor content in comparison to total cementitious content required in case of conventional concrete mixes.
- The modulus of elasticity of geopolymer concrete is lower than the conventional concrete of equivalent strength. The split and flexural strength of geopolymer and OPC based concrete of comparable compressive strength were observed to be similar for normal strength grade i.e. M40 grade. However, in case of high strength mixes, conventional mix showed higher flexural strength in comparison to geopolymer concrete mix. Increase in flexural and split tensile strength of high strength conventional concrete is higher by 10- 15% as compared to that of geopolymer concrete. This can be attributed to presence of 10-12% silica fume in high strength conventional concrete mix.
- The flexural performance of conventional and geopolymer concrete was observed to be comparable in 4-point bend test. The strength characteristics in terms of yield load and yield moment capacities were also comparable. This suggests that reinforced conventional and geopolymer concrete of equivalent strength behave similarly in flexure. The normalized yield strength as a percent of ultimate strength varies from 95 to 100 percent, this shows that beams are not undergoing strain hardening. The values of normalized yield deflection to ultimate displacement is in the range between

55 to 75 percent, from this it can be said that beams follow inelastic behavior for very long time after the yield points.

- Energy dissipation performance of conventional beams and geopolymer beams was observed to be identical. However, in high strength concrete the energy dissipation values are found out to be slightly lower in geopolymer concrete as compared to the conventional concrete. The added silica fume in higher compressive strength conventional concrete may be responsible for the improvement in energy dissipation capabilities of the beams.
- Based on the visual examination of flexural cracks, it can be concluded that the reinforced conventional concrete and reinforced geopolymer concrete depict similar number and type of cracks in flexure. The number of visible cracks in normal strength conventional concrete is 8 and in normal strength geopolymer beam is 10 where two cracks are smaller in size. The high strength conventional concrete bears 10 major cracks and the corresponding strength geopolymer concrete has 9 cracks of identical patterns and size.

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