Research Article

Performance of hybrid fibre reinforced geopolymer concrete beams

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Abstract

An experimental investigation was carried out to study the effect steel fibres and hybrid fibres (steel and polypropylene) on the performance of low calcium fly ash based geopolymer concrete beams under shear. The main variable considered are the volume fraction of steel fibres (0.5% and 1%) and volume fraction of hybrid fibres (0.25% steel fibres and 0.25% polypropylene fibres, 0.25% steel fibres and 0.75% polypropylene fibres and 0.5% steel fibres and 0.5% polypropylene fibres). Test results revealed that the split tensile strength, flexural strength and modulus of elasticity of hybrid fibre reinforced concrete are more than that of steel fibre reinforced concrete. For studying the performance of fibre reinforced and hybrid fibre reinforced beams under shear, shear deficient beams of size 1200 mm × 100 mm × 150 mm size were prepared with varying volume fractions of fibres. The beams were tested under two point loading after 28 days of casting. Experimental results indicated that the hybrid fibre reinforced geopolymer concrete beams are having better shear strength and superior behaviour than steel fibre reinforced beams.

Keywords Geopolymer · Hybrid fibre · First crack load · Ultimate load · Failure mode · Ductility · Energy absorption · Load–deflection behavior

1 Introduction

Concrete is an ubiquitous construction material having many advantages. Customarily concrete is produced by using Ordinary Portland Cement (OPC) as the binding material. Usage of OPC is on the increase to meet infrastructure developments. The worldwide demand for OPC would increase further in the future. It is well known that the cement production depletes significant amount of natural resources and releases large volume of CO_2 into the atmosphere [1, 2]. Now the world is also facing the problem of depletion of natural resources such as lime stone, which is the most important ingredient to produce cement. Attempts were made in the past to reduce the usage of cement in concrete by replacing it with other suitable materials so as to reduce the cost and make concrete more eco-friendly. One of the alternatives to produce more eco-friendly concrete is to replace cement in concrete with suitable eco-friendly material, such as fly ash, palm oil fuel ash rice husk ash (RHA), silica fume (SF), ground granulated blast furnace slag (GGBFS) and metakaolin [3–6]. An important investigation in this regard is the development of high volume fly ash concrete that contains about 60% fly ash [3]. Another alternative way to make more environmental friendly concrete is the development of inorganic alumina-silicate polymer, called geopolymer, synthesized from materials of geological origin or from by-product materials such as fly ash or Ground Granulated Blast Furnace Slag (GGBFS) which are rich in silica and alumina. The use of these industrial by-products in the development of sustainable construction materials substantially reduced environmental pollution.

Fly ash, one of the source materials for geopolymer binders, is available abundantly worldwide, but till date its utilization is limited. Currently, 300 million tons of fly ash is being generated annually in the world. The disposal of

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fly ash is also one of the major environmental threat. Now a days, the major quantity of fly ash produced is simply dumped in landfills creating several environmental problems. By exploring the use of the fly ash based geopolymer concrete, two environment related issues can be tackled simultaneously i.e. reducing the high amount of CO_2 released to the atmosphere during the production of OPC and protecting the water bodies and environment from fly ash disposal [3]. The fundamental difference between geopolymer concrete and conventional concrete is in the mechanism of strength gain. GPC attains its strength by the process of geopolymerization and not by hydration as in the case of conventional concrete. Geopolymer concrete requires temperature curing to activate the chemical reaction that takes place in geopolymer matrix [7, 8]. Therefore no water curing is required as in the case of conventional concrete. Recent studies proved that the properties of GPC are superior than conventional concrete [7–10].

The concept of using fibres to improve the characteristics of construction material is very old. Plain concrete possess a very low tensile strength, limited ductility and little resistance to cracking. Internal micro cracks are inherently present in the concrete and its poor tensile strength is due to propagation of such micro cracks eventually leading to brittle failure of concrete. In plain concrete micro cracks appear even before loading due to drying shrinkage or due to volume changes. During loading these narrow cracks propagate and additional cracks forms in areas of minor defects. The development of these micro cracks is the main cause for inelastic deformation of concrete [8, 11]. It has been recognized that randomly oriented fibres in concrete arrest micro cracking mechanisms and limit crack propagation thus improving the strength and ductility. The commonly used fibres in concrete are metallic and non metallic fibres like steel fibres,polypropylene fibres, carbon fibres, basalt fibres, waste carpet fibres etc. The combined use of waste carpet fibres and palm oil fuel ash in the production of sustainable green concrete is feasible both technically and environmentally. The use of waste carpet fibres in concrete can significantly reduce chloride penetration and has high split tensile strength and flexural strength [5, 6, 12].

Hybrid fibre reinforced concrete (HFRC) is the concrete containing combinations of different types of fibres. The hybridization of different types of fibers play important role in arresting cracks and thus achieving high performance. In HFRC the synergy of short and long fibres or of two different types of fibres leads to an improved tensile response. The incorporation of high elastic modulus steel fibres in concrete also enhances the flexural toughness and ductility. The contribution of steel fibres can be observed mainly after matrix cracking in concrete, when they help in bridging the propagating cracks. The addition of non metallic fibres such as polyester, polypropylene etc. results in good fresh concrete properties and reduced early age cracking [11, 13].

The main objectives of this study is to evaluate the role of steel fibres and hybrid fibres in enhancing the performance of geopolymer concrete beams under shear.

2 Experimental programme

The experimental programme involves the casting and testing of shear deficient plain, steel fibre reinforced and hybrid fibre reinforced geopolymer beam specimens under two point loading. Total 12 specimens were prepared, of which two specimens were of plain GPC, two each were made with steel fibres, having fibre volume fraction of 0.50% and 1%, six specimens were made as hybrid fibre reinforced GPC with hybrid fibres in the ratio 0.25% steel fibre and 0.25% polypropylene fibre, 0.25% steel fibre and 0.75% polypropylene fibres and 0.50% steel fibre and 0.50% polypropylene fibres respectively. The specimens are of size 1200 mm × 100 mm × 150 mm. The beams are provided with three 10 mm HYSD bars at the bottom and two 6 mm bars on top as stirrup holders. Two 6 mm stirrups were provided only at the ends to ensure shear failure. Dimensions and reinforcement details for all the specimens are shown in Fig. 1.

2.1 Properties of constituent materials

The ingredients of GPC were low calcium ASTM class F fly ash, fine aggregate, coarse aggregate and alkaline solution. Fly ash obtained from thermal power plant at Tuticorin in Thamilnadu, India contains silica 65.43%, alumina 20.67%, iron oxide 6.18% and calcium oxide 1.26%. Natural river sand conforming to zone-II of IS 383:2016 [14] is used as fine aggregate and is having specific gravity of 2.45 and fineness modulus of 2.80. Granite broken stones of size 20 mm down with a specific gravity 2.75 and fineness modulus 7.04 is used as coarse aggregate. The alkaline solution used is a mixture of sodium silicate solution and 10 M sodium hydroxide solution. Sodium silicate

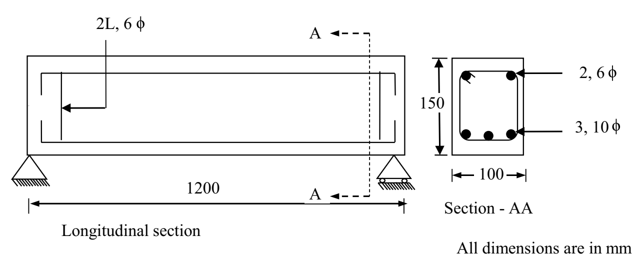

Fig. 1 Dimensions and reinforcement details

solution with SiO_2 to Na_2O ratio of 2 and water 55.90% by mass is used. Naphthalene based superplasticizer is also used in the mix for improving the workability. Hooked end steel fibres having length 30 mm and diameter 0.50 mm (aspect ratio 60) and ultimate tensile strength of 800 MPa and polypropylene fibres of length 12 mm and diameter 0.04 mm (aspect ratio 300) were used. HYSD steel bars of Fe 415 grade is used as reinforcement.

2.2 Mix proportion and preparation of specimens

As no relevant mix design codes are available for the preparation of geopolymer concrete mix, the mix proportion suggested by Ganesan et al. [8] is adopted for the GPC mix. For obtaining fibre reinforced mixes, steel and polypropylene fibres on various volume fractions were added to the mix. The super plasticizer content and water content are varied for different mixes in order to have a uniform slump value of 70–90 mm. The designations used for identifying various mixes and mix proportions are given in Table 1. Prior to the day of mixing, required quantity of alkaline solution is prepared with 10 molar sodium hydroxide solution and sodium silicate solution. Saturated surface dry aggregates were mixed with the required quantity of fly ash in the concrete mixer for 3 min. There after steel fibres and polypropylene fibres were added and then the pre-prepared alkaline solution is added in small dosages and mixed for 5 min. Then the super plasticizer is added and mixed further for 3 min. Fresh concrete property such as workability is determined by slump test. The slump values of all prepared mixes are given in Table 2. In order to find the hardened properties standard cube specimens of 150 mm size, cylinder specimens of 150 mm diameter and 300 mm length and prisms of size 100 × 100 × 150 mm were cast. For preparing beam specimens steel moulds are fabricated and the reinforcement cage is erected into the mould with a cover of 20 mm on all sides. The concrete is then poured into the mould in layers and vibrated. After casting, the specimens were left out at room temperature for one day. After that the specimens were shifted to an Oven along with the mould and cured at a temperature of 60 °C for 24 h. After this the specimens were taken out demoulded and kept in the laboratory ambient conditions for 28 days.

2.3 Fresh and hardened properties

From Table 2, it can be seen that as the percentage volume of steel fibre increases the workability decreases. This is due to the balling effect happening in the mix due to the presence of steel fibres. In the case of hybrid specimens also a decrease in workability is noticed as the percentage volume of fibres got increased but a higher workability is observed with the hybrid specimens when compared to

Table 1 Mix proportion for 1 m^3 of concrete

Mix designation	Steel fibre (%)	Propylene fibre (%)	Fly ash (kg/m^3)	Sodium silicate solution (kg/m^3)	Sodium hydroxide solution (kg/m^3)	CA (kg/m^3)	FA (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)
GPC	–	–	408	103	41	1248	600	14.30	10.20
SFRGPC-1	0.50	–	408	103	41	1248	600	14.30	10.20
SFRGPC-2	1.00	–	408	103	41	1248	600	16.00	14.50
HFRGPC-1	0.25	0.25	408	103	41	1248	600	14.30	14.50
HFRGPC-2	0.25	0.75	408	103	41	1248	600	14.30	14.5
HFRGPC-3	0.50	0.50	408	103	41	1248	600	16.00	14.50

CA coarse aggregate, *FA* fine aggregate, *SP* super plasticizer

Table 2 Fresh and hardened properties

Mix	Slump (mm)	Compressive strength (N/mm^2)	Split tensile strength (N/mm^2)	Flexural strength (N/mm^2)	Modulus of elasticity (N/mm^2)
GPC	93	41.44	3.68	3.82	36,100.55
SFRGPC-1	76	45.01	3.96	4.18	37,875.25
SFRGPC-2	63	46.85	4.42	4.61	38,200.00
HFRGPC-1	85	43.25	4.14	4.32	37,148.00
HFRGPC-2	78	42.40	4.32	4.58	36,755.30
HFRGPC-3	70	44.10	4.81	5.08	38,355.55

the specimens with steel fibres having the same percentage fibre volumes which indicates that the balling effect produced by the steel fibres is high when compared with polypropylene fibres.

The compressive strength, modulus of elasticity and split tensile strength were determined by testing specimens such as cubes, cylinders after 28 days of curing and prisms according to Indian standard specifications [15, 16]. The results hardened properties all the mixes are shown in Table 2. From the table, it can be observed that addition of fibres to GPC does not have significant effect on compressive strength. Only slight increase in compressive strength was observed as the volume fraction of steel fibre increases but a slight reduction in strength is noticed for hybrid fibre reinforced specimens as the volume fraction of polypropylene fibre increases with respect to the steel fibre volume fraction. The split tensile strength of hybrid specimens shows significant increase compared to steel fibre reinforced specimens of same fibre volume content. Similar to the split tensile strength the flexural strength of hybrid specimens also shows major increase when compared with steel fibre specimens of same fibre volume content. This may be due to the ability of hybrid fibres in arresting the micro and macro cracks.

2.4 Testing of specimens

The beams were tested in a loading frame of capacity 2000 kN. The ends of the beams were simply supported and are subjected to two point loading. The span of the beam was fixed as 990 mm. The schematic diagram of the test setup and test setup is shown in Figs. 2 and 3 respectively. Load was applied through a hydraulic jack fixed to the loading frame. The hydraulic jack was connected to a load cell of 100 kN capacity. A dial gauge of least count 0.01 mm was setup beneath the beam at mid span to measure the deflections. The load was applied by hand pumping in equal intervals of 2 kN. Loads and Corresponding dial gauge readings were noted along with the LVDT

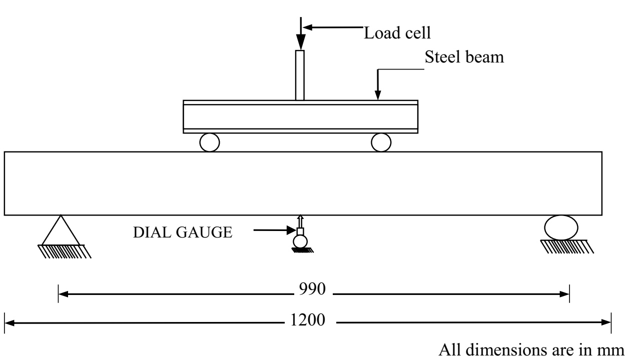

Fig. 2 Schematic diagram of test setup

Fig. 3 Test setup

reading at each 2 kN increment of load. The appearance and development of cracks during the progressive increment in load were carefully noted. The loading was continued until the failure of the beam. The tested specimens are shown in Fig. 4.

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2.6 Behaviour of specimens

As the loads were gradually increased cracks appeared on the flexural span after the first crack load. With further increase in loading, in addition to the flexural cracks diagonal shear cracks also appeared on the shear span. Further increase in loading led to the widening of existing cracks. For the plain beams (control beams) the diagonal cracks appeared at a faster rate leading to sudden shear failure. In the case of GPC beams with 0.50% steel fibre content (SFRGPC-I), predominant diagonal shear cracks as well as vertical tensile cracks are noticed at failure which indicates that the failure has occurred due to a combined effect of shear as well as flexural cracks. For SFRGPC-II beam which is having a steel fibre content of 1%, flexural cracks developed in the flexural span were seen significant than the shear cracks which indicates that the mode of failure changed from shear to flexure. In the case of hybrid GPC beam HFRGPC-I, which has got a fibre content of 0.25% steel fibre and 0.25% polypropylene fibre, at failure both shear cracks as well as tensile cracks were developed similar to that of SFRGPC-I. For HFRGPC-II specimen having a hybrid combination of 0.25% steel fibre and 0.75% polypropylene fibre, shear cracks were seen predominant than flexural cracks contributing shear nature of failure. For HFRGPC-III beams having a fibre content each of 0.50% steel and polypropylene fibre, flexural cracks are relevant than shear cracks similar to SFRGPC-II. The beams failed by flexure. From the failure modes as shown in Fig. 4 it can be noted that the specimens SFRGPC-II and HFRGPC-III shows a significant change in mode of failure from shear to flexure which is crucial in structural design on shear point of view when compared with other specimens which is having a fully or partly shear mode of failure.

3 Results and discussions

3.1 Load deflection behaviour

Using the data obtained from the experiment, load deflection curves were plotted and are shown in Fig. 5. All the curves were seen linear up to the first crack load (pre-cracking stage). Beyond this stage the slope of the graph decreases due to multiple cracking. In this stage the deflection increases nonlinearly with increase in load.

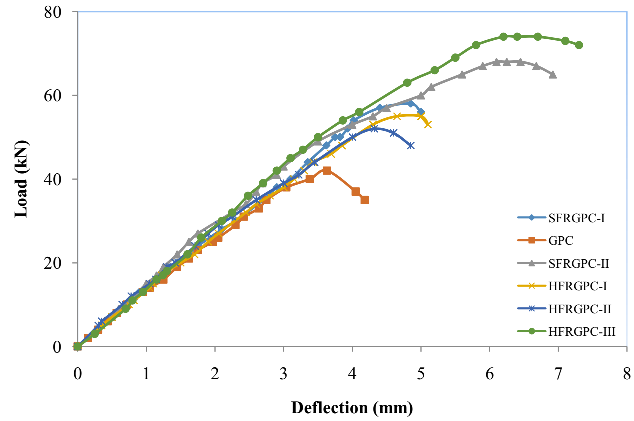

Fig. 5 Comparison of load deflection curves

The specimens without fibres showed a sudden drop in the load beyond peak load. The SFRGPC specimens exhibited flatter descending portion. This indicates the improvement in ductility and enhancement of stiffening effect of concrete between cracks in tension zone due to the presence of fibres. The specimens SFRGPC-II and the hybrid specimens HFRGPC-III shows a similar nature of flatter descending portion after the peak load. But the later one shows a much flatter descending portion even better than SFRGPC-II specimen. From the figure it can also be seen that the hybrid fibre reinforced beams shows better behaviour than steel and fibre reinforced specimens. This indicates the capacity of hybrid fibre combinations in enhancing the ductility and performance.

3.2 First crack load and ultimate load

The first crack load was found out from the load deflection curve corresponding to the point at which the curve changes from its initial linearity. The ultimate load is the maximum load sustained by the specimen. The first crack load, ultimate load and deflection corresponding to the ultimate load are given in Table 3. From the table, it can be seen that the first crack load tends to increases with the increase in volume fraction of steel fibres. This increment in first crack load may be due to the improvement in tensile strain carrying capacity of the concrete due to the presence of more amounts of steel fibres adjoining the concrete. The first crack load and ultimate load of SFRGPC specimens with 0.50% and 1% steel fibres is 28% and 57% respectively more than that of control specimens. In the case of hybrid fibre reinforced GPC specimens, it can be observed that as the polypropylene fibre volume increases the first crack load is slightly reduced comparatively with the steel fibre reinforced specimens. This may be happened due to the fact that the polypropylene fibres are

Table 3 First crack load, ultimate load and deflection at ultimate load

Beam designation	First crack load (kN)	% increase in first crack load	Ultimate load (kN)	% Increase in ultimate load	Deflection at ultimate load (mm)
GPC	14	–	42	–	3.63
SFRGPC-I	18	28.57	58	38.09	4.85
SFRGPC-II	22	57.14	67	59.52	6.10
HFRGPC-I	17	21.42	55	30.95	4.60
HFRGPC-II	15	7.14	52	23.80	4.32
HFRGPC-III	18	28.57	74	76.19	6.70

less effective in arresting initiation of micro cracks compared to steel fibres. The first crack load in the case of HFRGPC-III specimen which is having steel and polypropylene fibre in the ratio 1:1 is more than the other two hybrid combinations.

3.3 Energy absorption capacity and toughness index

Energy absorption capacity of a structural member is one of the crucial property that determines the seismic resistant capacity of a structural member. If the energy absorption capacity is more it will provide better resistance to fatigue, impact and seismic forces. It is determined from the area enclosed under the load deflection curve. The energy absorption capacities of all specimens were calculated as the area enclosed by the load deflection curve up to the ultimate load and is given in Table 4. From the table, it can be seen that as the steel fibre content increases, the energy absorption capacity also increases. In the case of hybrid specimen HFRGPC-III, which contains steel and polypropylene fibre percentage of 0.50 each a significant increase in energy absorption capacity is observed compared to SFRGPC specimen which having 1% steel fibre volume. This higher value may be attributed due to the higher load carrying capacity of the specimen tending to undergo more deflection due to the presence of large hybrid fibre volume near the crack front and high deformability of fibres during failure without pull out of fibres.

Toughness is related to the growth of cracks developed in a member. The ratio of the area of load deflection curve up to the ultimate load to the area up to first crack load is termed as toughness index [17]. The values of toughness index of all the specimens are given in Table 4. From the table it can be interpreted that the toughness index of fibre reinforced specimens are more than that of control specimens. This may be due to the fact that, when fibres present in concreter the cracks cannot propagate easier without stretching or debonding of the fibres. Thus fibre reinforced concrete needs more energy in order to stretch or debond them. Therefore, considerable energy is required for the complete fracture of the material.

3.4 Displacement ductility

Displacement ductility is the ability of a structural member to undergo large deformations without much reduction in load carrying capacity after the yielding of tensile reinforcement. This aspect is an important factor to be considered during the design of a structure in seismic regions. Ductility index (λ) is calculated as the ratio of ultimate deflection (δ_u) to yield deflection (δ_y) as given in Eq. (1) [17].

$$\lambda = \frac{\delta_u}{\delta_y} \tag{1}$$

The value of δ_u is obtained for each specimen from the test results. For obtaining δ_y the load at which the steel

Table 4 Energy absorption capacity and toughness index

Beam designation	Energy absorption capacity (kN mm)	% Variation	Toughness index	% Variation
GPC	82.98	–	10.98	–
SFRGPC-I	154.76	86.50	13.76	25.31
SFRGPC-II	241.83	191.00	15.51	41.25
HFRGPC-I	135.02	62.71	13.30	21.22
HFRGPC-II	123.56	48.90	13.27	20.85
HFRGPC-III	256.87	209.55	17.62	60.47

yields (P_y) is calculated and then from the load deflection curve, δ_y corresponding to P_y is obtained. For obtaining the load at which the steel yields the following procedure is adopted. From the elastic cracked section theory, assuming that the steel bars not stressed beyond its yield strength, the strain in concrete at the level of steel (ε_c) and the strain in steel(ε_s) can be calculated from Eq. (2).

$$\varepsilon_s = \varepsilon_c = \frac{M}{I_{cr}E_c}(d - x_n) \tag{2}$$

where d = defective depth of beam in mm, x_n = depth of neutral axis in mm, I_{cr} = cracked moment of inertia of the transformed section in mm^4

Then stress in steel (f_s) is calculated using Eq. (3)

$$f_s = \varepsilon_s E_s = \frac{M}{I_{cr}}(d - x_n)\frac{E_s}{E_c} \tag{3}$$

At yielding, $f_s = f_y$ (yield stress in N/mm^2) and $M = M_y$ (yield moment in N-mm) and substituting this in Eq. (3) and rearranging it Eq. (4) is obtained.

$$M_y = f_y \frac{E_c}{E_s} \frac{I_{cr}}{(d - x_n)} \tag{4}$$

M_y and P_y for the geometry of the loading as shown in Fig. 2 is given by Eq. (5)

$$M_y = P_y \frac{L}{6}, \quad P_y = \frac{6M_y}{L} \tag{5}$$

where L = effective span of beam in mm

Using the Eq. (1), the values of ductility factor for all the tested specimens were calculated and a relative comparison of ductility factor is given in Table 5. From the table it can be seen that as the volume fraction of steel fibre increases the ductility index also increases. This may be due to the fact that fibres prevents the propagation of cracks by bridging across the cracks, which reduces the crack width. Thus, the crack propagation is restricted, which increases the load capacity within the post cracking region. Therefore, the ability of the beam to absorb plastic deformations is increased. In the case of HFRGPC-III specimen a comparatively better ductility index is obtained. This may be attributed due to better ductile characteristics offered by an optimum combination of hybrid fibres when compared with other specimens which is an added advantage in the design of structural members located in seismic prone areas.

Table 5 Ductility index and load factor

Beam designation	Ductility index	Relative ductility	Load factor
GPC	2.07	1.00	1.82
SFRGPC-I	2.55	1.23	2.32
SFRGPC-II	2.83	1.36	2.39
HFRGPC-I	2.48	1.19	2.21
HFRGPC-II	2.36	1.14	2.08
HFRGPC-III	2.97	1.43	2.64

3.5 Load factor

In the limit state design of reinforced concrete structures the design should satisfy both the safety and serviceability criteria. The Load factor (LF) with respect to deflection for all the tested beams is calculated using Eq. (6).

$$L.F = \frac{P_u}{P_{\delta i}} \tag{6}$$

where P_u is the ultimate load and $P_{\delta i}$ is the load corresponding to immediate deflection (δ_i),which is obtained from Eq. (7). Long term deflection (δ_l) is calculated by using Eq. (7) [18]. The total deflection (δ_t) in mm is the sum of short term (immediate) and long term deflections and is given by Eq. (8). Substituting Eqs. (7) in (8) it changed to Eq. (9). For serviceability conditions, the allowable total deflection (δ_t) is limited to span/250 [19], substituting this in Eq. (9) δ_i can be calculated for all the specimens. From Fig. 5 the load $P_{\delta I}$ corresponding to δ_i values of all the specimens are obtained and then by using Eq. (6) the load factor for all the tested specimens are calculated and is given in Table 5.

$$\delta_1 = (2 - 1.20(Asc/Ast))\delta_i \tag{7}$$

$$\delta_t = \delta_i + \delta_l \tag{8}$$

$$\delta_t = \delta_i(3 - 1.20(Asc/Ast)) \tag{9}$$

where Asc, Ast are area of steel in compression and tension respectively in mm^2

From the table, it can be inferred that the load factor of HFRGPC- III specimens is 45% greater than control specimens. This may be due to the better load deflection characteristics of hybrid specimens after the initiation of first crack compared with other specimens.

4 Conclusions

In this study an attempt has been made to evaluate the shear behavior of heat cured geopolymer concrete beams. Based on the study following conclusions were made

- Addition of fibres in geopolymer concrete mixes shows a significant decrease in workability and does not have significant effect on the compressive strength.
- The tensile strength and the flexural strength of geopolymer concrete increase with increase in steel fibre content. Steel fibre reinforced beam with 1% volume fraction have 20% and 21% increase in split tensile strength and flexural strength respectively than plain GPC beams.
- The ultimate load carrying capacity of steel fibre reinforced and hybrid fibre reinforced (0.50% volume fraction of steel fibres and polypropylene each) geopolymer concrete beam is 59% and 76% respectively more than the control beams.
- Addition of fibres changed shear failure mode of beam specimens to more ductile mode and hybrid fibre reinforced geopolymer concrete beams having 0.50% volume fraction of steel fibres and 0.50% volume fraction of polypropylene fibres shows more ductile behaviour than geopolymer concrete beams having 1% volume fraction of steel fibres.
- The energy absorption capacity and ductility index of SFRGPC-II beams is 41% and 36% respectively higher than the plain GPC specimens where as it is 60% and 44% higher than the plain GPC beams for HFRGPC-III specimens.
- The load factor based on serviceability condition of deflection for HFRGPC-III specimen is 24% and 10% respectively than that of control beams and SFRGPC-II beams.

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Compliance with ethical standards

Conflict of interest All author declares that they have no conflict of interest.

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