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Experimental and analytical investigations on shear behaviour of reinforced geopolymer concrete beams

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ABSTRACT

Geo polymer materials are inorganic polymers synthesized by reaction of a strongly alkaline silicate solution and an alumino silicate source. Geo polymer is used as binder to completely replace the ordinary Portland cement in producing Geo polymer concrete(GPC). They possess the advantages of rapid strength gain, elimination of water curing, good mechanical and durability properties and are additional ecofriendly and sustainable alternative to Ordinary Portland Cement (OPC). While substantial research work has been reported on behaviour of reinforced concrete structural elements, similar studies have not been reported on GPCs. This paper describes an experimental and analytical investigation on shear behaviour of reinforced GPC and OPCC beams. The aim is to study the shear behavior of reinforced GPC and OPCC beams. Three GPC mixes and one OPCC mix were considered for the study. All the beams were provided with the same flexural and shear reinforcement and the beams were tested under two point loading with two shear span to depth ratios of 1.5 and 2 for each of the mixes. This paper presents the details of the mix designs of GPC mixes, parameters investigated, preparation of RGPC beams, testing and evaluation of structural behavior with respect to cracking, service load, deflections at various stages and failure modes. Comparison of shear design procedure of beams was made by conventional IS 456 2000 approach and Modified compression field theory. Non linear finite element analysis of beams by 3D modelling of concrete (solid65 element) and discrete modeling of reinforcement (Link8 element) was carried out using ANSYS software. For shear span to depth ratio of 1.5, load shear capacity, load deflection characteristics and failure modes and crack patterns obtained from the experimental and analytical study were compared for both RPCC and RGPCC beams. The results of the study indicate that the performance of RGPC is similar to that of RPCC beams and the ultimate loads are in the same order. The failure modes and crack patterns are also similar.

Keywords: Geo polymer concrete, ordinary Portland cement concrete, shear behaviour, Finite Element modeling, Flyash, Ground Granualted Blast furnace slag

1. Introduction

Producing one tonne of cement requires about 2 tonnes of raw materials (shale and limestone) and releases 0.87 tonne (≈ 1 tonne) of CO_2, about 3 kg of Nitrogen Oxide (NO_x), an air contaminant that contributes to ground level smog and 0.4 kg of PM_{10} (particulate matter of size 10 µm), an air borne particulate matter that is harmful to the respiratory tract when inhaled. The global release of CO_2 from all sources is estimated at 23 billion tonnes a year and the Portland cement production accounts for about 7% of total CO_2 emissions. These

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concretes are found to be less durable in some of the very severe environmental conditions, therefore there is a need for development of alternate concretes. In this regard, geopolymer concretes(GPCs) can be considered as potential candidate materials.

'Geo polymer Concretes' (GPC) are inorganic polymer composites, which are prospective concretes with the potential to form a substantial element of an environmentally sustainable construction by replacing/supplementing the conventional concretes. GPC have high strength, with good resistance to chloride penetration, acid attack, etc. These are commonly formed by alkali activation of industrial alumino silicate waste materials such as FA and GGBS, and have a very small Greenhouse footprint when compared to traditional concretes. The extensive research works carried out by several investigators corroborate the potential of GPC as a prospective construction material.

2. Research significance

One of the potential areas of application of GPCs, which provides significant value addition to the material and helps to realize the concept of green habitat, is their utility in structural concrete. However, the suitability of reinforced GPC to various structural components is to be established by large number of experimental studies. Rangan et al[5-8] have investigated this aspect using FA based heat treated GPCs. The CSIR-Structural Engineering Research Centre (CSIR-SERC), Chennai has developed structural grade Geo polymer concretes (GPC) and investigated its suitability for Reinforced Geo polymer Concrete (RGPC) beams critical in flexure for the first time in the country. In continuation of these studies, the shear behaviour of RGPC was considered for investigation in the present thesis. Adequate shear resistance in structural concrete members is essential to prevent shear failures which are brittle in nature. One of the critical parameters influencing the shear capacity of beams is shear span to depth ratio (a/d). Experimental and analytical studies were carried out on shear critical beams considering two shear span to depth ratios of 1.5 and 2 respectively. This paper considers reinforced GPC beams with different binder compositions and compressive strengths ranging from 17 to 63 MPa and produced by ambient temperature curing. The RPCC beams based on OPC were also prepared and tested for comparison of performance. Performance aspects such as load carrying capacity, moments, deflections, and strains at different stages were studied. The failure modes were also recorded for the beams. The paper compares the performance of RGPC beams vis a vis RPCC beams

3. Details of experimental work

3.1 Materials

Ordinary Portland cement conforming to IS 12269 (with specific gravity of 3.15), fine aggregates, coarse aggregates and potable water were used for the control RPCC test specimens. The RGPC was obtained by mixing different combinations of Ground Granulated Blast Furnace Slag (GGBS), Fly Ash (FA), fine aggregates, coarse aggregates and Alkaline activator solution(AAS). FA conforming to grade 1 of IS 3812 and GGBS from Andhra Cements, Vishakhapatnam conforming to IS 12089 were used. River sand available in Chennai was used as fine aggregates. They were tested as per IS 2386. In this investigation, locally available blue granite crushed stone aggregates of maximum size 12mm and down was used and characterization tests were carried out as per IS 2386. The properties of the materials used are shown in Tables 1. Potable water was used for the RPCC and distilled

water was used for the RGPCs. High strength deformed steel bars with 0.2% proof stress of 450 MPa and nominal diameters of 8mm, 16mm were used as reinforcements in beams.

Table 1: Physical Properties of Cement, Fly Ash and GGBS

S. No.	Descriptions	OPC	Fly ash	GGBS
1	Fineness (m^2/kg)	306	419	400
2	Normal Consistency (%)	31	-	-
3	Setting Time (minutes)			
	a) Initial	55	-	-
	b) Final	100	-	-
6	Specific gravity	3.15	2.20	2.90
7	Compressive Strength, MPa			
	1d	18.2		
	3 d	36.6	62*	
	7d	46.1	71*	87**
	28 d	58.5	88*	

* The pozzolanic activity index (%) of cement-fly ash mix as per ASTM C-1240
** The Slag activity index as per ASTM C-989

The alkaline activator solution (AAS) used in GPCC mixes was a combination of sodium silicate solution (SiO_2/Na_2O=2.2), sodium hydroxide pellets and distilled water. The role of AAS is to dissolve Si and Al present in the reactive portion of source materials such as FA and GGBS and provide a high alkaline liquid medium for condensation polymerization reaction. The sodium hydroxide was taken in the form of flakes of approximately 3mm in size. The sodium hydroxide (NaOH) solution with required concentration was prepared by dissolving the computed amount of sodium hydroxide flakes in distilled water. The NaOH solution and sodium silicate solution were prepared separately and mixed together at the time of casting. Since lot of heat is generated when sodium hydroxide flakes react with water, the sodium hydroxide solution was prepared a day earlier to casting. It should be noted here that it is essential to achieve the desired degree of workability of the GPC concrete mix. However, excess water can result in formation of pore network, which could be the source of low strength and low durability.

3.2 Specimen Details

The beam specimens were 100mm wide and 150mm deep in cross-section. They were 1500mm in length and simply-supported over an effective span of 1350mm. The clear cover of the beam was 20mm. The geometry of the beam specimen is shown in Figure 1and Figure 2. High yield strength deformed steel bars of diameter 16mm, 12mm and 8mm were used as the longitudinal reinforcement in the specimens. Three different percentages of tensile reinforcement of from 1.82 to 3.33% tension reinforcement (82-110% of corresponding balanced section reinforcement) were used. Two legged vertical stirrups of 8 mm diameter at a spacing of 100 mm centre to centre were provided as shear reinforcement. Electrical

resistance type strain gauges for were fastened at the mid span longitudinal tension steel, a day before casting.

3.3 Specimen details

3.3.1 Beam Geometry

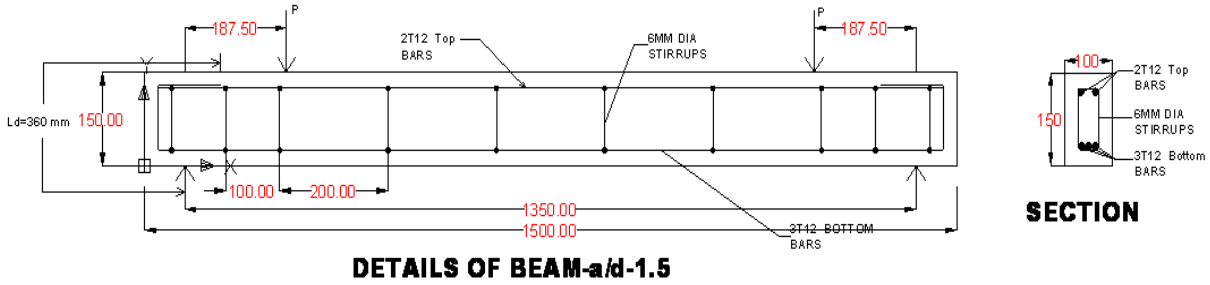


Figure 1: Reinforcement details for beams- a/d ratio 1.5

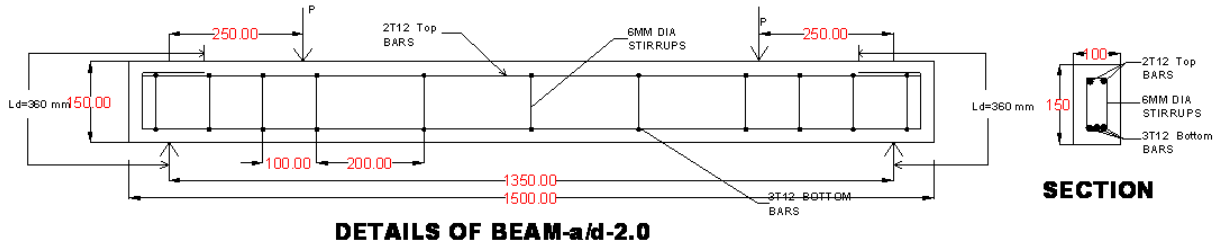


Figure 2: Reinforcement details for beams - a/d ratio 2

The test specimens were designed as per the provisions of IS-456-2000 assuming a characteristic compressive strength of 40 MPa for both OPCC and GPC. A total of sixteen beams, each with a rectangular cross section of size 100 mm x 150 mm and length of 1500 mm, were cast. The effective span of the beam is 1350mm.The beams were cast for different a_v/d ratios (1.5 and 2). All the beams were reinforced with 3 nos. of 12mm diameter TMT (Fe-500) rods provided at bottom, and 2 nos of 12mm diameter TMT (Fe-500)provided at the top of the beam(Figure 1 and Figure 2) . 6mm diameter mild steel bars were provided as transverse reinforcement in the beam at 100mm spacing in the shear span region and 200mm spacing at mid span. The beam was designed to fail in shear by designing it for 75% of the balanced section capacity in flexure and making it critical in shear by adopting low shear span to depth ratio (a_v/d). The beams were divided into two series according to the shear span to depth ratio:(ie a_v/d =1.5 and a/d =2) . The clear cover provided to the reinforcement was 20 mm. The geometry of the beam specimen is shown in Figure.1 and Figure. 2

3.4 Preparation of Test Specimens and Curing

The coarse aggregates and sand in saturated surface dry condition with binders OPC or FA and GGBS were first mixed in 300 kg capacity tilting drum mixer for about three minutes. The mix proportions of GPC and OPC concrete are presented in Table.2. At the end of this mixing, the alkaline activator solution (AAS) was added to the dry materials. Then mixing was continued for another four minutes till a uniform consistency was achieved. Immediately

after mixing, the fresh concrete was cast into the moulds. The beam specimens were cast horizontally in steel moulds in three layers. Prior to casting, the inner walls of moulds were coated with lubricating oil to prevent adhesion with the cured concrete. The beam moulds were kept on a vibrating table during the casting. The concrete was placed in the moulds in three layers of equal thickness and each layer was vibrated until the concrete was thoroughly compacted by the vibrating table. With each batch, a number of 150mm cubes, prism (100x100x500mm), and cylinders of size (150x300mm) were also cast to be tested after 28 days for the compressive strength. The slump of every batch of fresh concrete was also measured in order to observe the consistency of the mixtures. Figure.1 and Figure.2 shows the details of reinforcement bars, ready to be casted. All the OPCC beam specimens was water cured, whereas all the GPCC beam specimens were air cured under ambient conditions in the laboratory for a period of 28 days.

Table 2 Mix Proportions for the Present Study

Mix Id.	Mix Proportion (Bnder:Sand:CA) By mass	Liquid / Binder solid (by mass)	Super Plasticizer (% of binder by mass and type)	Binder Composition (% by mass)	Method of Curing
Control	1:2.5:2.86	0.45 - Water	0.-GB	-	Water
GBFC0015 GBFC0020	1:1.5:2.53	0.6 AAS	0.5-RB	0 FA, 100-GGBS	Ambient lab condition
GBFC2515	1:1.4:2.4	0.6 AAS	0.5-RB	25 FA, 75-GGBS	Ambient lab condition
GBFC5015	1:1.362:2.361	0.6 AAS	1-RB	50 FA, 50-GGBS	Ambient lab condition

Note : GB- Glenium B 233, RB – Rheobuild 1100i

3.5 Test Procedure

The schematic sketch of the test setup is shown in Figure.3. The beam specimen was mounted in a UTM of 1000 kN capacity. The beam specimen was supported on reaction blocks mounted on a sturdy steel box section of length 1700mm placed on the bottom plate of the UTM. The load was applied on two points at a distance of 187.5 mm for a_v /d ratio of 1.5 centre of the support through a load spreader. Two dial gauges of 0.01 mm least count were used for measuring deflections under the loading points i.e. deflections at one third span. Another dial gauge of the same least count was used at mid span for measuring the respective deflection. The steel strains were recorded by electrical resistance strain gauges connected to a digital strain indicator. All the specimens were white washed in order to facilitate marking of cracks. The beams were tested under two point static loading over a span of 1350mm. The load was applied in increments of 10 kN until the first crack was obtained. Later, the load was applied in increments of 20 kN. The deflections at mid span and under the load points were measured using dial gauges, while the longitudinal strains in the beams were measured using the pfender gauge. All the measurements including deflections, strain values and crack

widths were recorded at regular intervals of load until the beam failed. The failure mode of the beams was also recorded.

Figure 3: Photographic View of the Experimental Setup

4. Test results and discussions

4.1 Load Deformation Characteristics

The beam specimens were tested under two point static loading until failure. The **Figure 4 and Figure 5** show the load-deflection curves at mid-span of for OPCC and GPC beam specimens with a/d ratio 1.5 and 2, respectively. The load-deflection curves indicate the different events that take place during the test. These features mentioned above are typical characteristics of shear behavior of reinforced concrete beams. The load deflection characteristics at mid span of the OPCC beams and GPCC beams were found to be almost similar up to about 80% of the peak load and the load deflection curve was approximately trilinear. After the peak load, the OPCC beam with av/d=1.5 registered a sharp fall in load and failure occurred with very little increase in deflection, which is typical of small av/d due to predominance of arch action over beam action. However, GPC beams showed a mild ramp followed by a drooping segment signifying higher ultimate deflection and yielding of main tension reinforcement. The behavior was similar for $a_v/d=2$ also except that all the beams showed a second segment which had a mild rising slope followed by a drooping segment due to increased role of beam mechanism.

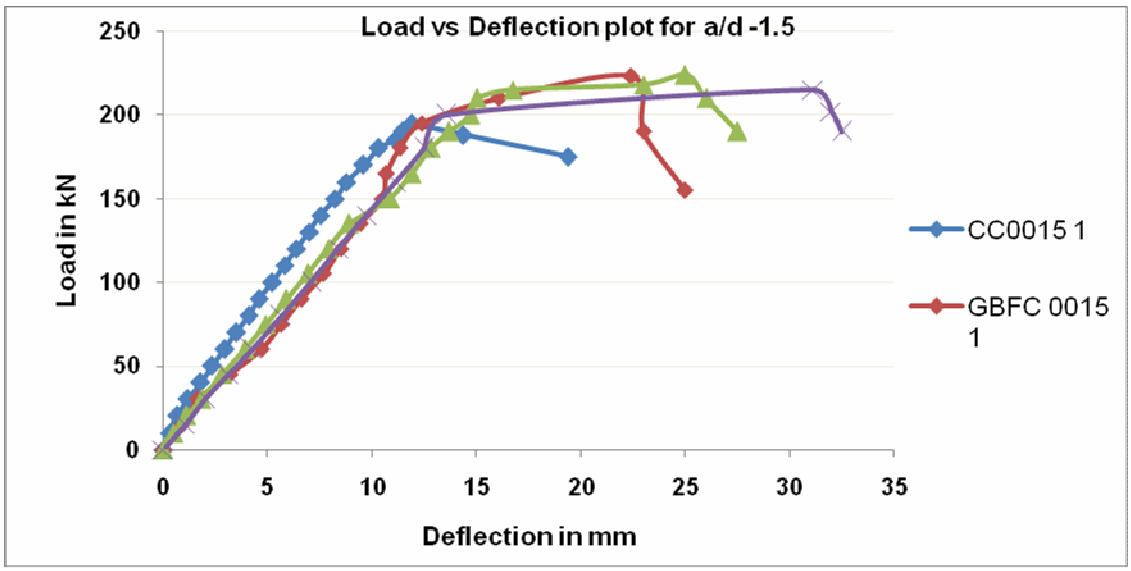


Figure 4: Load vs Mid Span Deflection curves for a /d Ratio 1.5

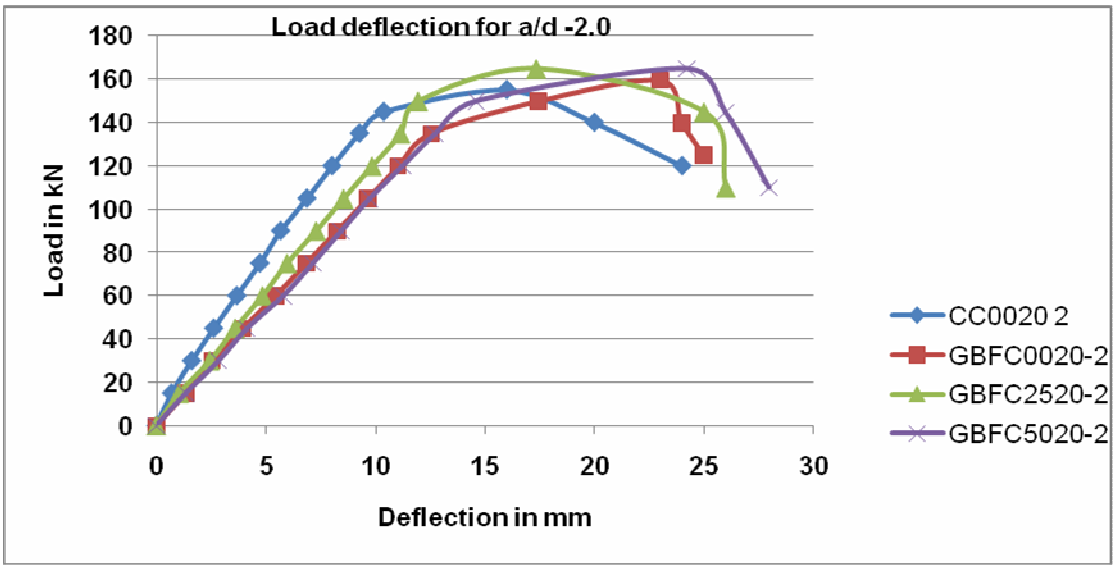


Figure 5: Load vs Mid Span Deflection curves for a /d Ratio 2

4.2 Cracking Moment

Cracking of concrete is believed to occur whenever the tensile strength/strain of the concrete is exceeded. The cracking in reinforced concrete is attributable to various causes such as flexural tensile stresses, diagonal tension, lateral tensile strains, etc. The moment at which the first visible crack appears in the beam is termed as cracking moment. During the test, the loads at first crack in the beam specimens were visibly observed using a hand held microscope. The values were recorded from the observation. From these values, the cracking loads , service loads and ultimate loads are given in Table.3. The load at appearance of first crack was almost same in the case of OPC and GPC beams, whereas the load at appearance of the first crack in case of a /d ratio 2 GPC beam was pretty early. This is obvious since

more load is resisted by arch action in a/d=1.5 compared to a/d=2 in which the beam action dominates. The service loads were calculated at loads corresponding to a deflection of span/250 or maximum crack width of 0.3mm, whichever is less. GPCC beams with av/d =1.5 had about 30% higher service load than av /d ratio 2 as the latter experience more deflection for the same load. The ultimate load carrying capacity of GPCC beams, were found to be almost same and marginally more than OPCC beams in numerical terms due to higher compressive strength.

Table 3: Load Carried at various Stages by the Beams

Specimen ID	First crack load, P_{CR} (kN)	Service load, P_{SL} (kN)	Ultimate load, P_{UL}(kN)
CC0015	40	116	195.4
GBFC0015	45	78	224.25
GBFC2515	45	82	222.97
GBFC5015	45	76	213.05
CC0020	45	80	150.05
GBFC0020	30	58	161.44
GBFC2520	30	60	164.17
GBFC5020	30	65	170.22

4.3 Ultimate moment capacities

The ultimate moment carrying capacity of the beam specimens are shown in Table 4. The normalized cracking moment was higher for GPCs compared to OPCCs for a_v/d=1.5 as well as for a_v/d=2. The normalized service moment capacity is considerably less for GPCCs compared to OPCCs since they undergo more deflection in view of their lower modulus of elasticity and lower modulus of rupture compared to OPCCs. At failure loads, the GPCC beams deflected significantly. The failure pattern of the beam specimens was found to be similar. The crack patterns and failure mode of several test beams are shown in Figures.9 and 10.

Table 4: Normalized moment capacities at Various Stages for the Different Beams

Series	σ_{cu} MPa	Mcr kNm	σ_b MPa	$M_{cr}/\sigma_b bd^2$	Msl kNm	$M_{SL}/\sigma_{cu} bd^2$	M_u kNm	$M_u/\sigma_{cu} bd^2$
CC0015	49.03	3.72	5.89	0.41	10.79	0.18	18.32	0.24
GBFC0015	61.52	4.92	5.53	0.58	7.25	0.09	21.02	0.22
GBFC 5015	64.07	4.45	4.84	0.60	7.63	0.10	20.90	0.21
GBFC 2515	62.45	4.92	4.86	0.66	7.07	0.09	19.97	0.21
CC0020	48.12	4.21	5.89	0.46	9.92	0.17	18.76	0.25

GBFC 0020	65.60	4.92	5.53	0.58	7.19	0.09	20.15	0.20
GBFC 5020	54.61	4.45	4.84	0.60	7.44	0.11	20.52	0.24
GBFC 2520	62.44	4.92	4.86	0.66	8.06	0.10	21.28	0.22

4.4 Finite element modelling

The experimental results of the RPCC and RGPC beams are verified theoretically, using the updated version of the finite element software 'ANSYS'. The zero values for the Z coordinates coincide with the center of the cross-section for the concrete beam. To obtain good results from the Solid65 element, the use of a mapped mesh is recommended. The mesh size used for the study is 12.5mm x 12.5mm. The solid element has eight nodes with three degrees of freedom at each node translations in the nodal x, y and z directions. Beams are modeled using 8 nodded solid 65 elements. Link8 elements were used to create the flexural and shear reinforcement. Reinforcement exists at a plane of symmetry in the beam. The area of steel at the plane of symmetry is one half the normal area for a 12mm diameter bar because one half of the bar is cut off. Shear stirrups are modeled throughout the beam. Only half of the stirrup is modeled because of the symmetry of the beam. The overall mesh of the concrete, plate, and support volumes is shown in Figure.6. Displacement boundary conditions are needed to constrain the model to get a unique solution. To ensure that the model acts the same way as the experimental beam, boundary conditions need to be applied at where the supports and loadings exist. Loading was applied at loading point. Since it is a quarter beam model, at one end of the beam support, U_y is restrained to ensure roller support conditions and other end is restrained against x direction ensuring the symmetry boundary conditions along the longitudinal section. Similarly along the z direction all the nodes are constrained ensuring symmetry boundary condition along cross section. The load applied was about 50kN since it is a quarter beam model, one fourth of the total load is taken. The loading was applied at a distance of 187.5mm from the support for shear span to depth ratio 1.5. The stress-strain curves measured from the experiments are used for analysis. The theoretical and experimental load –deflections curves are correlated and in Figures.7-8 for RPCC and RGPCC beams. The load –deflection curves predicted by finite element analysis is compared with experimental results. A reasonably good correlation is observed between finite element results and experimental curves.

4.5 Comparison of experimental and analytical results for different series of beams

4.5.1 Load deformation Characteristics for Shear Span to depth ratio-1.5

The load-deformation response for all the specimens from the finite element results were compared with experimental result as shown in Figure 7-8. A reasonable good correlation is observed between the finite element results and experimental results. The analytical deflection values were about 10 to 25 % more than experimental values in all the cases. This may be due to the inability to account for the actual heterogeneity existing in the test beam in the analytical model as the same property is assigned to all concrete elements in both RPCC and RGPC beam.

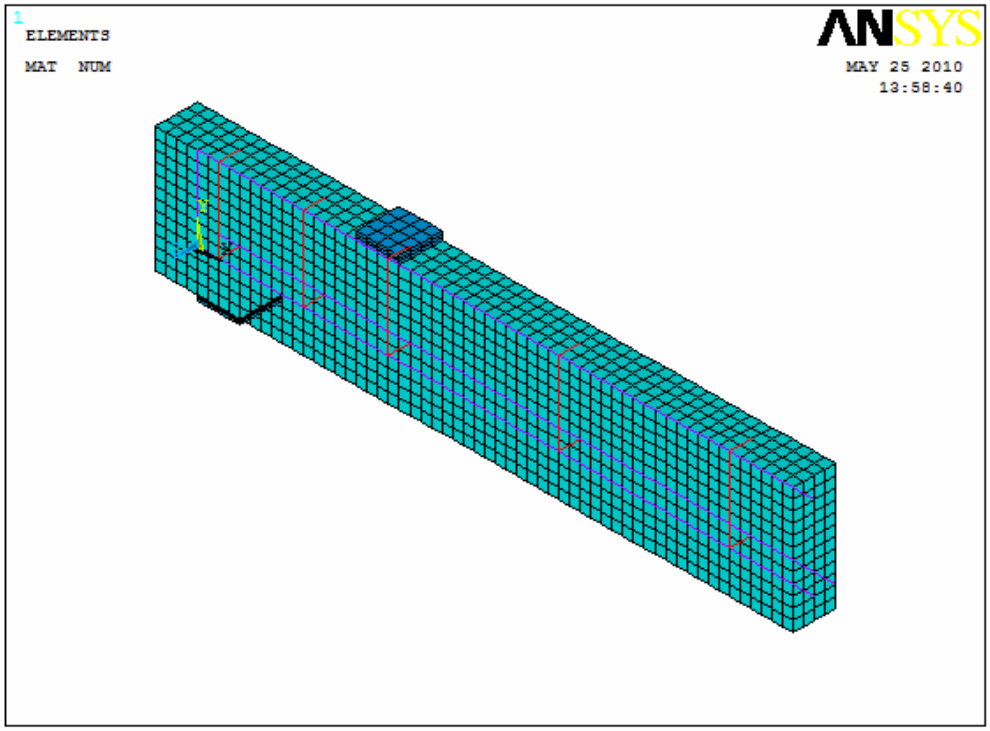
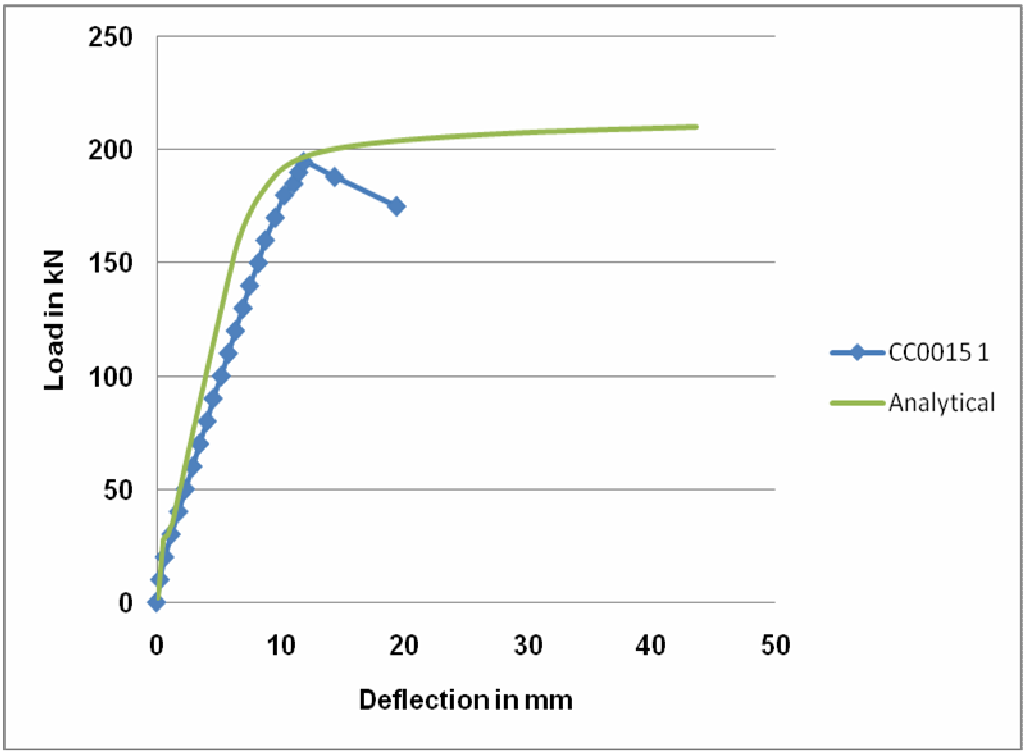
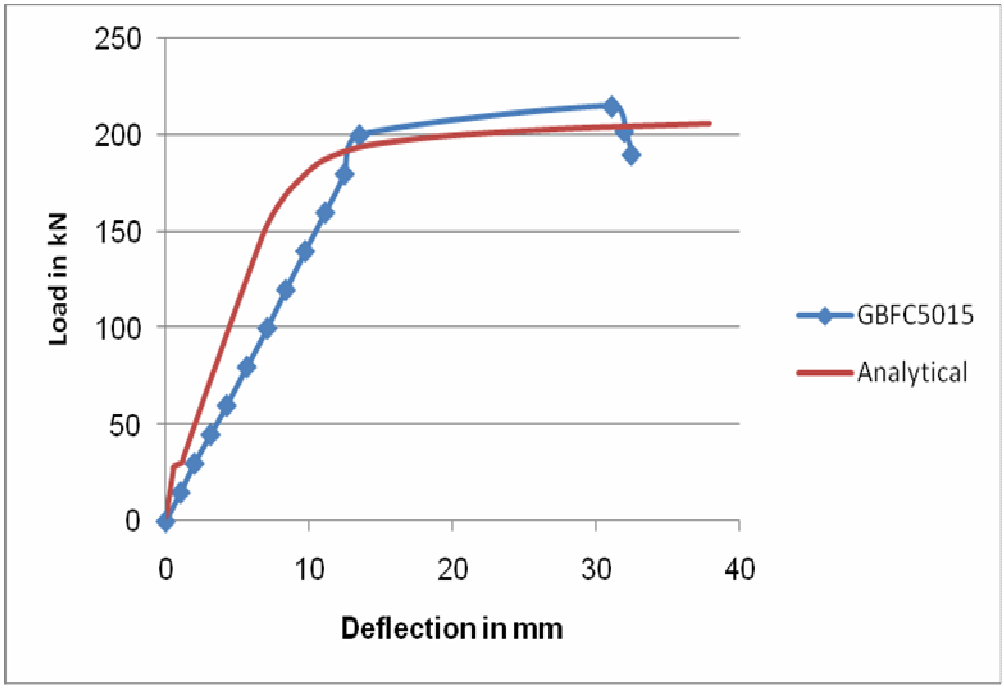


Figure 6: 3D Beam Model in ANSYS Before and After Meshing

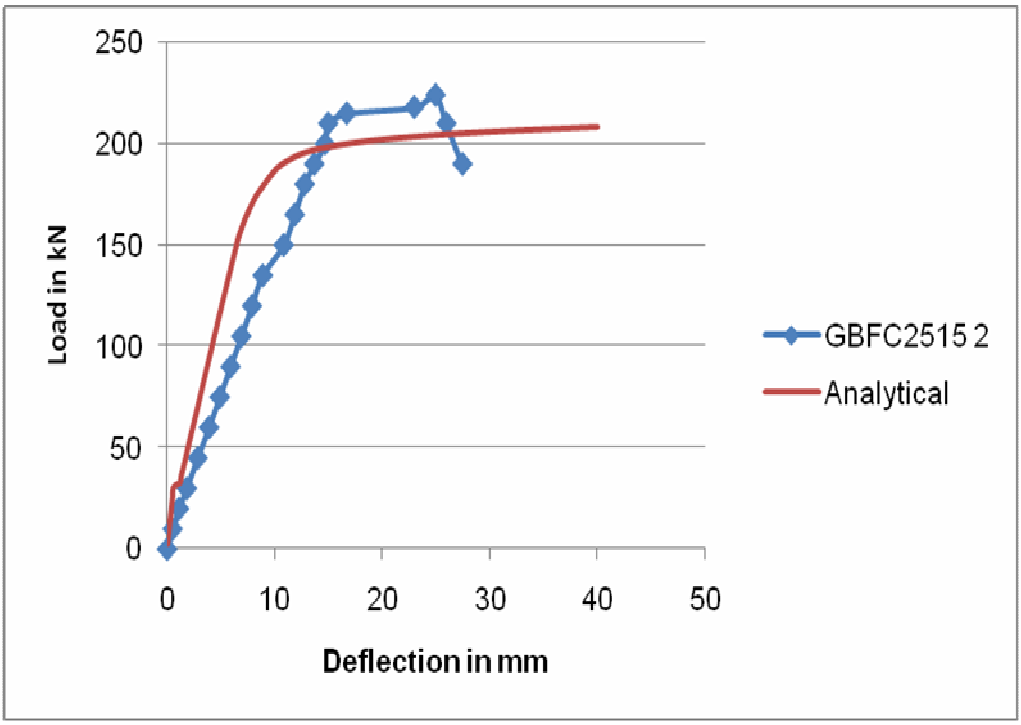


(a) The load deformation curves –RPCC BEAM

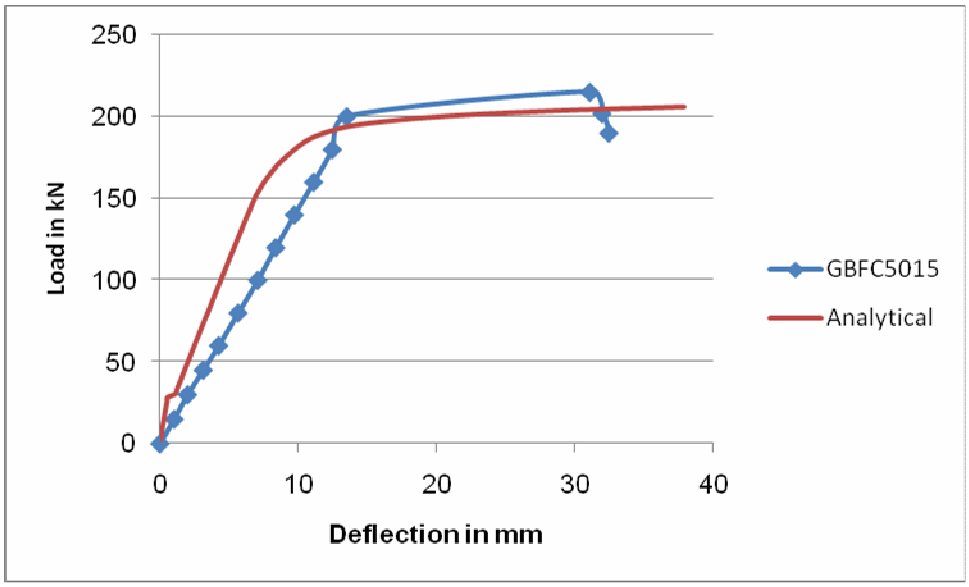


(b) The load Deformation curves RGPC-5015 Beam

Figure 7: Comparison of load Deformation curves for RGPC and RPCC beams



(c) The load deformation curves –RGPC-GBFC2515 BEAM



(d) The load deformation curves –RGPC-GBFC5015 BEAM

Figure 8: Comparison of load deformation curves for RGPC-GBFC5015
Shear span to depth ratio 1.5

The cracking and ultimate loads obtained from experimental and Analytical results is shown in Table 5. The propagation of the critical diagonal crack provokes growth of concrete plastic strain and relevant material softening, although the aggregate interlock mechanism is on through beta factors. The tensile steel yielding begins at deflection value of about *10 mm* and after that the solution needs more and more iterations to converge. The numerical curve becomes flat, unlike the experimental curve, and after sudden and large increasing of deflection of about 10 to 15mm after the peak load, solution stops due insurmountable convergence problems .

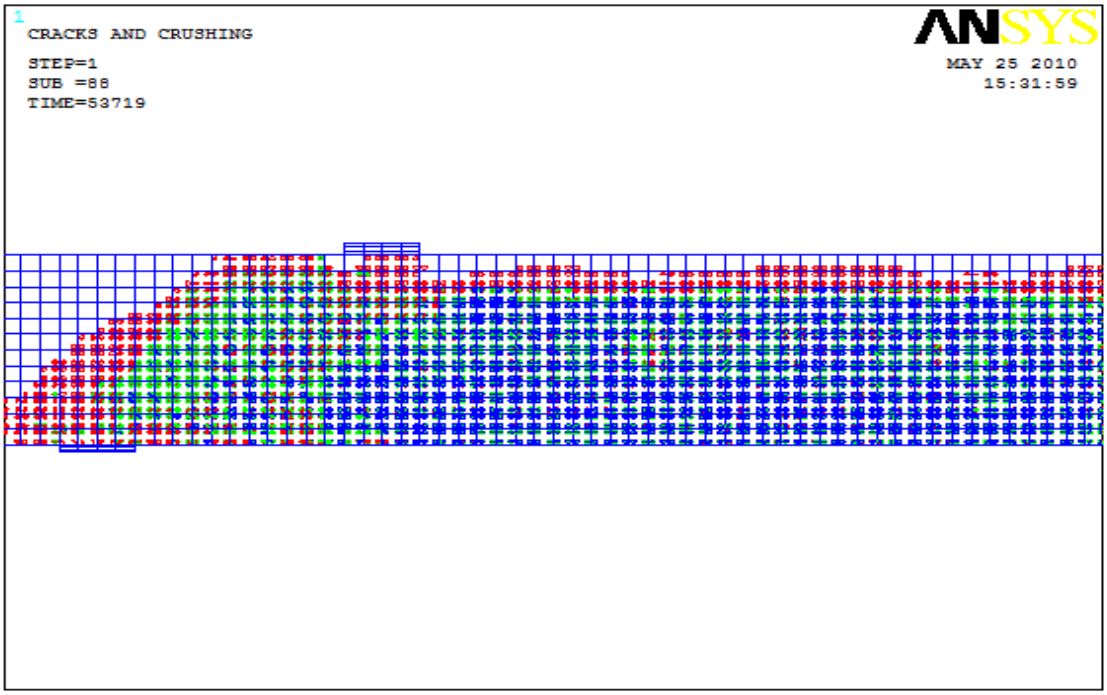
Table 5: Comparison of ultimate loads obtained from Experimental and Analytical studies

ID	Cracking load, P_{CR} (kN)		Ultimate load, P_U(kN)	
	Experimental	By ANSYS	Experimental	By ANSYS
CC0015	40	35	195.4	215
GBFC0015	45	40	224.25	210
GBFC2515	45	35	222.97	219
GBFC5015	45	35	213.05	210

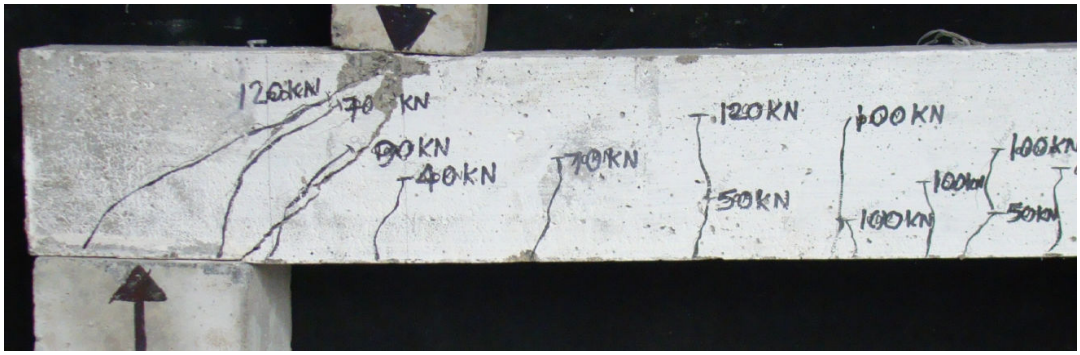
4.6 Failure modes and Crack Patterns of RPCC and RGPC beams

Figure.9-10 shows the comparison of failure modes and crack pattern of RPCC and RGPC beams from experimental and finite element analysis. The solid 65 element uses smeared cracking idea and plots cracks at the integration points. The first crack at an integration point is shown with a red circle outline, the second crack with a green outline, and the third crack with a blue outline. After the load stage of 75kN the cracks increases both in the shear compression zone and the flexural zone. The diagonal crack extends from the support towards the loading plate and results in crushing below the loading plate towards the support

at a failure load of around 210kN in all the beams. Mean while lots of flexure crack develops at the constant moment region. The beam no longer can support additional load as indicated by an insurmountable convergence failure. Hence by the cracking patterns and the modes of failure of the RGPC beam behaves in the same way as that of the RPCC beam. ANSYS 3D concrete element is very good concerning shear crack development but poor concerning the crushing state. It may be possible to overcome the deficiency employing a certain multilinear plasticity model available in ANSYS but the lack of experimental data for material parameters especially GPCs is a drawback. There was a good agreement between experimental and predicted values of deflection, crack pattern and failure modes of GPC and RPC beams.

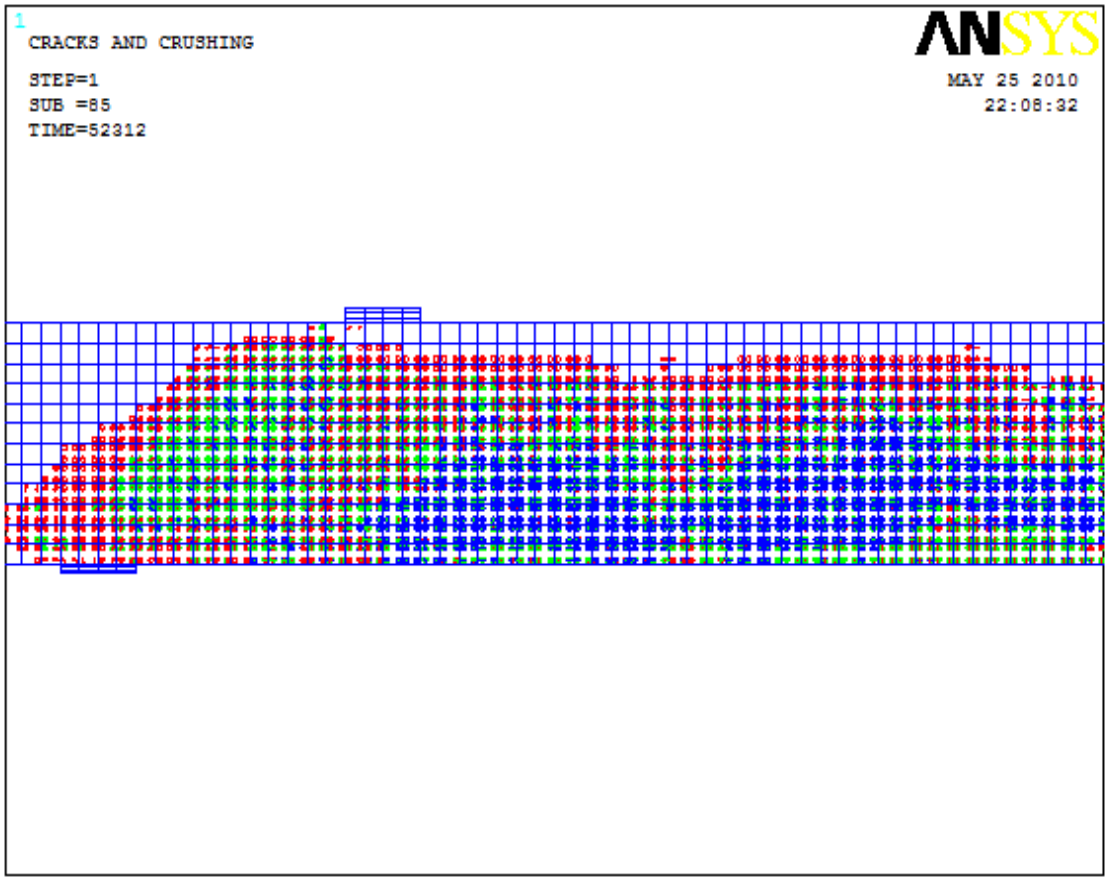


(a) Cracking pattern at failure stage –RPCC BEAM-Analytical

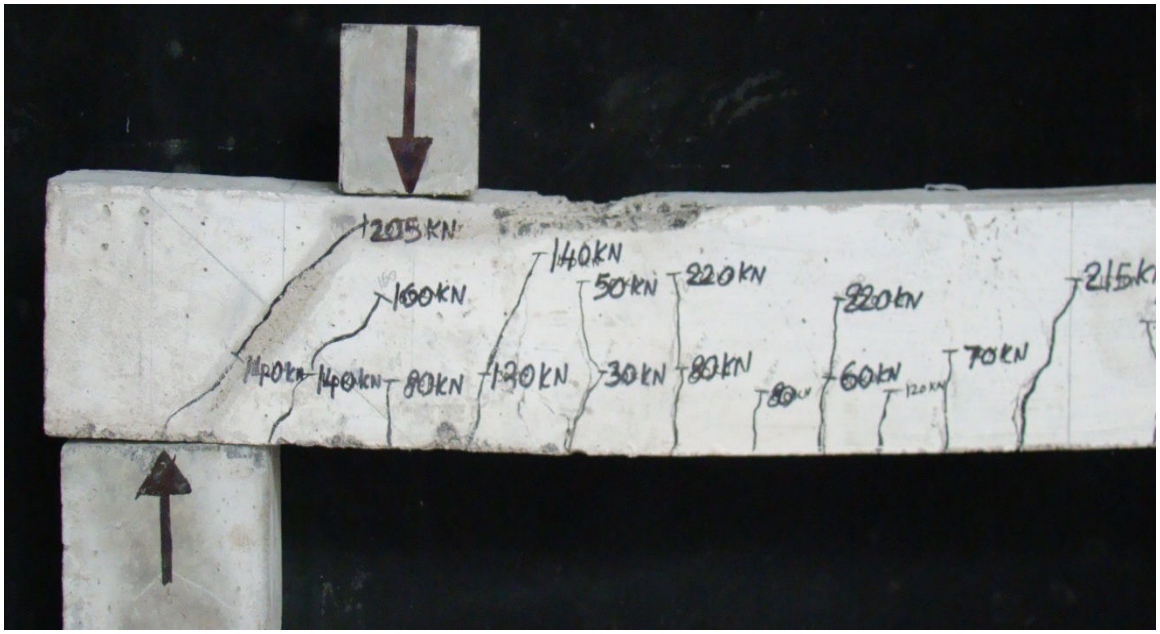


(b) Cracking pattern at failure stage –RPCC BEAM-experimental

Figure 9: Cracking pattern At Failure Stage of RPCC beam –Analytical and Experimental a/d-1.5



(a) Cracking pattern at failure stage –RGPC BEAM-GBFC0015 Analytical



(b) Cracking pattern at failure stage –RGPC BEAM-GBFC0015 Experimental

Figure 10: Cracking Pattern At Failure Stage of GBFC0015 beam–Analytical and Experimental a/d-1.5

5. Conclusions

The experimental and analytical investigations on the shear behavior of geopolymer concrete beams and conventional Portland cement concrete beams were carried out. Based on the analysis of results, the following conclusions are drawn,

1. The load deflection characteristics at mid span of the OPCC beams and GPC beams were found to be almost similar. Also, the GPC beams showed slightly more deflections at the same load than the OPCC beams and underwent higher deflection at failure stage compared to OPCCs.
2. The 3D ANSYS modeling is able to properly simulate the nonlinear behaviour of RPCC and RGPCC beams with shear reinforcement for both shear spans (a/d=1.5). The load-deflection behavior of GPC and RPCC beams observed from experiments and predicted by ANSYS are in good agreement.
3. The ultimate load capacity of the GPC beams was only 15 % more than the OPCC beams inspite of a 20% higher compressive strength.
4. As expected, the shear capacity of the beams was influenced by the av /d ratio and the concrete compressive strength .The shear capacity increased only marginally when the compressive strength of concrete increased and the ultimate moment carrying capacities of beams normalized with respect to compressive strength are of the same order.
5. The test results showed that the cracking load determination methods used for finding cracking moment of OPCC beams GPC beams are inadequate as they are based only on the modulus of rupture. The cracking moment was marginally higher for GPCs but the service load was considerably less compared to OPCCS due to higher deflections caused by their lower elastic modulus
6. The crack patterns observed for both a /d ratio 1.5 and 2 GPC beams were found to be similar to the OPCC beams. The failure modes of all the beam specimens was found to be similar. At early load stages, flexural cracks appeared in the centre portion of the beam, and gradually spread towards the supports. As the load increased existing cracks propagated and new cracks developed along the span.
7. ANSYS 3D concrete element is very good concerning shear crack development but poor concerning the crushing state. It may be possible to overcome the deficiency employing a certain multilinear plasticity model available in ANSYS but the lack of experimental data for material parameters especially GPCs is a drawback. There was a good agreement between experimental and predicted values of deflection, crack pattern and failure modes of GPC and RPC beams.
8. Both the RPCC and RGPC beams behave in the same manner but for some differences in case of RGPC depending on the fly ash content in the binder.
9. Overall, the GPCs were found to perform adequately as structural components and could be considered as a potential candidate material for replacing OPCC.

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