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DEVELOPMENT OF FLY ASH BASED GEOPOLYMER PRECAST CONCRETE ELEMENTS

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ABSTRACT

In view of the serious impact of carbon dioxide on the environment and the continued anticipated growth of industrialization and urbanization, there is a need to redirect the building industry away from its overwhelming reliance on Portland cement by developing alternative binder systems like geopolymer binders. It is proposed that an alkaline liquid could be used to react with the silicon (Si) and the aluminum (Al) in a source material of geological origin or in by-product materials such as fly ash to produce cementitious binders. Experiments have been conducted at Annamalai University, India on the behaviour of fly ash based geopolymer concrete and structural elements such as beams. The mechanical properties of geopolymer concrete such as compressive strength, split tensile strength and flexural strength have been found out and compared with that of ordinary cement concrete. Five beams of size 125 x 250 x 3200 mm were cast and tested. Out of this five beams,one beam is control beam with normal cement concrete and the remaining four are geopolymer concrete beams with Alkali –Activator Solution / Fly ash ratio 0.40, 0.45, 0.50, 0.55 and comparable compressive strength. The alkaline Alkali –Activator Solution used in this study is a combination of sodium hydroxide and sodium silicate. The load-deflection and moment-curvature behaviours obtained from the experimental results are compared with analytical solutions.

Keywords: Fly ash, geopolymer, precast and steam curing

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1. INTRODUCTION

Concrete usage around the world is second only to water. Ordinary Portland Cement (OPC) is conventionally used as the primary binder to produce concrete. The environmental issues associated with the production of OPC are well known. The amount of the carbon dioxide released during the manufacture of OPC due to the calcination of lime stone and combustion of fossil fuel is in the order of 0.825 Ton for every Ton of OPC produced. In addition, the extent of energy required to produce OPC is only next to steel and aluminium. On the other hand, the abundant availability of fly ash worldwide creates opportunity to utilize this by-product of burning coal, as a substitute for OPC to manufacture concrete. In India, 30 percent of power generated is coming from Thermal power stations and the coal available is sufficient for the next two hundred years at the current rate of usage. This ensures the availability of fly ash as a sustainable material.

2. LITERATURE REVIEW

The climate change is not only due to the global warming, but also due to the paradoxical global dimming due to the pollution in the atmosphere. Global dimming is associated with the reduction of the amount of sunlight reaching the earth due to pollution particles in the air, blocking the sunlight. With the effort to reduce the air pollution that has been taken into implementation, the effect of global dimming may be reduced; however it will increase the effect of global warming [1].

The low-calcium (ASTM Class F) fly ash based geopolymer is used as the binder instead of Portland or other hydraulic cement paste, to produce concrete. The fly ash based geopolymer paste binds the loose coarse aggregates, fine aggregates and other unreacted materials together to form the geopolymer concrete, with or without the presence of admixtures [2]. It is well known that alkali activation of aluminosilicates can produce X-ray amorphous aluminosilicates gels or geopolymers with excellent mechanical as well as chemical properties [3]. The structural backbone of these aluminosilicate (geopolymeric) gels has historically been depicted as consisting of a three dimensional frame work of SiO_4 and AlO_4 tetrahedra interlinked by shared O atoms. The negatively charged and tetrahedrally co - ordinate Al (III) atoms inside the network are charge-balanced by alkali metal cations such as Na , K and Ca [4]. These gels can be used to bind aggregates, such as sand or natural rocks, to produce mortars and concretes. In other words, geopolymers are inorganic binders that function as the better-known Portland cement.

The most common alkaline liquid used in geopolymerisation is a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate or potassium silicate. Palomo et al. [5] concluded that the type of alkaline liquid plays an important role in the polymerisation process. Reactions occur at a high rate when the alkaline liquid contains soluble silicate, either sodium or potassium silicate, compared to the use of only alkaline hydroxides.

Xu and Deventer [6] reported that the proportion of alkaline solution to alumino-silicate powder by mass should be approximately 0.33 to allow the geopolymeric reactions to occur. Alkaline solutions formed a thick gel instantaneously upon mixing with the alumino-silicate powder. The specimen size in their study was 20×20×20 mm, and the maximum compressive strength achieved was 19 MPa after 72 hours of curing at 35°C with stilbite as the source material. On the other hand, Jaarsveld et al. [7] reported the use of the mass ratio of the solution to the powder of about 0.39. In their work, 57 percent fly ash was mixed with 15 percent kaolin or calcined kaolin. The alkaline liquid comprised of 3.5 percent sodium silicate, 20 percent water and 4 percent sodium or potassium hydroxide. In this case, they used specimen size of 50×50×50 mm. The maximum compressive strength obtained was 75 MPa when fly ash and builders' waste were used as the source material.

Motivated and enthused by the above works, a detailed study on the development of geopolymer concrete has been initiated at Annamalai University, India. The study comprises of geopolymer material characterization, mix proportioning, basic strength tests and flexural behavior of precast beam elements.

3. EXPERIMENTAL INVESTIGATION

3.1 Material

Low-calcium fly ash has been success fully used to manufacture geopolymer concrete when the silicon and aluminum oxides constituted about 80 percent by mass, with the Si-to-Al ratio of about 2. The content of the iron oxide usually ranged from 10 to 20 percent by mass, whereas the calcium oxide content was less than 5 percent by mass. The carbon content of the fly ash, as indicated by the loss on ignition by mass, was less than 2 percent. Coarse and fine aggregates used by the concrete industry are suitable to manufacture geopolymer concrete.

For the development of geopolymer concrete class F fly ash collected from Mettur Thermal Power Station has been used. The chemical composition of fly ash as determined by XRF (mass percentage) is presented in Table 1. The fly ash and its constituents are shown in Figure1.

Table 1: Chemical composition of fly ash

Compound	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	TiO_2	MgO	P_2O_5	SO_3	*LoI
Percentage (mass)	52.54	26.74	11.12	1.28	0.47	0.82	1.57	0.87	1.53	1.70	1.36

*Loss on Ignition

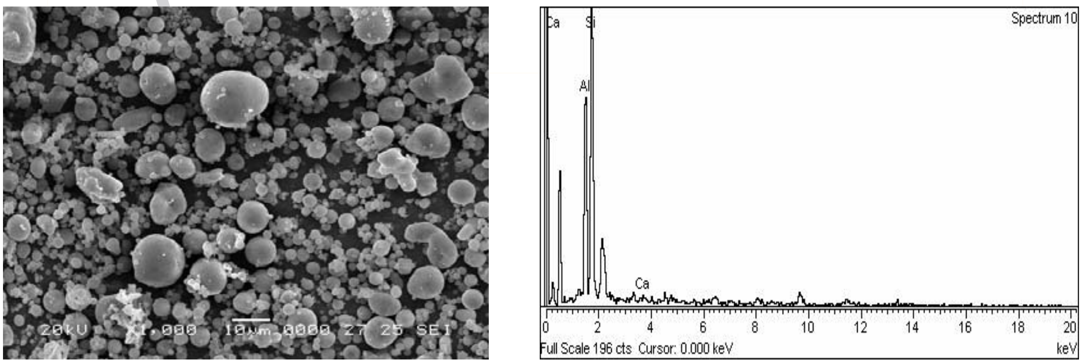

Figure 1. Fly ash and its constituents

Locally available river sand with fineness modulus of 2.72 and specific gravity of 2.64 has been used. Crushed granite coarse aggregates of size ranging from 7 mm to 20 mm have been used at the saturated surface dry condition. A combination of sodium silicate solution and sodium hydroxide (NaOH) solution can be used as the alkaline liquid. It is recommended that the alkaline liquid is prepared by mixing both the solutions together, at least 24 hours prior to use. The sodium silicate solution is commercially available in different grades. The sodium silicate solution with SiO_2-to-Na_2O ratio by mass of approximately 2, i.e., SiO_2 = 29.4 percent, Na_2O = 14.7 percent, and water = 55.9 percent by mass, is generally used.

The sodium hydroxide with 97-98 percent purity, in flake or pellet form, is commercially available. The solids must be dissolved in water to make a solution with the required concentration. The concentration of sodium hydroxide solution can vary in the range between 8 Molar and 16 Molar; however, 8 Molar solution is adequate for most applications. The mass of NaOH solids in a solution varies depending on the concentration of the solution. For instance, NaOH solution with a concentration of 8 Molar consists of 8×40 = 320 grams of NaOH solids per litre of the solution, where 40 is the molecular weight of NaOH. The properties of Sodium Hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions used to desiccate the Silicate and Aluminum compounds in the fly ash have been listed in Tables 2 and 3.

Table 2: Properties of NaOH

Molecular formula	NaOH
Molar mass	39.9971 g/mol
Appearence	White solid
Density	2.13 g/cm^3
Melting point	318°C,591K, 604°F
Boiling point	1388°C,1661K,2350°F
Solubility in water	111 g/100ml
Solubility in ethanol	13.9 g/100ml
Solubility in methanol	23.8 g/100ml
Solubility in glycerol	Soluble
Acidity(pKa)	~13
Refractive Index(nD)	1.412

Table 3: Properties of Na_2 SiO_3

pH value	Neutral
Assay of Na_2O	7.5percent - 8.5percent
Assay of SiO_2	25percent - 28percent
Free alkali	Passes test

3.2 Mix Design and preparation of specimens

3.2.1 Mix Proposition

A mix ratio 1:1.3:2.7 (1 fly ash: 1.3 fine aggregate: 2.7 coarse aggregate) with a water cement ratio of 0.38 has been obtained for normal concrete for a cube compressive strength of 40 N/mm^2 (approximate) by adopting the mix design procedure given in IS 10262-2009

[8]. The same mix ratio has been retained for Geopolymer concrete mix with the replacement of cement with fly ash and water cement ratio with Alkali –Activator Solution / Fly ash ratio. The constituent materials used in the mix for 8 Molarity solutions are shown in Table 4. In this study, various concentrations of NaOH solutions 8M, 10M and 12M were used along with different Alkali –Activator Solution /fly ash ratios 0.40, 0.45, 0.50 and 0.55.

Table 4: Constituents of geopolymer concrete (Per $1m^3$)

Sl. No.	**Mix Ratio**	**Fly Ash kg**	**Fine Agg. kg**	**Coars Agg. kg**	**NaOH Solution**		**Sodium Silicat kg**	**Sodium Silicate / Sodium Hydroxide**	**Alkali –Activator Solution / Fly ash**
					Mass kg	**Molarity**			
1	1:1.3:2.7	450	579.35	1211.9	51.45	8 M	128.63	2.5	0.40
2					57.88		144.68		0.45
3					64.31		160.78		0.50
4					70.74		176.85		0.55

3.2.2 Mixing, casting and curing

The solids constituents of the fly ash based geopolymer concrete, i.e., the aggregates and the fly ash were dry mixed by pan mixer for about three minutes. The wet mixing of liquid mixture of sodium silicate and sodium hydroxide solutions and dry mixture of aggregates usually continued for another four minutes. The slump of this concrete is measured as 80 mm. Then the specimen were covered with vacuum bagging film and cured in steam curing chamber at 60^0 C for 24 hours. The steam boiler and the steam curing chamber are shown in Figures 2 and 3.

Figure 2. Steam boiler and controls

Figure 3. Steam curing chamber

3.3 Strength Tests

The compressive test on hardened fly ash-based geopolymer concrete was performed on a 2000 kN capacity hydraulic testing machine in accordance to the relevant Indian standards**.**

3.3.1 Compressive and tensile Strength of cubes and cylinders

Normal and geopolymer concrete cubes of size 100 ×100 ×100 mm were cast to find out the compressive and tensile strength. Cylinders of size 100 mm diameter x 200 mm height were cast to find out the compressive and split tensile strength. The cubes and cylinders were tested on the seventh day of casting. The test results are shown in Table 5. Each strength value given in this table is the average of results of 8 specimens.

It can be seen from Table 5 that for each Alkali –Activator Solution / Fly ash ratio, NaOH of Molarity 8 gives higher strength. The possible reason for this is when the NaOH concentration is less, polymerization process starts immediately and this increases adhesive action of geopolymer with aggregates. Further, it is observed that the strength parameters increase with increase in Alkali –Activator Solution / Fly ash ratio upto 0.5 and beyond that decreases.

Table 5: Strength of concrete

Sl. No	*Molarities of NaOH*	*Alkali – Activator Solution / Fly ash*	*Cube compressive strength (N/mm^2)*	*Cube Tensile strength (N/mm^2)*	*Cylinder compressive strength (N/mm^2)*	*Cylinder split tensile strength (N/mm^2)*
1	8M	0.40	49.50	9.18	36.18	4.66
2	10M		48.33	10.22	35.83	4.13
3	12M		46.72	8.63	34.92	3.96
4	8M	0.45	50.02	9.37	37.36	5.13
5	10M		49.13	10.56	36.23	4.78
6	12M		47.24	8.69	35.67	4.02
7	8M	0.50	52.08	9.86	38.72	5.48
8	10M		50.73	10.88	37.00	4.97
9	12M		49.26	8.93	36.45	4.24
10	8M	0.55	49.75	9.02	36.27	4.58
11	10M		48.63	10.13	35.54	4.17
12	12M		47.84	8.09	36.13	3.85
13	Normal Concrete		41.89	5.46	30.92	2.53

4. TESTS ON GEOPOLYMER CONCRETE BEAMS

Totally five beams of size 125 x 250 x 3200 mm were cast and tested in the laboratory over an effective span of 3000 mm. Out of this one is control beam made out of normal concrete using ordinary Portland Cement having a mean compressive strength of 41.89 N/mm^2. The remaining four beams are made out of geopolymer concrete as detailed in Table 6. The beams were designed as under reinforced section, reinforced with 2-Y12 at bottom, 2-Y10 at top using 6 mm diameter stirrups at 150 mm c/c and the yield strength of steel used is 451 N/mm^2. Beams were tested in four point bending the maximum stress is present over the center, 1/3 portion of the beam under static monotonic loading which is schematically represented in

Figure 4. Deflections were measured at the 1/3 points and midpoint and strains were measured at the extreme compression fibre and at the level of steel in the middle third zone.

Table 6: Test beam details

Sl. No	Beam Designation	Details
1.	CB	Ordinary concrete beam
2.	GCB1	Geopolymer concrete beam with Alkali –Activator Solution /fly ash ratio 0.4 (NaOH-8M)
3.	GCB2	Geopolymer concrete beam with Alkali –Activator Solution /fly ash ratio 0.45(NaOH-8M)
4.	GCB3	Geopolymer concrete beam with Alkali –Activator Solution /fly ash ratio 0.5(NaOH-8M)
5.	GCB4	Geopolymer concrete beam with Alkali –Activator Solution /fly ash ratio 0.55(NaOH-8M)

Figre 4. Loading set up

The moment - curvature and load - deflection relationships were obtained using deflection measurements from LVDTs and strain data collected from demec gauges for the control beam and geopolymer concrete beams under static monotonic loading, and are presented in Figures 5 and 6. From the load - deflection, it is seen that the geopolymer concrete beams exhibit decreased deflection and appreciable flexural strength when compared to control beam. The first crack loads were obtained by visual examination only. The crack width with respect to load under monotonic condition is shown in Figures 7 and the corresponding crack patterns are shown in Figure 8. Strength and deformation properties of the control beam and geopolymer concrete beams are reported in Table 7.

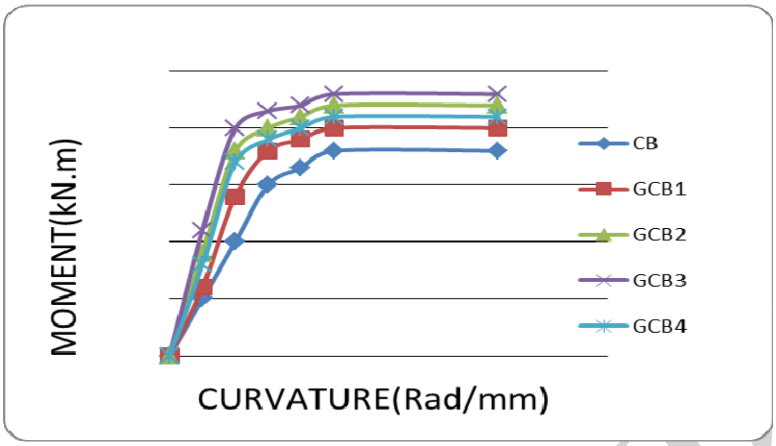

Figure 5. Moment - Curvature relationship

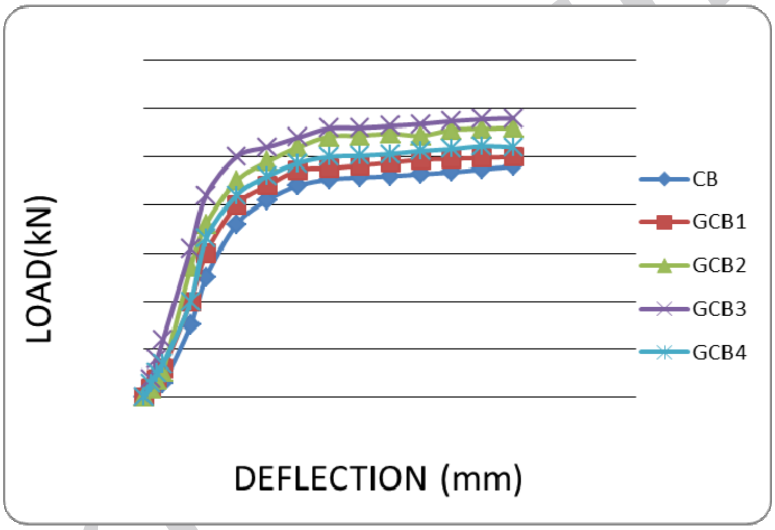

Figure 6. Load - Deflection curve

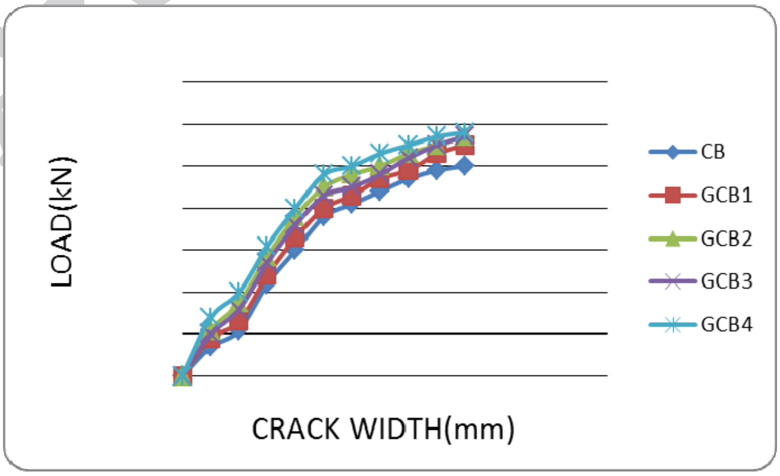

Figure 7.Variation of crack width with load

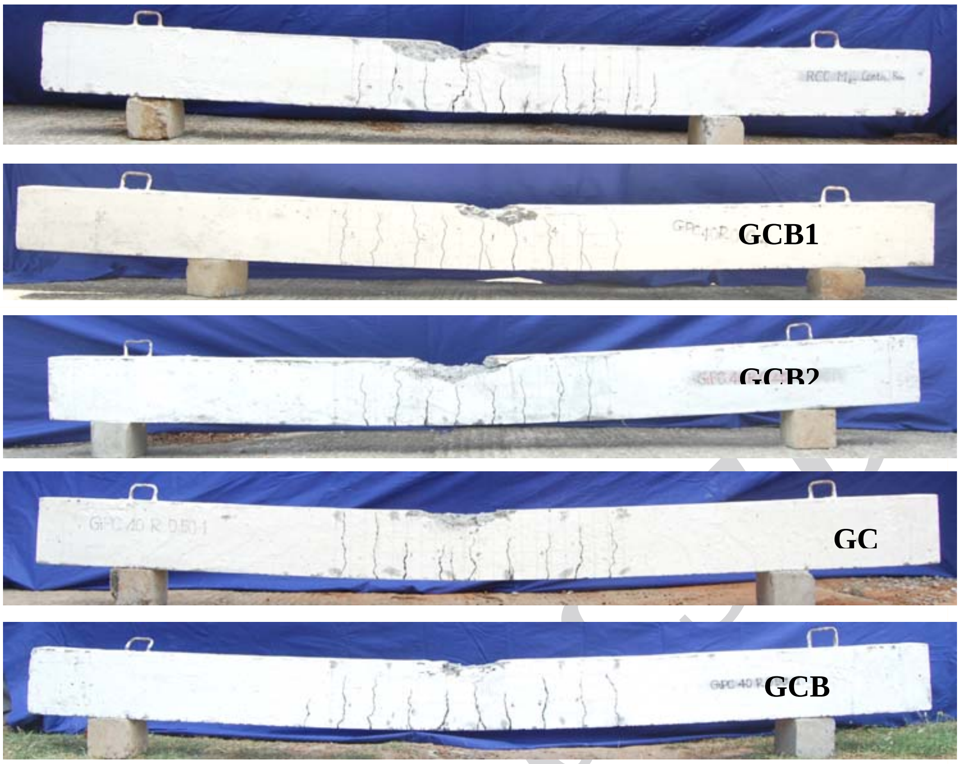

Figure 8. Crack pattern

Table 7: Strength and deformation properties of beams

Beam code	First crack stage		Service stage		Yield stage		Ultimate stage		Average crack width at service load(mm)
	Load (kN)	Central deflection (mm)	Load (kN)	Central deflection (mm)	Load (kN)	Central deflection (mm)	Load (kN)	Central deflection (mm)	
CB	15.00	5.32	30.00	25.50	34.15	21.00	42.75	46.19	0.20
GCB1	32.50	7.28	46.45	41.50	51.50	30.83	62.50	55.37	0.09
GCB2	34.00	7.35	46.75	41.33	52.00	29.85	61.75	58.25	0.11
GCB3	35.00	7.70	47.25	42.15	53.00	31.76	61.00	60.18	0.12
GCB4	37.25	8.64	47.75	42.40	52.50	32.03	61.50	62.28	0.12

5. THEORETICAL LOAD-DEFLECTION BEHAVIOUR (SECTION ANALYSIS)

The theoretical multi-linear moment - curvature (M-∅) relationships were derived for the control beam following the procedure given in Park and Paulay [9]. The three important stages or points identified in the M-∅ curve are the cracking stage, yielding stage, and ultimate stage. In this study one more stage which corresponds to the start of non-linearity in stress - strain curve of steel is proposed and thus making it a multi-linear curve. From the multi-linear M-∅ relationship multi-linear load-deflection curve was derived by adopting a curvature distribution similar to that of a bending moment variation and conjugate beam method of analysis. The same procedure was adopted for geopolymer concrete beams. The experimental and theoretical moment - curvature and load-deflection curves are compared for both control beam (CB) and geopolymer concrete beam GCB1 and are shown in Figures 9 and 10. It can be seen that the predicted deflections are in fairly close agreement with the experimental results.

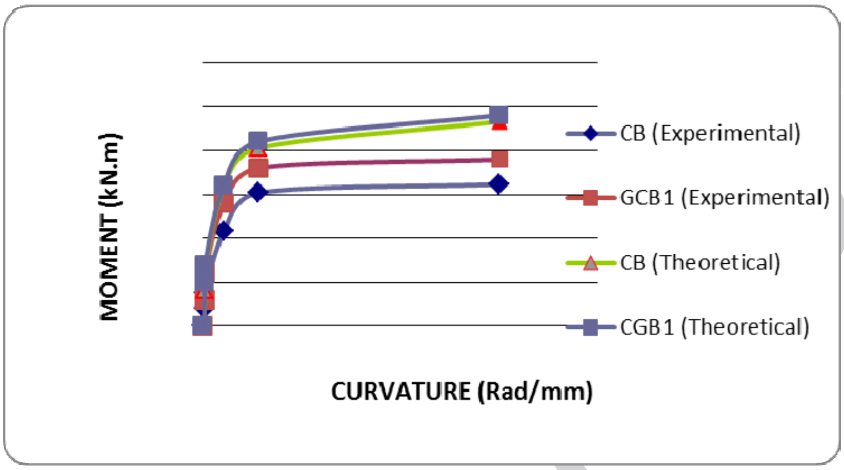

Figure 9. Theoretical moment - curvature curve

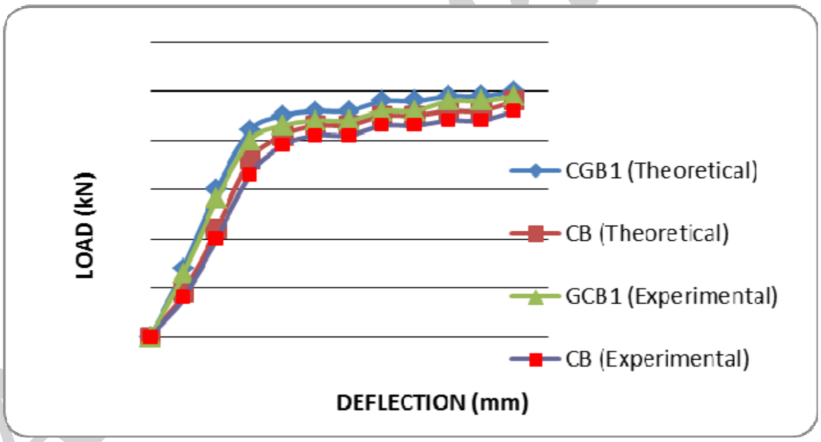

Figure 10. Theoretical load - deflection curve

6. CONCLUSIONS

Following conclusions are made from the limited experimental study reported:

1. Geopolymer Concrete can be developed for structural applications from low calcium fly ash.
2. The strength of Geopolymer Concrete increases with increase in Alkali –Activator Solution / fly ash ratio up to 0.5
3. Geopolymer Concrete with 8 molarity NaOH solution gives higher strength

4. The behaviour of Geopolymer concrete beams are comparable with that of ordinary concrete beams made out of concrete using OPC.

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