Investigation on Fracture Parameters of Geopolymer Concrete

Divya K.K.
(Associate Professor, Department of Civil Engineering, Vedavyasa Institute of Technology, Kerala, India)

Vidya Venugopal
(M.Tech student, Department of Civil Engineering, Vedavyasa Institute of Technology, Kerala, India

ABSTRACT:

This paper aims in determining the fracture properties of geopolymer concrete and comparing their properties with those of ordinary concrete of same grade. Geopolymer concrete of grade M30 was developed after performing various trials and the fracture study was conducted with the final mix. The test results showed that geopolymer concrete exhibited enhanced performance when compared to ordinary concrete of same grade.

Keywords – Crack mouth opening displacement, fracture energy, fracture toughness, geopolymer concrete, three-point bending

I. INTRODUCTION

Concrete is a versatile construction material and is extensively used in civil engineering practice because of its low production cost, formability and much desirable response in compression. Despite its many advantages, it is susceptible to cracking with limited deformation capacity in tension. The severity of the problem varies with the type of structure and importance of the structure. Some inherent disadvantages of OPC are still difficult to overcome. There are two major drawbacks with respect to its sustainability. The production of one tonne of Ordinary Portland Cement (OPC) requires about 1.5 tonnes of raw materials and releases about one tonne of carbon dioxide (CO_2) into the environment. Also concrete made of OPC deteriorates when exposed to the severe environments, either under normal or severe conditions. Cracking and corrosion have significant influence on its service behaviour, design life and safety [1].

The global warming is caused by the emission of greenhouse gases, such as CO_2, to the atmosphere by human activities. The cement industry is held responsible for some of the CO_2 emissions into the atmosphere. Several efforts are in progress to reduce the use of OPC in concrete in order to address the global warming issues. Efforts have, therefore, been made to promote the use of pozzolanas to replace part of Ordinary Portland Cement. Recently another form of cementitious materials using silicon and aluminium activated in a high alkali solution was developed. This material is usually based on fly ash as a source material and is termed geopolymer or alkali activated fly ash cement. They utilize supplementary cementing materials such as fly ash, silica fume, granulated blast furnace slag, rice-husk ash and metakaolin, and the development of alternative binders to Portland cement. The mortar and concrete made from this geopolymer possess similar strength and appearance as those made from Ordinary Portland Cement [2].It is found that heat cured low calcium flyash based geopolymer concrete possess high compressive strength, less drying shrinkage, moderately low creep, and shows excellent resistance to sulphate and acid attack [3].The advantages of Geopolymer Concrete (GPC) are availability of raw material resources, energy saving and environment protection, good volume stability, excellent durability, high fire resistance and low thermal conductivity [4,5].

Fracture Mechanics (FM) deals with the study of behaviour of materials in the presence of cracks and crack like defects and offers convenient means to measure the fracture strength or toughness of the material. The term “fracture mechanics” refers to a vital specialization within solid mechanics in which the presence of a crack is assumed, and we try to find quantitative relations between the crack length, the material’s inherent resistance to crack growth, and the stress at which the crack propagates at high speed to cause structural failure, In quasi brittle materials like concrete, a large Fracture Process Zone (FPZ) is usually formed in front of a crack like defect that consumes large amounts of energy prior to failure. This provides concrete with nonlinear post peak (tension softening) response. The main difficulty in designing against fracture is that the presence of cracks can modify the local stresses to such an extent that the elastic stress analyses by the designers are inaccurate. When a crack reaches a certain critical length, it can propagate catastrophically through the structure, even though the gross stress is much less than would normally cause yield or failure in a tensile specimen. In general, we consider three basic modes for crack growth, Mode I, Mode II and Mode III, although mixed-mode growth is also possible. The three basic loading modes are shown in fig.1. The energy release rates related to these modes are termed GI, GII, and GIII respectively. In mixed mode problems we simply add the energy release rates of different contributing modes to obtain the total energy release rate. The objective of the present work is to determine the fracture parameters of GPC and to compare the results with that of ordinary concrete of the same grade. The final mix of GPC is obtained after conducting various trials. An ordinary Portland Cement Concrete (PCC) of same grade is also designed and prepared as per IS 10262-2009.Three-point bending tests are performed on notched specimens in order to determine the fracture parameters.

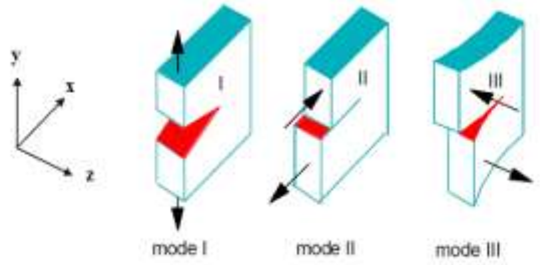


Fig. 1 Three basic loading modes for a cracked

II.EXPERIMENTAL PROGRAMME

The experimental investigation aims at developing a geopolymer concrete of compressive strength 30MPa and comparing its fracture properties with that of ordinary concrete of same grade. With the developed GPC and PPC mixes, a fracture study has been conducted by varying the notch depth to evaluate the fracture properties such as fracture toughness and fracture energy.

A. Constituent Materials

Fly Ash: The binder used in GPC is fly ash. In GPC, cement is completely replaced by flyash. Flyash is a waste product generated by coal burning power plants. Flyash Hitepozzo R-34 grade is the variety of flyash used in the study. The physical and chemical tests were conducted by Pierce Leslie Surveyors and Accessors Ltd. The test results confirm to ASTM C 618 F specifications.

Coarse Aggregate: Coarse aggregate used with nominal size 20 mm was used for making GPC and PCC. Laboratory tests were conducted on coarse aggregate to determine the different physical properties as per IS 2386 (Part –III)-1963.

Fine Aggregate: Locally available river sand was used as fine aggregate. Laboratory tests were conducted on fine aggregate to determine the different physical properties as per IS 2386 (Part –III)-1963. The results depicted that the river sand conformed to zone II as per IS 383.

Cement: Ordinary Portland cement (53 grade) confirming to IS 8112-1989 was used for the experimental programme. Different experiments were conducted to determine initial and final setting time and compressive strength as per 4031-1967. The results confirm to IS 12269-1967 recommendations.

Alkaline Solution: The solution comprises a mixture of sodium silicate solution and sodium hydroxide solution. Commercially available sodium silicate solution A53 with SiO2–to-Na2O ratio by mass of approximately 2, ie., Na2O=14.7%, SiO2=29.4% and water=55.9% by mass, was selected. The sodium hydroxide solution with 97-98% purity is purchased from commercial sources and mixed with water to make a solution of appropriate concentration.

Superplasticizer: The action of superplasticizers in concrete is to reduce the surface tension of water by increasing the wetting ability as well as internal friction of solid components of concrete. The superplasticizer used in the study was Conplast SP 430. The properties of superplasticizer used are given in table 1.

Table 1 Properties of superplasticizer

Property	Value
Specific gravity at 30ºC	1.25
Chloride content	Nil
Air entrainment	1 to 2 %

B. Mix Design

Since there is no code recommendation for the design of GPC, the mix design was done by performing various trials. Mix proportion corresponding to a compressive strength of 30MPa was adopted from the trial mixes. For the first trial mix, the mass of combined aggregates was between 75% and 80% of the mass of geopolymer concrete. The alkaline liquid to fly ash ratio by mass was chosen in the range of 0.3 to 0.45. The ratio of sodium silicate to sodium hydroxide solution by mass was taken as 2.5.

The coarse aggregates and the sand in saturated surface dry condition were first mixed in laboratory pan mixer with the fly ash for about three minutes. At the end of this mixing, the alkaline solutions together with the super plasticizer and the extra water were added to the dry materials and the mixing continued for another four minutes. The appearance of GPC was similar to that of PCC. Immediately after mixing, the fresh concrete was cast into the moulds. All specimens were cast horizontally in moulds in three layers. Each layer was compacted using a tamping rod. The slump and compaction factor of fresh concrete was also measured in order to observe the consistency of the mixtures. For GPC, no water curing is required. Temperature curing for 1 day was sufficient. After casting, all specimens were kept at room temperature for one to two days. After that, the specimens were placed inside the oven and cured at 60oC for 24 hours. After curing, the specimens were removed from the chamber and left to air-dry at room temperature for another 24 hours before demoulding. The test specimens were then left in the laboratory ambient conditions until the day of testing. The final mix proportion for GPC and PCC is given in table 2.

Table 2 Final mix proportion for GPC and PCC

Materials	**GPC Mass (kg/m^3)**	**PCC Mass (kg/m^3)**
Coarse aggregates	1294	1140
Fine aggregates	554	700
Fly ash	408	Nil
Cement	Nil	360
Sodium silicate solution	103	Nil
Sodium hydroxide solution	41	Nil
Superplaticizer	10	10
Water	22.5	170

C. Fracture Test

For the fracture study, three-point bending tests were performed on notched beam specimens. To study the effect of notch depth, the notch depth was varied and notched specimens were prepared with notch depth to depth (a/W) ratio 0.3, 0.4 and 0.5 (notch depth 30, 40 and 50 mm). The fracture parameters such as fracture toughness and fracture energy were determined. Fracture energy is defined as the consumed energy divided by newly generated fracture surface or it can also be defined as the energy absorbed to create a unit area of the fracture surface. The size of beam is 100 x100 x 500 mm with an effective span of 400 mm. The ratio of span to depth is 4. The specimen details with notch depth to depth ratio 0.5 is shown in fig. 2. The test setup is shown in fig. 3 and the loading arrangement is shown in fig. 4. During testing, the central deflection and Crack Mouth Opening Displacement (CMOD) were measured. The deflection was noted using the dial gauge and the CMOD was noted using the LVDT.

Fracture energy is determined as below

$$G_f = \frac{W_0 + mg\delta_{\max}}{A_{lig}} \qquad (1)$$

where,

W_0 – area under load deflection curve (Nm)
mg – self weight of the specimen between supports (kg)

δ_{max} – maximum displacement (m)
A_{lig}, - fracture area = [W (B-a)] (m^2)
B, W- width and height of beam
a -depth of notch

The critical stress intensity factor (KIC), has in the past been used to represent the fracture toughness. Fracture toughness is determined as below

$$K_{IC} = 6YM_{max}\frac{\sqrt{a}}{BW^2} \tag{2}$$

where,

Y – function of geometry
Mmax = M1 + M2
M1 – bending moment due to the applied load
M2 – bending moment due to self-weight of the beam
B – width of beam
W – depth of beam
a – notch depth

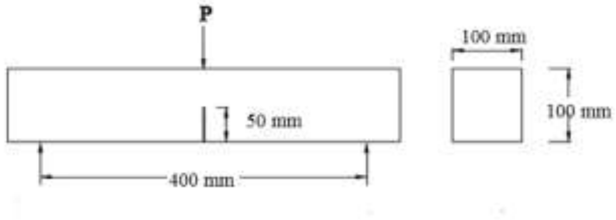


Fig. 2 Specimen Details

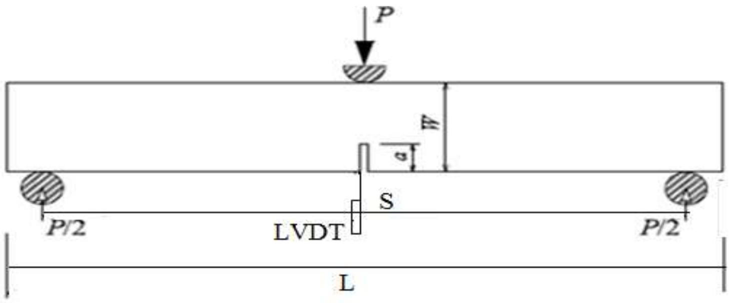


Fig. 3 Test Setup

Fig. 4 Loading Arrangement

III. RESULTS AND DISCUSSIONS

To determine the fracture parameters of notched specimens, three-point bending tests were performed on beam specimens. The observations made were load-deflection curves, load-CMOD curves, first crack load, ultimate load, energy absorption capacity, stiffness, deflection ductility and the fracture parameters.

A. Load Deformation Behaviour

The mid span deflections were noted with the help of dial gauge at 10 kg intervals. The load deflection curves for PCC are shown in fig. 5 and the load deflection curve for GPC is shown in fig. 6. The comparison of deflections is shown in fig.7. From the test results it was observed that GPC had more load carrying capacity compared to PCC. When the notch depth increased, the load carrying capacity and stiffness of the both GPC and PCC specimens decreased. CMOD was also measured with the help of LVDT. The load CMOD curves for PCC is shown in fig. 8 and the load CMOD curve for GPC is shown in fig. 9. From the results, it was observed that when the load increased, CMOD also increased. When the notch depth decreased, the load carrying capacity decreased and the CMOD decreased. The comparison of load-CMOD curves is shown in fig. 10.

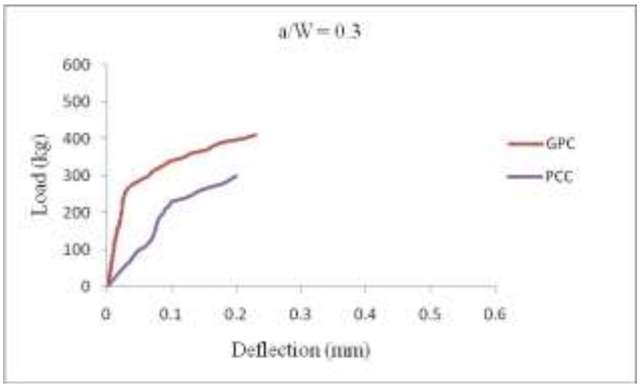
B. First Crack Load and Ultimate Load

The first crack load and the ultimate load were observed for all the specimens. The first crack load denotes the point where the load deflection tends to change from the linear behaviour. The details regarding the first crack load, ultimate load and the mode of failure are tabulated in table 3. From the results it was observed that the load carrying capacity was more for GPC when compared to PCC.

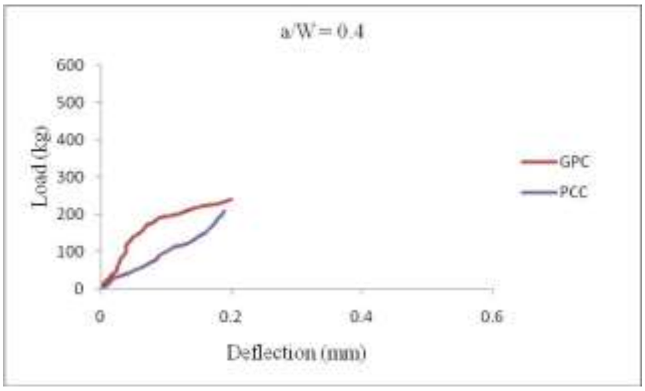
When compared to PCC, the increase in first crack load for GPC was 50 to 70% and that for ultimate load was 10 to 20%. It was also observed that as the notch depth increased, the load carrying capacity decreased. When the notch depth was increased from 30 to 40 mm, the load carrying decreased to 65% for GPC and 45% for PCC.

C. Ductility

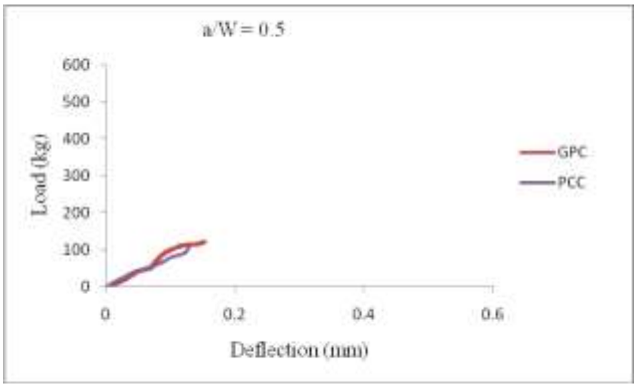
The ductility factor was also determined and it was defined as the ratio of deflection at ultimate load to deflection at yield load. The values are tabulated in table 4.GPC was found to be more ductile compared to PCC. The increase in ductility is due to the effective bond and confinement between the particles. The ductility factor for GPC was found to be 2 times that for PCC. The stiffness for GPC was found to be 1.5 times that for PCC. When the notch depth increased, the stiffness was found to decrease for all the specimens. When the notch depth was increased from 30 to 40 mm, the decrease in stiffness and ductility were by a factor of 1.3 and 1 for PCC and 1.5 and 1.86 for GPC.



(i) a/W ratio 0.3



(ii) a/W ratio 0.4



(iii) a/W ratio 0.5

Fig. 7 Comparison of load-deflection curves with a/W ratio 0.3, 0.4 and 0.5

D. Fracture Parameters

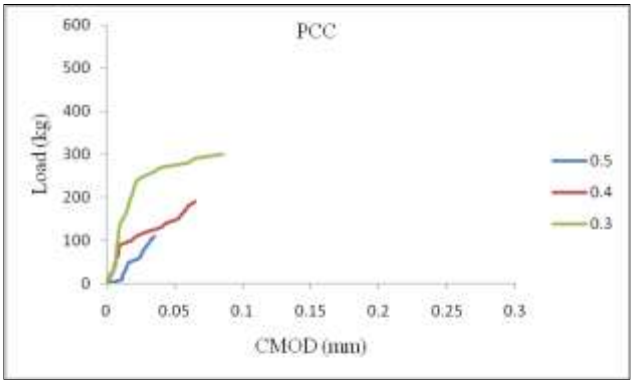


Fig. 8 Load-CMOD curves for PCC

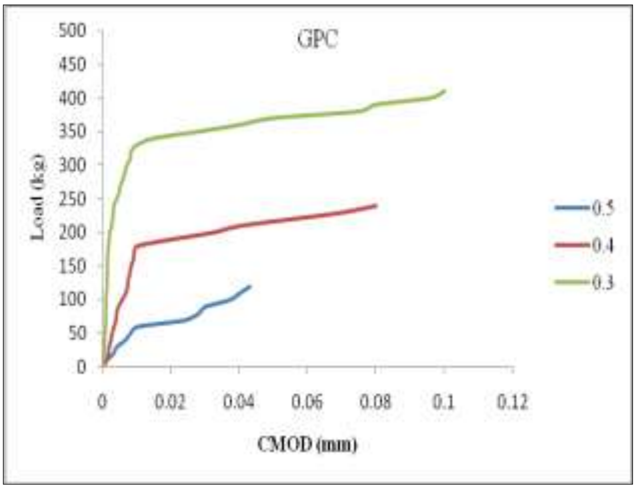


Fig.9 Load-CMOD curves for GPC

Table 4 Ductility Factor

Specimen	Ultimate load (N)	Ductility factor	Stiffness, k (x10^6) (N/m)
PCC 0.3	2943	2.17	14.715
GPC 0.3	4022.1	4.26	17.487
PCC 0.4	2109.15	2.11	11.101
GPC 0.4	2403.45	2.44	12.017
PCC 0.5	1079.1	1.43	8.301
GPC 0.5	1255.68	1.5	8.371

The fracture parameters such as fracture toughness and fracture energy were calculated after doing the three-point bending tests on notched specimens. The central deflection and CMOD were measured with the help of dial gauge and LVDT. The observations were noted and the fracture parameters were calculated using the equations. The values of peak CMOD, fracture toughness and fracture energy are shown in table 5. From the test results, it was observed that the fracture toughness and fracture energy was more for GPC compared to PCC. When the notch depth increased, the fracture toughness and fracture energy decreased. As the notch depth increased, the load carrying capacity and the ductility decreased. Therefore, the fracture toughness decreased. When compared to PCC, the increase in fracture toughness for GPC was around 40%. When the notch depth increased, the decrease in fracture toughness was almost 10% for all the mixes. The fracture energy was a measure of the energy absorption capacity for the notched specimens. The fracture energy was more for GPC compared to PCC. Increase in notch depth of a structure required less fracture energy for extending the crack. A decrease in fracture energy for crack extension indicated the brittleness of the structure. It can be concluded that a crack present in a structure caused brittle failure when the notch depth increased.

E. Failure Pattern

The failure patterns observed were flexural cracks for all the specimens starting from the notch depth and continuing up to the top of the beam. The failure pattern observed for GPC and PCC were almost similar. They split up into two halves after attaining the ultimate load. The typical fracture pattern of GPC beam is shown in fig. 11.

F. Analytical Study

The fracture parameters obtained from experiments were analytically validated by modeling the notched specimens in ANSYS 11. The results obtained were almost similar and the percentage variation was around 10 to 20. The results are shown in table 6.

Table 5 Fracture Parameters

Specimen	Fracture toughness $(MPa\sqrt{m})$	Fracture energy (N/m)
PCC 0.3	0.5742	53.217
GPC 0.3	0.7814	105.217
PCC 0.4	0.4108	26.045
GPC 0.4	0.6117	56.431
PCC 0.5	0.3944	27.581
GPC 0.5	0.5383	9.773

Fig. 11 Failure pattern of GPC beam

Table 6 Stress intensity factor

Sl. No.	Specimen	Stress Intensity Factors	
		Analytical	Experimental
1.	PCC 0.3	0.5234	0.5742
2.	GPC 0.3	0.7465	0.7814
3.	PCC 0.4	0.5115	0.5383
4.	GPC 0.4	0.5829	0.6117
5.	PCC 0.5	0.3197	0.3944
6.	GPC 0.5	0.3336	0.4108

V. CONCLUSION

From the present study, the following conclusions were made,

- The load carrying capacity was found to be more for GPC than PCC for all notch depth. When the notch depth increased, the load carrying capacity, deflections and CMOD were found to be decreasing for GPC and PCC.
- When compared to PCC, the increase in ultimate load was 15 to 25% for GPC.
- The ductility was found to be more for GPC compared to PCC. The energy absorption capacity and thus the fracture energy for GPC was 2 times that for PCC. When the notch depth increased, these properties were found to be decreasing.
- The fracture toughness for GPC was found to be 20 to 30% increasing when compared to PCC.

- The fracture toughness obtained from experiment was finally compared with analytical results. The analytical results were found to be less and almost comparable with that of experiments and thus it was validated.

It was concluded that GPC exhibited better mechanical properties and excellent durability compared to ordinary concrete of same grade. The fracture parameters were also found to be superior for GPC compared to PCC. Therefore, GPC can be considered as an environment friendly alternative for PCC for certain constructions.

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