Fracture Properties of Fibre Reinforced Geopolymer Concrete

Deepa Raj S., Ruby Abraham, N. Ganesan, Divya Sasi

Abstract— The global demand of concrete for construction of infrastructures is continuously increasing in order to maintain the ongoing growth and to accommodate the needs of the increasing population. The production of cement is highly energy intensive and it emits a lot of CO_2 into the air which adds to global warming. One of the efforts to produce more environment friendly concrete is to reduce the use of ordinary Portland cement (OPC). Geopolymer concrete (GPC) is a 'new' concrete that does not need cement for its production. This is usually based on fly ash as a source material. The behaviour of GPC has to be studied in detail to check its suitability in construction industry.In the present study, the influence of the volumetric fraction of steel fibers on the fracture behaviour of geopolymer concrete was investigated. Three-point bending test on notched prisms with a/W (notch depth/beam depth) ratio equal to 0.4 was used. The values of ultimate load, fracture toughness, fracture energy, ductility and critical crack mouth opening displacement were measured. A total of 24 specimens were prepared using M30 grade geopolymer concrete and conventional concrete (PCC) of same grade and the fibre content was varied from 0 to 0.75% with an increment of 0.25%. According to the experimental results, geopolymer concrete exhibited enhanced fracture properties compared to conventional concrete of the same grade.

Index Terms— CMOD, Ductility, Fracture energy, Fracture parameters, Fracture toughness, Geopolymer concrete, Stress intensity factor.

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1 INTRODUCTION

CONCRETE is a versatile construction material and is extensively used in civil engineering practice. Ordinary Portland Cement (OPC) is conventionally used as the primary binder to produce concrete. Some inherent disadvantages of OPC are still difficult to overcome. There are two major drawbacks with respect to its sustainability. The amount of CO_2 released during the manufacture of OPC due to the calcination of limestone and combustion of fossil fuel is in the order of one ton for every ton of OPC produced. i.e., the contribution of OPC production worldwide to the greenhouse gas emission is estimated to be about 7% of the total greenhouse gas emission to the earth's atmosphere. Cement is also among the most energy intensive construction materials after aluminium and steel. 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].

On the other scenario, the abundant availability of fly ash worldwide creates opportunity to utilise this by-product of burning coal, as a substitute for OPC to manufacture concrete. The development and application of high volume fly ash concrete, which enabled the replacement of OPC up to 60% by mass is a significant development. In 1978, Davidovits proposed that binders could be produced by a polymeric reaction of alkaline liquids with the silicon and aluminum in source materials of geological origin or by-product materials such as fly ash and rice husk ash. He termed these binders as geopolymers to represent the mineral polymers resulting from geochemistry. Geopolymers have emerged as novel engineering materials with the potential to form a substantial element of an environmentally sustainable construction and building products industry. They have a very small greenhouse footprint when compared to traditional concrete, and since they utilize abundantly available wastes they are also economic [2], [3].

The requirements imposed on construction materials are so demanding and diverse that no material is able to satisfy them completely. This has led to a resurgence of the ancient concept of combining different materials in a composite material to satisfy diverse user requirements. Several studies have shown that fiber reinforced composites are more efficient than other types of composites. The main purpose of the fibre is to control cracking and to increase the fracture toughness of the brittle matrix through bridging action during both micro and macro cracking of the matrix. Debonding, sliding and pulling-out of the fibers are the local mechanisms that control the bridging action. In the beginning of macro cracking, bridging action of fibers prevents and controls the opening and growth of cracks. This mechanism increases the demand of energy for the crack to propagate. The linear elastic behavior of the matrix is not affected significantly for low volumetric fiber fractions. However, post-cracking behavior can be substantially modified, with increases of strength, toughness and durability of the material [4], [5], [6].

Fracture mechanics is the field of solid mechanics concerned with the study of the propagation of cracks in materials and the 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 consume large amount of energy prior to failure. This provides concrete with non-linear 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 that would

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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. Mode I is the opening mode and the displacement is normal to the crack surface. Mode II is a sliding mode and the displacement is in the plane of the body- the separation is antisymmetric and the relative displacement is normal to the crack front. Mode III also causes sliding motion but the displacement is parallel to the crack front, thereby causing tearing [7].

The objective of the present work is to determine the fracture parameters of Fibre Reinforced GPC (FRGPC) of M30 grade and to compare the results with that of conventional fibre reinforced concrete (FRC) of the same grade. The fracture parameters include fracture energy (G_f), Critical stress intensity factor (K_{IC}) and Crack Mouth Opening Displacement (CMOD). G_f is the amount of energy necessary to create a crack on unit surface area projected in a plane parallel to the direction of propagation of crack. It is calculated by the equation (1) [7]. Stress intensity factor is defined to quantify the stresses at the crack tip. A material fails by fracture when the stress intensity factor reaches a critical value K_{IC}, called fracture toughness which is given by the equation (2) [8].These fracture parameters were determined by conducting three point bending test on notched prisms.

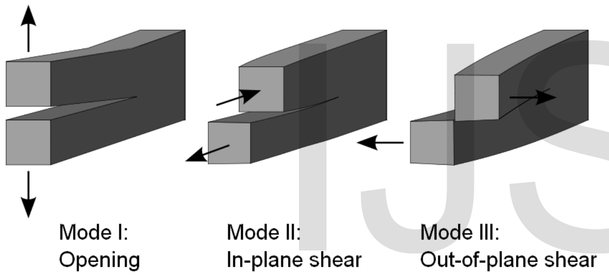

Fig.1. The basic loading modes for a cracked body

2 EXPERIMENTAL PROGRAMME

An experimental investigation was carried out to develop geopolymer mix (GPC) and conventional concrete mix (PCC) of grade 30MPa. Corresponding fibre reinforced geopolymer concrete (FRGPC) and fibre reinforced conventional concrete (FRC) mixes were also developed. With the developed GPC, PCC, FRGPC and FRC mixes, a fracture study has been conducted by using notched prisms. The variable considered in this study is volume fraction of fibres.

2.1 Materials Used

1) *Fly Ash:* In GPC, cement is completely replaced by low calcium fly ash (CaO-2.14%). The test results conform to ASTM C 618 F specifications.

2) *Coarse Aggregate*: Coarse aggregate of 20 mm nominal size was used for making the specimens. Laboratory tests were conducted on coarse aggregate to determine the different physical properties as per IS 2386 (Part –III)-1963 (Reaffirmed on 1997).

3) *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 (Reaffirmed on 1997). The results depicted that the river sand conformed to zone II as per IS 383-1970 (Reaffirmed on 1997)..

4) *Cement*: Ordinary Portland cement of 53 grade conforming to IS 12269-1987 was used for the experimental programme. Various experiments were conducted to determine the initial and final setting time and compressive strength.

5) *Alkaline Solution*: A combination of sodium silicate solution and sodium hydroxide solution was chosen as the alkaline liquid. The sodium hydroxide solids were purchased from commercial sources in pellets form with 97-98% purity and mixed with water to make a solution of appropriate concentration. Commercially available sodium silicate solution with SiO_2–to-Na_2O ratio by mass of 2 (Na_2O=14.7%, SiO_2=29.4%) and water = 55.9% by mass, was used for the study.

6) *Super Plasticiser*: The action of super plasticisers (SP) 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 properties of super plasticizer used are given in Table 1.

TABLE 1
PROPERTIES SUPER PLASTICIZER

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

7) *Steel fibre*: Steel fibres with aspect ratio 60 were used and the properties of the steel fibres are given in Table 2.

TABLE 2
PROPERTIES OF STEEL FIBRES

Property	Value
Length (mm)	30
Diameter (mm)	0.5
Aspect ratio	60
Specific gravity	7.8
Elastic modulus (N/mm^2)	2x10^5

2.2 Mix Design

Since there is no codal recommendation for the design of GPC, the mix design was done by trial and error method. Mix proportion corresponding to a compressive strength of 30MPa was adopted from the trial mixes. A mix design for M30 grade PCC was also done as per IS 10262-2009 for comparison. The final mix proportions for GPC and PCC with different fibre contents are given in Table 3.

TABLE 3
MIX PROPORTIONS OF DIFFERENT MIXES

Mix	Cement (kg/m³)	Fly ash (kg/m³)	Sodium Silicate Solution (kg/m³)	Sodium hydroxide (kg/m³)	CA (kg/m³)	FA (kg/m³)	Water (kg/m³)	SP (kg/m³)	Fibre content (%)
GPC	-	408	103	41	1294	554	22.5	10	0.00
FRGPC1	-	408	103	41	1294	554	22.5	10	0.25
FRGPC2	-	408	103	41	1294	554	22.5	10	0.50
FRGPC3	-	408	103	41	1294	554	22.5	10	0.75
PCC	360	-	-	-	1140	700	170	10	0.00
FRC1	360	-	-	-	1140	700	170	10	0.25
FRC2	360	-	-	-	1140	700	170	10	0.50
FRC3	360	-	-	-	1140	700	170	10	0.75

For the first trial mix, the mass of combined aggregates was between 75% and 80% of the mass of geopolymer concrete and the alkaline liquid to fly ash ratio by mass was chosen in the range of 0.3 to 0.45 as in [1]. The molarity of sodium hydroxide solution was selected as 10M and the ratio of sodium silicate to sodium hydroxide solution by mass was taken as 2.5.

2.3 Casting of Specimens

The coarse aggregates and the sand in saturated surface dry condition were first mixed in laboratory pan mixer with the fly ash and steel fibre for about three minutes. At the end of this mixing, the alkaline solutions together with the super plasticiser and the extra water were added to the dry materials and the mixing was continued for another four minutes. Immediately after mixing, the fresh concrete was filled in the moulds. All specimens were cast horizontally 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 one day is sufficient. After casting, all specimens were kept at room temperature for one day. After that, the specimens were placed inside the oven and cured at 60°C 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. In the case of PCC, all the specimens were kept for water curing.

2.4 Fresh and Hardened Concrete Properties

The workability of all the mixes was determined by conducting slump test and compacting factor test. The compressive strength of hardened concrete mixes were determined by testing cubes of size 150mmx150mmx150mm on a compression testing machine in accordance to the IS Standards.

2.5 Fracture Test

For the fracture study, three point bending tests were performed on notched beam specimens with 3mm notch width and notch depth to total depth (a/W) ratio 0.4 (notch depth = 40mm). 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 100mm x100mm x 500 mm with an effective span of 400 mm. The test setup is shown in Fig. 2 and the loading arrangement is shown in Fig. 3. During testing, the central deflections were noted using the dial gauge and Crack Mouth Opening Displacement (CMOD) was noted using the LVDT.

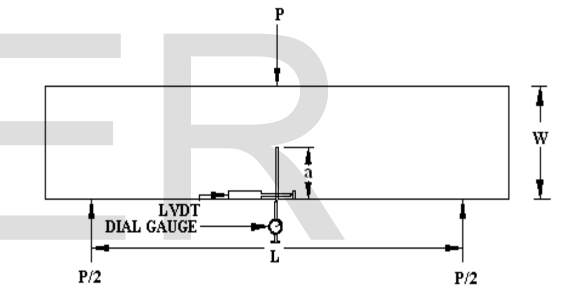

Fig. 2 Test Setup

Fig. 3 Loading Arrangement

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Fracture energy is determined using the following equation,

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

Where,

W_0 – area under load deflection curve (Nm)
mg – self weight of the specimen between supports (N)
$\delta_{\max}$ – maximum displacement (m)
A_{lig} – fracture area = [B (W-a)] (m^2)
B, W – width and depth of beam (m)
a – depth of notch (m)

The critical stress intensity factor (K_{IC}), has been used to represent the fracture toughness. Fracture toughness is determined using the following equation,

$$K_{IC} = \frac{PS}{BW^{3/2}} f(\alpha) \quad (2)$$

Where *f(α)* is determined using the equation,

$$f(\alpha) = \frac{3\alpha^{1/2}[1.99 - \alpha(1-\alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)]}{2(1+2\alpha)(1-\alpha)^{3/2}} \quad (3)$$

α – a/W
S – Span of the beam
P – Applied Load

3 RESULTS AND DISCUSSIONS

The observations made during the tests (Load-deflection, Load-CMOD) were used to draw the load-deflection curves and load-CMOD curves. The first crack load, ultimate load, and the fracture parameters were determined.

3.1 Fresh and Hardened Concrete Properties

The workability and compressive strength of all the mixes were tabulated in Table 4. From the test results, it was found that the workability of the mixes decreased as the fibre content increased.

TABLE 4
FRESH AND HARDENED PROPERTIES

Mix Designation	Slump (mm)	Compacting Factor	Compressive Strength (N/mm^2)
GPC	140	0.93	39.0
FRGPC1	123	0.9	41.5
FRGPC2	93	0.88	42.3
FRGPC3	80	0.84	43.7
PCC	128	0.92	35.2
FRC1	93	0.9	37.1
FRC2	80	0.85	39.5
FRC3	76	0.81	40.2

3.2 Load - Deformation Behaviour

The mid span deflections were noted with the help of dial gauge at 100 N intervals. The load deflection curves for GPC and PCC with 0 to 0.75% fibre content is shown in Fig. 4. From the test results it was observed that GPC had more load carrying capacity compared to PCC. When the fibre content increased, the load carrying capacity also increased.

3.3 Load – CMOD Behaviour

CMOD was also measured with the help of LVDT mounted across the notch. The load - CMOD curves for GPC and PCC with 0 to 0.75% fibre content is shown in Fig. 5. From the results, it was observed that when the fibre content increased, the CMOD also increased.

3.4 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. First crack load increased with increase in fibre content, which is due to the increase in tensile strain carrying capacity of concrete in the neighbourhood of fibres. This has lead to improvement in load carrying capacity. The first crack load and ultimate load for all the specimens were tabulated in Table 5. Results show an increase of up to 120% in first crack load for specimens with 0.75% fibres. When compared to PCC, the increase in first crack load for GPC was 60 to 70%.

From the table it was also observed that the load carrying capacity was more for GPC than PCC. Results show an increase of up to 180% in ultimate load for specimens with 0.75% fibres. When compared to PCC, the increase in ultimate load for GPC was 10 to 20%. As fibre content increased, load carrying capacity was also found to be increased. The ultimate loads for FRGPC1, FRGPC2 and FRGPC3 were 1.78, 2.24 and 2.8 times respectively that of GPC. The ultimate load for FRGPC1, FRGPC2 and FRGPC3 specimens are 6, 18 and 42% more than that of FRC1, FRC2 and FRC3 respectively.

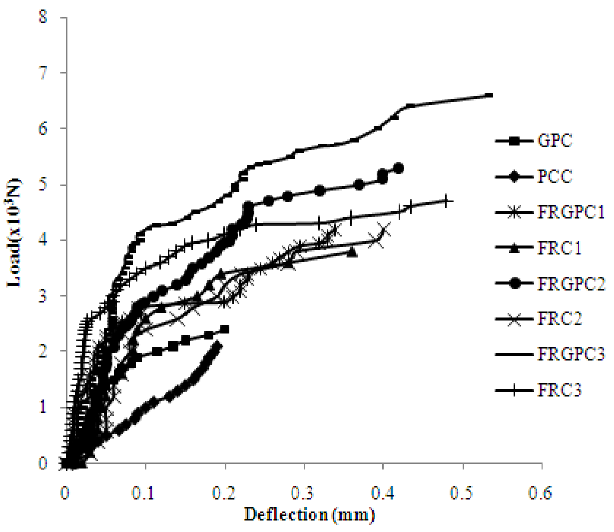


Fig. 4 Load - deflection curves

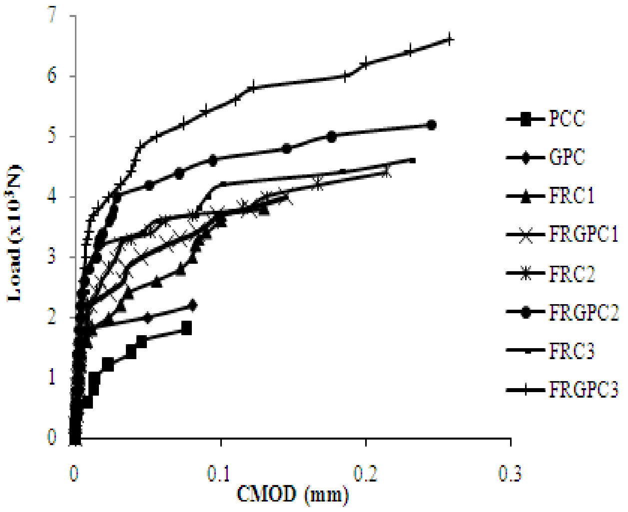
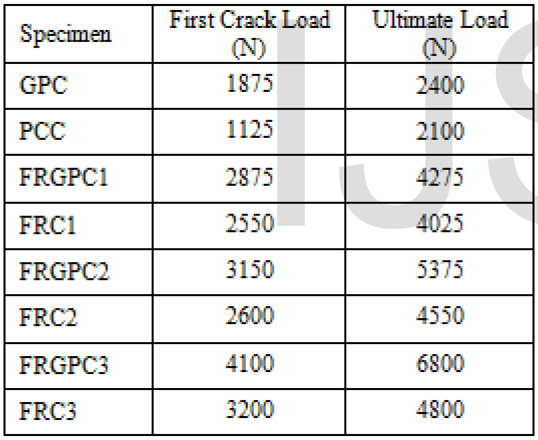


Fig. 5 Load - CMOD curves

3.5 Fracture Parameters

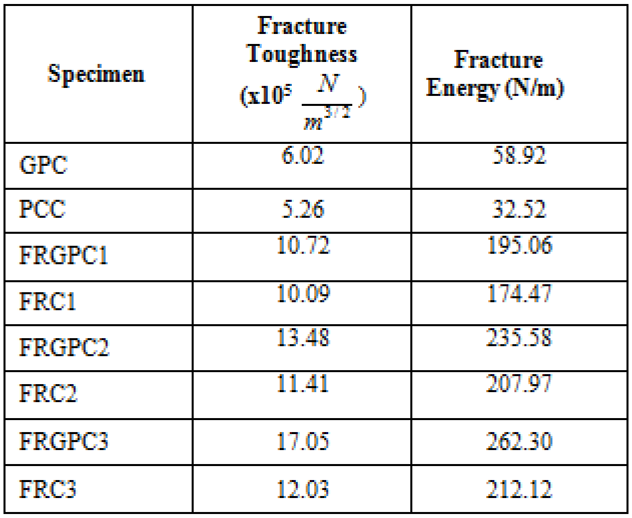
TABLE 5
FIRST CRACK LOAD AND ULTIMATE LOAD



Specimen	First Crack Load (N)	Ultimate Load (N)
GPC	1875	2400
PCC	1125	2100
FRGPC1	2875	4275
FRC1	2550	4025
FRGPC2	3150	5375
FRC2	2600	4550
FRGPC3	4100	6800
FRC3	3200	4800

The fracture parameters such as fracture toughness and fracture energy were calculated using the equations. The values of fracture toughness and fracture energy are shown in Table 6. From the test results, it was observed that the fracture toughness and fracture energy were more for GPC compared to PCC in all fibre contents. When compared to PCC, the increase in fracture toughness for GPC was around 14%. As the fibre content increased, the fracture toughness and fracture energy were also found to be increased for both GPC and PCC and the values for PCC and GPC with 0.75% fibre content were 2.3 and 2.8 times that of concrete without fibre. The fracture energy was a measure of the energy absorption capacity for the notched specimens. The fracture energy was 80% more for GPC compared to PCC. When fibre content increased, fracture energy also increased in the case of both PCC and GPC. Addition of 0.25, 0.5 and 0.75% steel fibre resulted in an increase of fracture energy by 3.3, 4 and 4.5 times compared to GPC without fibre. When fibres are added to concrete, crack propagation gets arrested which results in requirement of more energy. Fracture energy for FRGPC specimens were 10 to 40% more than that of FRC specimens.

TABLE 6
FRACTURE PARAMETERS



Specimen	Fracture Toughness $(\text{x}10^5 \frac{N}{m^{3/2}})$	Fracture Energy (N/m)
GPC	6.02	58.92
PCC	5.26	32.52
FRGPC1	10.72	195.06
FRC1	10.09	174.47
FRGPC2	13.48	235.58
FRC2	11.41	207.97
FRGPC3	17.05	262.30
FRC3	12.03	212.12

4 CONCLUSION

From the study conducted, the following conclusions were made,

- The load carrying capacity, deflections and CMOD of GPC are more than that of PCC at ultimate stage.
- The first crack load and ultimate load of GPC are 60-70% and 10-20% respectively more than that of PCC. An increase in fibre content by 0.0 to 0.75% increased the ultimate load of GPC by 1.78 to 2.8 times. The ultimate load for FRGPC specimen with 0.75% fibre content was 42% more than that of FRC specimens with same fibre content.
- The fracture energy for GPC is 80% more than PCC. An increase in fibre content increased the fracture energy of both GPC & PCC. FRGPC specimens exhibited 10 - 40% more fracture energy than FRC specimens.
- GPC exhibited 10-40% more fracture toughness than PCC. An increase in fibre content increased the fracture toughness.

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