Fracture properties of OPC included ambient cured geopolymer concrete by size effect method

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Abstract. This paper presents the details of experimental study on the fracture properties of high strength geopolymer concrete. The geopolymer concrete prepared in this study was cured in ambient temperature. This was achieved by adding small amount of OPC in the mixture. A total of 42 notched beam specimens with varying span to depth ratio (l/d) between 8 and 6 and notch depth to total depth ratio (a₀/d) between 0.2 and 0.4 was cast. All beam specimens were tested under three point bending test. The fracture properties, namely, fracture energy (G_f), critical stress intensity factor (K_{ic}), process zone length (c_f), and crack tip opening displacement corresponding to peak load (δ_c) were determined by size effect law (SEL). The results show that the fracture properties of ambient cured geopolymer concrete are comparable with that of ordinary concrete of same strength.

1. Introduction
In the scenario of attempts for the reduction of greenhouse gases, concrete production using ordinary cement cannot be advised in future. The concrete made by using geopolymer which was introduced by Davidovits [1] has a promissory role as a green construction material to be considered in future to minimise the environmental impact. However, its application is limited to precast members because it is to be heated to attain the designed strength. Geopolymer materials are cementitious inorganic polymer materials synthesised by combining source materials which are rich in silica and alumina with the activation by alkali activators such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate (Na₂SiO₃) or potassium silicate (K₂SiO₃) [2]. The strength is achieved by the application of heat curing. These can contribute comparable and better performance in the properties such as, high compressive strength, low shrinkage, acid resistance, fire resistance etc. of construction materials made by OPC [3]. These geopolymer binders can replace the traditional binders and can be used for the production of structural elements [4].

The certain admixtures such as silica fume, rice husk ash, metakaolin and blast furnace slag were used to avoid heat curing of geopolymer made from low calcium fly ash (class F) as rich source of silica and alumina [5], [6]. Rashad [7] pointed out that the geopolymerisation process can be enhanced by incorporating the materials containing calcium oxide. The studies by Nath and Sarkar [8], [9] indicated that addition of small quantity of ordinary portland cement along with the geopolymer mix enable the concrete to cure under ambient temperature (23-27°C). Metha and Siddique [10] investigated and found out the properties of increased compressive strength and resistance to permeation due to improvement of micro structure of geopolymer concrete incorporating OPC as partial replacement of fly ash. In this study fracture properties of ambient cured geopolymer concrete...
are evaluated. The test data given in this paper will help the designers to compute economical section when the material is used for structural applications.

Like conventional concrete, geopolymer concrete also is considered as quasi-brittle materials. It exhibits a post peak softening behaviour which lies between brittle and ductile materials. In those materials, fracture process zone (FPZ) comes as an important and critical role in the failure of large sized structures. Due to the heterogeneity in the microstructure of geopolymer concrete, there will be the weakest links and initial defects happened in manufacturing or can be created during service life. It leads in microcracks within the concrete which will lead to propagation of cracks under service loads. The three point bending test with point load in the middle is a standard test for quasi brittle materials. An effective crack model, known as size effect model by which fracture properties can be derived from the peak load of notched specimens of different sizes [11].

The test results of Pires et al. [12] showed that replacement 20% of metakol inl with fly ash or rice husk ash will help to improve the fracture properties of geopolymer cement concrete. Nath and Sarkar [13] suggested to add ground granulated blast furnace slag (GGBS) to attain better fracture properties in geopolymer concrete. Pan et al. [14] showed the characteristic length of the geopolymer concrete is three times. The geopolymer concrete is found to be brittle than the OPC. It is stated that the fracture properties of both geopolymer and OPC concrete are correlated to its compressive strength. Reports on the fracture behaviour of ambient-cured geopolymer concrete are scarce in literature. Nath and Sarker [9] examined the fracture properties of Class F FA-based geopolymer concrete cured in ambient temperature and found that geopolymer achieved higher fracture energy compared with its OPC counterpart. Ding et al. [15] determined the fracture properties of slag/fly ash based geopolymer concrete (SGC). The test results indicated that CEB-FIP model under estimates with Bazant Becq-Giradoun model gives close prediction of fracture. They found that the fracture energy of SGC was larger than its PCC counterpart because of its more homogeneous and denser interfacial transition zones.

From the above studies, it can be noted that the fracture properties of cement (OPC) included geopolymer concrete has not been investigated. In this study, the fracture properties such as fracture energy ($G_f$), critical stress intensity factor ($K_{IC}$), process zone length ($c_f$), and crack tip opening displacement corresponding to peak load ($\delta_c$) were determined by size effect law (SEL). Bazant and Yu [16] note that the total fracture energy ($G_T$) is not constant and computationally verified that initial tangent of the stress–separation diagram, the area under which represents the initial fracture energy ($G_i$). The maximum loads of specimens and structures are generally controlled by $G_T$ and not $G_F$. Much more experimental data show that $G_F$ is statistically much more variable than $G_T$ [17], [18].

2. Experimental programme

2.1. Materials

The constituent materials such as Low calcium fly ash, cement, sodium hydroxide, sodium silicate, water, fine aggregate and coarse aggregate were used after conducting tests for general properties. Low calcium fly ash (Class F) conforming to IS 3812 [19] and having specific gravity of 1.98 was used. In this study, OPC 53 grade cement conforming to IS 12269 [20] having specific gravity of 3.10 was used as the additive to avoid the heat curing and enhance the early compressive strength of geopolymer mortar. The laboratory grade (97%) flakes of sodium hydroxide and 52 grade sodium silicate were used. Crushed granite fines having specific gravity of 2.62 and conforming zone II of IS 383 [21] were used as fine aggregate. Coarse aggregates of mixture of 20 mm and 12 mm aggregate in the proportion of 60% and 40 % respectively, having the following properties: - Specific gravity is 2.69 and bulk density is 1594 kg/m$^3$.

2.2. Details of mix proportion

The Mix design was adopted on the basis of test result from the optimized mortar mix for highest compressive strength mortar mix. By considering the workability and strength (92.42 MPa) criterion, a
mortar mix of 6/12/2.8/0.50 in which OPC of 6%, molarity of NaOH of 12, ratio SS/SH of 2.8 and alkali-binder ratio of 0.50 was selected. The details of geopolymer concrete mix are given in Table 1.

Table 1. Details of geopolymer concrete mix

| Designation of mortar mix | Fly ash | OPC | Sodium silicate solution | Sodium hydroxide solution | Fine aggregate | Coarse aggregate |
|---------------------------|---------|-----|--------------------------|---------------------------|---------------|-----------------|
| GPC                       | 400     | 26  | 157                      | 56                        | 647           | 1200            |

The mix proportioning of mortar was carried out based on density method proposed by Rangan [22] and Nath and Sarkar [23]. The target density of fresh geopolymer mortar mix was 2200 kg/m³. The weight of binder content of 33% by weight was used in this mix design.

2.3. Preparation of specimens

The 12M solution was prepared by dissolving 480 g NaOH solid flakes in water and made to 1 litre of solution. The solution was allowed to cool to room temperature. The sodium hydroxide solution was added to the required quantity of sodium silicate solution and stirred thoroughly. This forms the alkali activator, which is allowed to cool for about 1 hour in water bath. The required coarse aggregate and fine aggregate was put in the laboratory mixer and mixed for 1 minutes and then the binder materials, namely, fly ash and cement mixed dry for 2 minutes. The alkali activator was poured and mixed to the dry mixture of binders and aggregates. The mixing operation was continued for 4 minutes to get uniform colour and consistency.

The fresh mix was placed in moulds and compacted. The specimens were demoulded after 12 hours of adding activator to binder and cured in ambient condition. The room temperature was recorded and found to be between 25ºC -34ºC. The relative humidity in the room was found to be between 65%-80%. The specimen after curing was tested using 3000 kN digital compressive strength testing machine. The 12 standard concrete cubes of size 150 mm x150 mm x 150 mm, 12 cylinders of size 150 mm diameter and 300 mm height, notched beams as per Table 2 were prepared. The figure 1 shows the beams under ambient curing after its casting and demoulded.

Figure 1. Beams left under ambient curing.
### Table 2. Details of specimens

| Property                        | Shape               | Designation | Qty | L mm | b mm | d mm | Span l | l/d | a_0/d |
|--------------------------------|---------------------|-------------|-----|------|------|------|--------|-----|-------|
| Compressive strength           | Cube                | 12          | 150 | 150  | 150  |       |        |      |       |
| Splitting tensile strength     | Cylinder            | 3           | 150 |      | 300  |       |        |      |       |
| Modulus of elasticity & compression | Cylinder         | 12          | 150 |      | 300  |       |        |      |       |

| Fracture property              | Notched beam        |             |     |      |      |      |        |     |       |
| A1                             | 3                   | 900         | 100 | 100  | 800  | 8    | 0.2    |
| A2                             | 3                   | 1100        | 100 | 125  | 1000 | 6    |        |
| A3                             | 3                   | 1300        | 100 | 150  | 1200 | 8    | 0.4    |
| B1                             | 3                   | 700         | 100 | 100  | 600  | 6    |        |
| B2                             | 3                   | 900         | 100 | 125  | 750  | 6    |        |
| B3                             | 3                   | 1100        | 100 | 150  | 900  | 8    |        |
| B4                             | 3                   | 1300        | 100 | 100  | 1200 | 8    |        |
| C1                             | 3                   | 900         | 100 |      | 800  | 6    |        |
| C2                             | 3                   | 1100        | 100 | 125  | 1000 | 8    |        |
| C3                             | 3                   | 1300        | 100 | 150  | 1200 | 6    |        |
| D1                             | 3                   | 700         | 100 | 100  | 600  | 8    |        |
| D2                             | 3                   | 900         | 100 | 125  | 750  | 6    |        |
| D3                             | 3                   | 1100        | 100 | 150  | 900  | 8    |        |
| D4                             | 3                   | 1300        | 100 | 200  | 1200 | 6    |        |

2.4. Fracture properties

With reference to a typical size effect curve on a full log plot is shown in figure 2 [23]. The horizontal dashed line represents the failure status according to the strength or yield criterion. The inclined dashed line exhibits a strong size effect predicted by LEFM. The curve between the two limiting curves represents the real situation for most structures. From figure 2, it is observed that for very small structures the curve approaches the horizontal line and, therefore, the failure of these structures can be predicted by a strength theory. For large structures the curve approaches the inclined line and, therefore, the failure of these structures can be predicted by linear elastic fracture mechanics.

The size effect method proposes to determine the fracture energy and process zone length from the maximum loads of geometrically similar beams of different sizes. Nonlinear fracture can be characterized by two material parameters, the fracture energy ($G_f$) and the effective length of the FPZ ($c_f$). The identification of these material parameters can be reduced to linear regression, and the regression can be arranged in such a way that the slope of the regression line gives the fracture energy, $G_f$. It is also possible to calculate the critical effective crack tip opening displacement (CTOD) from
the above fracture parameters, \( G_f \) and \( c_f \). Fracture behaviour of plain concrete is the basis for all the studies on behaviour of reinforced concrete and pre-stressed concrete structures.

Fracture mechanics for concrete can be a useful tool for the designer because of the insight it provides on size effect which means how the size of a structural element will affect the ultimate load carrying capacity. Geometry of notched specimen subjected to three point bending is shown in Figure 3.

![Figure 2. Comparison of fracture energy](image1)

![Figure 3. Comparison of critical stress intensity factor](image2)

Due to the presence of micro cracks, the tip of the crack in concrete is not well defined, instead of a process zone is observed at the crack tip. The energy absorbed during crack growth depends on the size of process zone. The size of process zone depends on the size of specimen size or structural member. Hence the structural strength of concrete member depends on the size of member [23].

Size effect law for geometrically similar specimen is given by

\[
\sigma_N = \beta f'_t \left( 1 + \frac{d}{\lambda_0} \right)^{-1/2}
\]

(1)

\( \sigma_N \) is the size corrected nominal strength, \( \beta \) is the relative size of beam, \( f'_t \) is the tensile strength, \( d \) is the characteristic size of geometrically similar beams and \( \lambda_0 \) is a material constant, \( \beta \) and \( \lambda_0 \) depend on the fracture properties of concrete and the geometry of the structure and not on the structure size.

A linear equation is obtained by rearranging the terms of equation (1) as below:

\[
Y = AX + C
\]

(2)

Where, \( X = d \), \( Y = \left( \frac{1}{\sigma_N} \right)^2 = \left( \frac{bd_j}{P_f} \right)^2 \) and

\[
A = \frac{1}{(\beta f'_t)^2 \lambda_0}, \quad C = \frac{1}{(\beta f'_t)^2}
\]

(3)

The slope \( A \) and the intercept \( C \) are evaluated from the regression analysis of the experimental data \( (X, Y) \) which is computed based on the ultimate load \( P_f \) in the specimen.

Now, based on RILEM committee recommendation [23], the fracture energy is given by:

\[
G_f = \frac{g(\alpha)}{E_c A}
\]

(4)

Where \( E_c \) is the elastic modulus of concrete, \( g(\alpha) \) is the non dimensionless energy release rate. Also \( \alpha = a_0/d \), the ratio of notch depth to the total depth of beam.
But \( E_c = 5000 \sqrt{f_{ck}} \) (MPa) \hspace{1cm} (5)

Where, \( f_{ck} \) is the characteristic strength of concrete cube specimen (IS 456-2000) [25]

In equation (4) \( g(\alpha) \) is computed as:

\[
g(\alpha) = \left( \frac{l}{d} \right)^{2} n \alpha [1.5 F(\alpha)]^{2}
\]

Here, \( l \) is the span of the beam, \( d = \) depth of beam and \( F(\alpha) \) is the geometrical function.

\( F(\alpha) \) for three point loading is given by:

For \( l/d = 4 \) : (with \( \alpha = \frac{a_0}{d} \)):

\[
F_4(\alpha) = 1.090 - 1.735\alpha + 8.20 \alpha^2 - 14.18 \alpha^3 + 14.57 \alpha^4
\]

for \( l/d = 8 \):

\[
F_8(\alpha) = 1.107 - 1.735\alpha + 7.71 \alpha^2 - 13.55 \alpha^3 + 14.25 \alpha^4
\]

for values of \( l/d \) between 3 and 10, the geometrical function \( F(\alpha) \) can be computed by linear interpolation of equation (7) and (8) which takes the form:

\[
F(\alpha) = F_4(\alpha) + \left( \frac{1}{4} - \frac{a_0}{d} \right) [F_8(\alpha) - F_4(\alpha)]
\]

The critical stress intensity factor of concrete is determined by the theory of linear fracture mechanics as below:

\[
K_{lc} = \sqrt{\frac{G_f E_c}{\pi}} \text{ unit of which is MPa}\sqrt{m}
\]

The length of fracture process zone is calculated as below as recommended by RILEM committee [23].

\[
c_f = \frac{g(\alpha)c}{g'(\alpha)A} \text{ (mm)}
\]

where, \( C \) and \( A \) are the regression coefficients given by equation (3)

Here \( g'(\alpha) \)is the derivative of \( g(\alpha) \). The critical effective crack tip opening displacement \( \delta_c \) at the peak load of an infinitely large specimen as per model recommended by RILEM committee [23] is given by:

\[
\delta_c = \frac{32G_f c_f}{\pi E_c} \text{ (mm)}
\]

3. Results and discussion

The fresh mix was checked for workability and cast as per standard procedure for different type specimens. Cast specimens were cured in room air temperature for 28 days and the following tests were conducted.

1. Cube compressive strength test, 2. Cylinder compressive strength test, 3. Modulus of elasticity, 4. Split tensile strength and 5. Three point beam bending tests for fracture properties.

3.1. Cube compressive strength

All compressive strength specimens failed in shear. The conical failure may be the interaction between frictional force mobilised at the specimen surface due to the platen of testing machine and
lateral bulging force developed in the specimen. This is a typical failure pattern in ordinary concrete specimen, which indicates that the force transfer and redistribution in OPC included geopolymer concrete as similar. The average 28 days cube compressive strength was 64.82 MPa.

3.2. Cylinder compressive strength and Modulus of elasticity
The average 28 days cylinder compressive strength was 38.81 Mpa. The average value of Young’s modulus was 29.7 GPa. The E value of OPC blended geopolymer concrete is slightly lower value than E value of OPC concrete having the same range of compressive strength.

3.3. Split tensile strength
The average value of split tensile strength was found to 3.62 MPa. The split surface texture of the specimens indicates breaking across the coarse aggregate. It is an indication of the high binding strength of geopolymer. The split specimen is given in figure 4.

3.4. Fracture test
A total of 42 beams were subjected to three point bending. The peak load was observed at failure of specimen. The crack was formed at the place of notch and grew in the vertical direction towards the loading point. The peak load was observed at failure of specimen. The crack was formed at the place of notch and grew in the vertical direction towards the loading point. Test results are reported in Table 4. The test set up, crack developed after failure are in figure 5 and the figure of failure plane are given in the figure 6.

For each set of notched beams, regression analysis was done and its values of slope (A) and intercept (C) were used for finding fracture properties. Their line regression curves are approximately linear. The regression curves are plotted in the Figure 7 to 10.

The test results show that the fracture properties of OPC blended geopolymer concrete are nearly similar to OPC of same compressive strength. Comparison of each fracture property is given with the test data obtained plain cement concrete of compressive strength of 62.5 MPa given in the literature [26].

Fracture properties of OPC included geopolymer concrete and plain cement concrete presented in the Figure 11 to Figure 14.

The average value of fracture energy was found to be 32.67 N/m. Fracture energy is the specific energy required for the growth of fracture in an infinitely large test specimen. In a comparison with PCC of near value of compressive strength, the value found for OPC blended geopolymer is very similar value of fracture energy.

The nominal maximum bending stress \( (\sigma_N)_b \) by the following equation:

\[
(\sigma_N)_b = \frac{3Pl}{2bd^2}
\]  

(13)
Table 4. Test results

| a₀/d | l/d | Designation | Fracture Energy (Gf) in N/m | Critical stress intensity (KIC) in MPa·m^{1/2} | Process zone length (cₚ) in mm | δc in mm (CTOD) |
|------|-----|-------------|-----------------------------|---------------------------------------------|--------------------------------|----------------|
| 0.20 | 8   | A1,A2,A3    | 31.36                       | 0.96                                        | 113.3                          | 0.012          |
| 0.40 | 6   | B1,B2,B3,B4 | 28.90                       | 0.99                                        | 157.8                          | 0.015          |
| 0.20 | 8   | C1,C2,C3    | 33.30                       | 0.99                                        | 118.0                          | 0.013          |
| 0.40 | 6   | D1,D2,D3,D4 | 36.95                       | 1.04                                        | 179.4                          | 0.022          |
| Average |    |             | 32.67                       | 0.98                                        | 144.4                          | 0.016          |
Size effect law representation shows the variation in the bending stress against the size for OPC included geopolymer concrete. As the size increases the nominal bending stress at failure was reduced. For an increase of crack size from 0.20 to 0.40 of the depth of the structure, the nominal bending stress at failure was reduced considerably. The average reduction in strength for OPC included GPC specimens was about 62.1% with respect to the notch variation from 0.20 to 0.40. This bending stress variation in the various notch depth to depth ratios of 0.2 to 0.40 can be observed from the Figure 13.
4. Conclusion
In this investigation, an attempt was made to study the fracture properties using of OPC included geopolymer concrete.

- The value of fracture energy of OPC blended GPC was found to be nearly equal to the value of PCC of approximate same strength.
- The value of other fracture properties such as critical stress intensity, the length of fracture process zone, crack tip opening displacement were shown as 86.7%, 73.8% and 40% respectively of the value of PCC. It indicates that OPC included GPC is slightly brittle than PCC.
- The size effect law representation for nominal bending stress against the size of member was developed for OPC included GPC cured at ambient temperature. It showed that as the size increases, the nominal bending stress at failure was reduced. For an increase of crack size from 0.20 to 0.40 of the depth of the structure, the nominal bending stress at failure was reduced considerably. The average reduction in strength for OPC blended GPC specimens was about 62.1% with respect to the notch variation from 0.20 to 0.40.

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