ASIAN JOURNAL OF CIVIL ENGINEERING (BHRC) VOL. 16, NO. 1 (2015)
PAGES 127-134

Technical Note

FRACTURE PROPERTIES OF GEOPOLYMER CONCRETE

N. Ganesan[1], Ruby Abraham[2], S. Deepa Raj[2*] and Divya Sasi[2]
[1]Department of Civil Engineering, NITC, Kerala
[2]Department of Civil Engineering, College of Engineering Trivandrum, Kerala

Received: 14 January 2014; **Accepted:** 20 August 2014

ABSTRACT

This paper describes the results of an experimental investigation carried out to determine the fracture properties of geopolymer concrete. Geopolymer concrete of grade M30 was developed and the results were compared with that of conventional concrete of the same grade. A total number of 18 notched prisms of size 150mmx150mmx500mm with varying notch depth were prepared and subjected to bending test. Load deflection and load CMOD (crack mouth opening displacement) characteristics of each prism were observed. Based on this, the fracture parameters such as fracture energy and stress intensity factor were determined. The test results showed that geopolymer concrete exhibited enhanced performance compared to conventional concrete of the same grade. The results of experimental investigation have also been compared with those obtained by FEM analysis, and the comparison was found to be satisfactory.

Keywords: Geopolymer concrete; fracture; notch; CMOD; deflection.

1. INTRODUCTION

Concrete is a versatile construction material and is extensively used in civil engineering practice because of its low production cost, mouldability and much desirable response under compression. Global warming is caused by the emission of greenhouse gases such as CO_2 to the atmosphere by human activities. The cement industry is responsible for the major share of CO_2 emissions into the atmosphere. The production of one ton of Ordinary Portland Cement (OPC) requires about 1.5 tons of raw materials and releases about one ton of carbon dioxide (CO_2) into the environment [1]. Also concrete made of OPC deteriorates when exposed to normal or severe environmental conditions. Cracking and corrosion have significant influence on its service behaviour, design life and safety [2]. Several efforts are in progress to reduce the use of OPC in concrete in order to address the global warming issues. Efforts were made to

*E-mail address of the corresponding author: DeepaAjayan@yahoo.com (S. Deepa Raj)

promote the use of pozzolanas to replace part of OPC.

Recently another form of cementitious material using silicon and aluminum activated in a high alkali solution known as geopolymer (aluminosilicate mineral binder) was developed [3]. Two main constituents of geopolymers are source materials and alkaline liquids. The source materials should be rich in aluminum and silicon and they can be by-products such as fly ash, silica fume, slag, rice husk ash, red mud etc. The alkaline liquid system is an alkaline activator solution which is a combination of alkali silicates, hydroxides and water. The mortar and concrete made from these materials possess similar strength and appearance as those made from Ordinary Portland Cement [3, 4]. Geopolymer concrete (GPC) attains its strength by geopolymerization. The polymerization process involves a substantially fast reaction under alkaline solution on Si-Al minerals, those results in three dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds. Heat is essential for geopolymerization [1,5]. It is found that heat cured low calcium fly ash based geopolymer concrete possess high compressive strength, less drying shrinkage, moderately low creep, and shows excellent resistance to sulphate and acid attack [5, 6]. The major advantages of Geopolymer Concrete (GPC) are the availability of raw material resources, energy saving and environmental protection, good volume stability, excellent durability, high fire resistance and low thermal conductivity [6,7].

Fracture Mechanics 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. In quasi brittle materials like concrete, a large Fracture Process Zone is usually formed in front of a crack like defect that consumes more energy prior to failure [7]. This provides concrete with nonlinear post peak (tension softening) response [8]. A notch is defined as a geometric discontinuity which has a definite path and root radius [8, 9]. The redistribution of stress in a body due to the existence of a crack or a notch can be analyzed by the Linear Elastic Fracture Mechanics method. Maximum attention should be paid to the stress concentration at the vicinity of the crack tip. The fracture behaviour of concrete is governed by the fracture parameters such as fracture energy (G_F), Critical stress intensity factor (K_{IC}) and Crack Mouth Opening Displacement (CMOD) [10]. A three point bend test can be used to determine the fracture parameters [11, 12] as shown in Fig. 1.

Fracture energy is the amount of energy required to create a crack of unit surface area projected in a plane parallel to the crack direction. It is determined as the energy required for creating unit crack surface, which is calculated as the work done during fracture divided by the area of the uncracked ligament [7, 13].

$$G_f = \frac{W_0 + mg\,\delta_{\max}}{A_{lig}} \tag{1}$$

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

The stress intensity factor, K_I, which reflects the severity of the notch, is defined as the

ratio of the maximum (elastic) stress at the root of a notch to the nominal applied stress [7]. The stress intensity factors characterize the stress fields surrounding the fracture plane. Stress intensity factor is defined to quantify the stresses at the crack tip. A material fails by fracture when K_1 reaches a certain critical value K_{1C}, which is called the fracture toughness [13, 14].

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

Y – Function of geometry,
M_{max} = M1 + M2,
M1 – bending moment due to the applied load,
M2 – bending moment due to self-weight of the beam

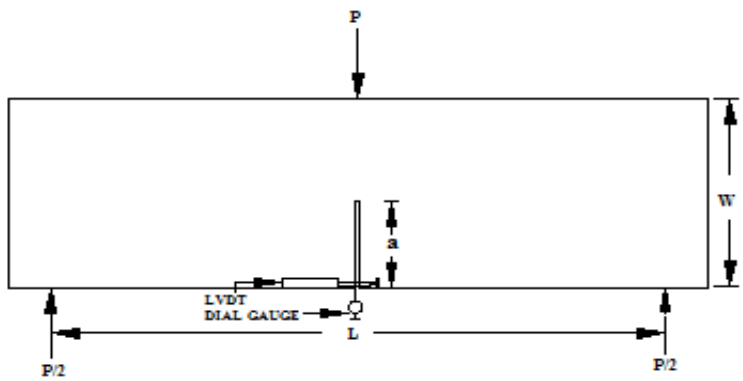

Figure 1. Three Point Bend Specimen

2. EXPERIMENTAL PROGRAMME

The experimental investigation was carried out to develop a geopolymer concrete mix of compressive strength 30 MPa and to compare its fresh, hardened, and fracture properties with that of conventional concrete of the same grade. With the developed GPC and conventional Portland cement concrete (PCC) mixes, a fracture study was conducted by using notched prisms. The variables considered in this study include different values of notch depth.

2.1 Constituent Materials

Fly ash: Low calcium fly ash (CaO-2.14%) obtained from Tuticorin Thermal Power Plant was used for the study.

Coarse Aggregate: Coarse aggregate of nominal size 20 mm was used for making GPC and PCC. Laboratory tests were conducted on coarse aggregate to determine the different physical properties and grading as per IS 2386 (part-III)-1963 (Reaffirmed on1997).

Fine Aggregate: Locally available river sand was used as fine aggregate. Laboratory tests were conducted on fine aggregate to determine the different physical properties. The results depicted that the river sand conformed to zone II of IS 383-1970 (Reaffirmed on 1997).

Cement: Ordinary Portland cement (53 grade) conforming to IS12269-1987 was used for

preparing PCC mixes.

Alkaline Solution: The solution comprises a mixture of sodium silicate solution and sodium hydroxide solution. Sodium silicate solution with SiO_2 to Na_2O ratio of 2 (Na_2O=14.7%, SiO_2=29.4% and water =55.9%) by mass was used [3]. The sodium hydroxide pellets with 97-98% was mixed with water to make sodium hydroxide solution.

Superplasticiser*:* Superplasticiser selected for the study was conplast SP 430 to obtain workability of 125mm slump for all the mixes.

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 [3, 4]. Mix proportion corresponding to a compressive strength of 30MPa was adopted from the trial mixes. A mix design for M30 PCC was also done as per IS 10262-2009 for comparison purposes. The final mix proportion arrived at are shown in Table 1.

2.3 Preparation of GPC

The coarse aggregates and the sand in saturated surface dry condition were first mixed in a laboratory mixer along with fly ash for about three minutes. Then the alkaline solutions, super plasticizer and some extra water were added to the dry materials. The mixing was continued for four minutes. The appearance of GPC was similar to that of PCC. After mixing fresh concrete properties were determined.

Table 1: Final mix proportion for GPC and PCC

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

2.4 Casting of Test Specimens

In order to determine the hardened properties, standard specimens like cubes, cylinders and prisms were prepared. For determining fracture parameters, prisms of size 150 mmx150 mmx500 mm were prepared. The prisms were given a central notch of 3mm width and varying depth by taking the ratio of notch depth to beam depth as 0.3, 0.4 and 0.5 (notch depth 45 mm, 60 mm and 75 mm). As hydration process is not taking place in GPC water curing is not required and temperature curing for one day was 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 condition at room temperature for another 24 hours before demoulding. After demoulding the test specimens were left in the laboratory ambient conditions until the day of testing. In the case of PCC, after casting ,all the specimens were kept in the mould for 24 hours. After this time the specimens were demoulded and immersed in water for 28 days for curing.

2.5 Testing of Specimens

Fresh and Hardened Properties: The workability of both GPC and PCC were determined by conducting slump test and compacting factor test. The hardened properties such as compressive strength, splitting tensile strength, modulus of elasticity and flexural strength for both GPC and PCC were determined by testing standard cubes, cylinders and prisms.

Fracture Test: For the fracture study, three point bending tests were performed on notched specimens of size 150mm x150mm x 500 mm. During testing, the central deflection and Crack Mouth Opening Displacement (CMOD) were measured. The deflection was noted using the dial gauge placed at the midpoint and CMOD was noted using the LVDT mounted across the notch. The fracture parameters such as fracture toughness and fracture energy were determined by using equations (1) and (2). The experimental observations were used to draw the load-deflection and load-CMOD curves. The test set-up is as shown in Fig. 2.

Figure 2. Test set-up

3. RESULTS AND DISCUSSIONS

Fresh and Hardened Properties: Test results of fresh and hardened properties of both GPC and PCC are given in Table 2. From the test results, it can be observed that GPC has enhanced values of fresh and hardened properties compared to conventional concrete of same grade.

Table 2 Results of hardened properties

Properties	Slump (mm)	Compacting factor	Cube Compressive Strength(MPa)	Modulus of elasticity (MPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)
GPC	135	0.94	38.5	25590	2.51	4.10
PCC	128	0.92	37.9	25387	2.31	3.05

Fracture Test: The load deflection data observed during fracture test were used to draw the load deflection curve of GPC and PCC specimens. Fig. 3 shows load deflection curve for both GPC and PCC specimens with different notch depths. First crack load was noted from

the load deflection curves (the point where the curve deviates from linearity). Table 3 shows the first crack load and ultimate load for both GPC and PCC. From the results it can be observed that there was significant improvement for the load carrying capacity of GPC specimens than PCC specimens for all notch depths. Compared to PCC, the increase in first crack load for GPC was 50 to 70% and that for ultimate load it 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 capacity decreased to 65% for GPC and 45% for PCC. Using the CMOD data, load versus CMOD curves were plotted for both GPC and PCC specimens for all notch depths. Fig. 4 shows load CMOD curve for both GPC and PCC specimens with different notch depths. Fracture energy (G_f) and stress intensity factor (K_{IC}) were calculated using equations (1) and (2) and are shown in Table 3. From the table it may be noted that G_f and K_{IC} were significantly higher for GPC specimens than PCC specimens. The percentage increase in G_f and K_{IC} were 95-180% and 35-45% respectively for GPC than PCC. The above test indicates that GPC exhibits higher fracture parameters than conventional PCC of the same grade.

4. ANALYTICAL STUDY

The fracture parameters obtained from experiments were analytically validated by FEM analysis using ANSYS 11. One half of the specimens were modeled with singular elements around the crack tip to obtain stress intensity factor. The element selected was SHELL 41. The model is shown in Fig. 5. The element has three degrees of freedom at each node. The boundary conditions were assumed as simply supported at the ends. The results obtained from the analysis are shown in Table 3. It may be noted from the Table that the analytical values of K_{IC} are comparing satisfactorily with the experimental values and the variation is only about 10 to 20 %.

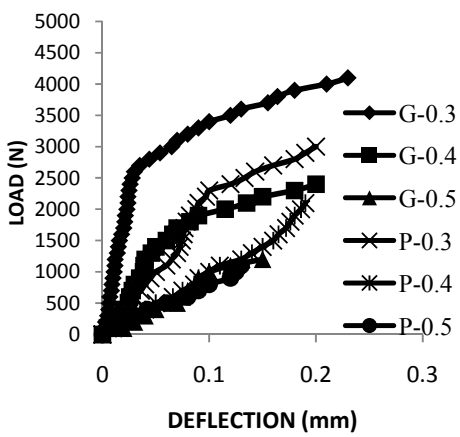

Figure 3. Load versus Deflection curves for GPC and PCC

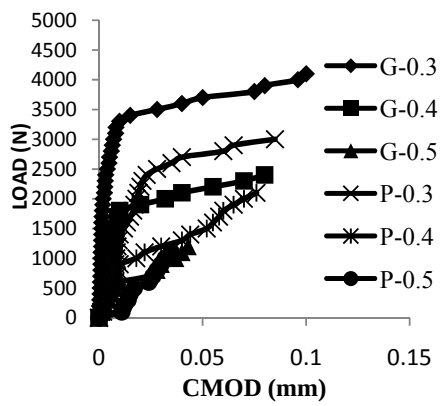

Figure 4. Load versus CMOD curves for GPC and PCC

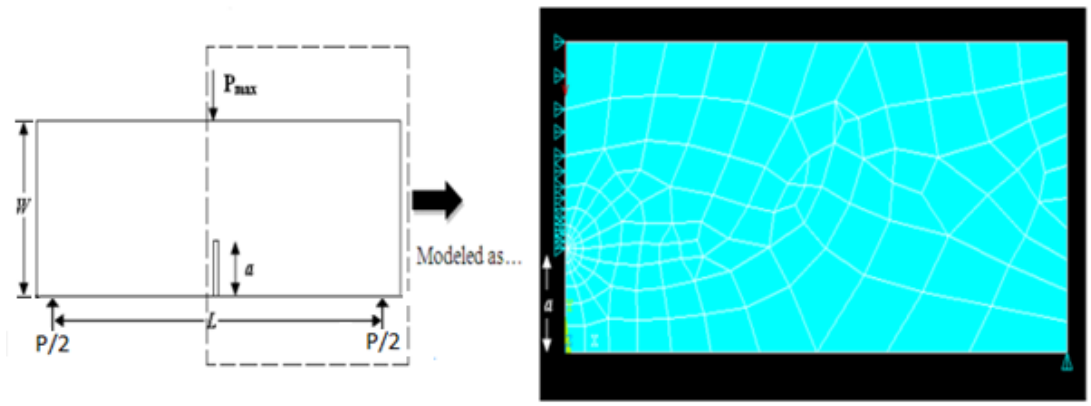

Figure 5. Three point bend specimen modeled in ANSYS

Table 3: Fracture Parameters

Specimen	First crack load (N)	Ultimate load (N)	Fracture energy (G_f) (N/mm)	Fracture Toughness	
				K_{IC} (experimental) $N/mm^{3/2}$	K_{IC} (Analytical) $N/mm^{3/2}$
PCC 0.3	1962.00	2943.00	0.05321	18.1577	16.5514
GPC 0.3	2943.00	4022.10	0.10521	24.7100	23.6064
PCC 0.4	1079.10	2109.15	0.02604	12.9906	16.1751
GPC 0.4	1863.90	2403.45	0.05643	19.3436	18.4329
PCC 0.5	588.60	1079.10	0.00977	12.4720	10.1098
GPC 0.5	981.00	1255.68	0.02758	17.0225	10.5494

5. CONCLUSIONS

From the present study, the following conclusions were made,

- Compared to PCC, GPC showed slightly higher values for the hardened properties such as modulus of elasticity, splitting tensile strength and flexural strength.
- The load carrying capacity of GPC is more than that of PCC for all notch depths. When the notch depths were increased, the load carrying capacity, deflections and CMOD of GPC and PCC decreased.
- The fracture energy of GPC was twice that of PCC and fracture toughness of GPC was 20 to 30% higher than that of PCC. These properties decreased for a corresponding increase in notch depth.

- The experimental values of fracture toughness were compared with analytical values and the comparison was found to be satisfactory.
- As GPC exhibited better mechanical and fracture properties compared to conventional concrete of the same grade, it can be considered as an environment friendly alternative for conventional concrete.

Acknowledgments: The authors would like to thank Centre for Engineering Research and Development for providing financial assistance to this work.

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