Fracture properties of GGBFS-blended fly ash geopolymer concrete cured in ambient temperature

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ABSTRACT

Fracture characteristics are important part of concrete design against brittle failure. Recently, fly ash geopolymer binder is gaining significant interest as a greener alternative to traditional ordinary Portland cement (OPC). Hence it is important to understand the failure behaviour of fly ash based geopolymers for safe design of structures built with such materials. This paper presents the fracture properties of ambient-cured geopolymer concrete (GPC). Notched beam specimens of GPC mixtures based mainly on fly ash and a small percentage of ground granulated blast furnace slag (GGBFS) were subjected to three-point bending test to evaluate fracture behaviour. The effect of mixture proportions on the fracture properties were compared with control as well as OPC concrete. The results show that fracture properties are influenced by the mixture compositions. Presence of additional water affected fracture properties adversely. Fracture energy is generally governed by tensile strength which correlates with compressive strength. Critical stress intensity factor varies with the variation of flexural strength. Geopolymer concrete specimens showed similar load-deflection behaviour as OPC concrete specimens. The ambient cured GPC showed relatively more ductility than the previously reported heat cured GPC, which is comparable to the OPC specimens. Fly ash based GPC achieved relatively higher fracture energy and similar values of K_{IC} as compared to those of OPC concrete of similar compressive strength. Thus, fly ash based GPC designed for curing in ambient condition can achieve fracture properties comparable to normal OPC concrete.

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1 Introduction

Fracture properties such as fracture toughness and fracture energy of a material are used to describe the formation and progress of cracks in members made of that material. Furthermore, continuous improvements of binders are improving concrete behaviour approaching that of a homogeneous material (Juenger et al. 2011). Though concrete is generally referred as a brittle material, it actually differs from an ideal brittle material in many aspects. In modern fracture mechanics concrete is considered as a quasi-brittle material exhibiting a post-peak softening behaviour which lies between a brittle and a ductile material behaviour. Increased ductility can be provided by increasing the fracture energy by careful choice of the constituent materials (Bharatkumar et al. 2005; Trussoni et al. 2013) or by reinforcing the matrix with fibres (Deepa Raj et al. 2013).

Fracture characteristics of concrete are influenced by the material properties such as strength, mixture constituents, and types of aggregate used, and the maturity of concrete. The size of the specimens is also important factor affecting fracture properties (Gettu et al.1990). Darwin et al. (2001) found a small variation of fracture energy of OPC concrete when water-cement ratio varied between 0.25 to 0.45 at any age from 7 days to 180 days. For concretes at least five days old, fracture energy is independent of compressive strength, w/cm, and age. Fracture energy of concrete is governed principally by the properties of the coarse aggregate, with higher strength aggregates (basalt) producing concretes with higher fracture energies. In contrast, Gettu et al. (1990) found that, as the strength increases, the fracture energy and the fracture toughness of concrete also increase.

In another study on high performance concrete (HPC), the results showed that there is a reduction in the fracture energy due to addition of fly ash or slag (Bharatkumar et al. 2005).

Geopolymer binder is a relatively new material that requires extensive research into various properties to ensure its suitability for structural applications. The binder is produced by chemical reaction of an aluminosilicate material such as fly ash, blast furnace slag or metakaolin with an alkali (Juenger et al. 2011; Davidovits 2008). Since geopolymers utilise by-products as the principle source material, the binders are considered as a low CO_2-emiting alternative of Portland cement (Yang et al. 2013). Low-calcium fly ash geopolymer concretes cured in high temperature have been extensively researched for the last two decades and are reported to have good mechanical properties (Wallah and Rangan 2003; Fernandez-Jimenez et al. 2007). The structural properties of heat-cured fly ash geopolymer concrete were reported to be similar or superior to that of OPC concrete (Sumajouw et al. 2005; Sarker 2011; Sarker et al. 2013). However, reports on the structural behavior of ambient-cured geopolymer concrete are scarce in literature.

Sarker et al. (2013) reported fracture properties of heat cured fly ash based geopolymer concrete and compared with OPC concrete. They found higher peak load in the geopolymer than the OPC concrete of similar strength grade. The heat-cured geopolymer concrete specimens were found to be more brittle than the OPC concrete specimens. Fracture energy was found to be similar in both types of concrete for similar compressive strengths. The results suggest that the different fracture behaviour of geopolymer concrete is mainly because of its higher tensile and bond strengths than OPC concrete of the same compressive strength.

Pan et al. (2011) reported the results of experimental research on fracture properties of heat-cured fly ash based geopolymer concrete and paste with various mix parameters. The results indicate that the fracture energy and elastic modulus of geopolymer paste and concrete are lower than those of OPC paste and concrete. The tensile strength of geopolymer paste and concrete is higher than that of OPC paste and concrete. The characteristic length of the geopolymer concrete was approximately three times less than that of ordinary Portland cement (OPC) concrete. The geopolymer concrete exhibited higher brittleness than its OPC counterpart.

Deepa Raj et al. (2013) worked on the fracture properties of fibre reinforced fly ash based geopolymer concrete. The study concluded that the load carrying capacity, deflections and crack mouth opening deflection of geopolymer are more than those of OPC concrete at ultimate stage. Fracture energy and fracture toughness are found to be greater than the OPC concrete.

These studies reported the properties of fly ash based geopolymers cured in elevated temperature. High curing temperature and the activation method of the aluminosilicate source material played the most important roles on the fracture properties of geopolymers in these studies. However, the fracture behaviour of fly ash based geopolymer concrete cured in ambient condition has not been studied. Since the curing method has a significant influence on development of the hardened properties, it is necessary to study the fracture behaviour of low-calcium fly ash geopolymer concrete cured at ambient condition. Curing in normal ambient condition will also help reduce the cost and energy associated with heat curing. Therefore, this study aimed to investigate the fracture properties of low calcium fly ash based geopolymer concrete mixtures suitable for curing in ambient condition. Geopolymer concrete mixtures were produced using fly ash as the principle binder and including a small percentage of GGBFS in order to improve the setting and hardening properties of the mixtures at the early ages (Nath and Sarker 2014). Fracture properties such as load-deflection behaviour, fracture energy and critical stress intensity factor were determined from the test results. Effects of the mixture variables were evaluated by comparing these properties for different geopolymer concrete and those of the OPC concrete.

2 Experimental program

2.1 Materials

Geopolymer binder was prepared with a Class F fly ash (ASTM C 618), collected from a West Australian power plant. A commercially available ground granulated blast furnace slag (GGBFS) was added as a small part of the binder. The chemical compositions and loss on ignition of fly ash and GGBFS are shown in Table 1. The alkaline liquid used was a mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions. Sodium hydroxide solution of 14 Molar concentration was prepared by mixing 98-99% pure NaOH pellets with normal tap water. Sodium silicate solution with SiO_2 to Na_2O mass ratio of 2.61 (SiO_2 = 30.0%, Na_2O = 11.5% and water = 58.5%) was used. Locally available natural sand was used as fine aggregate, and coarse aggregates were a combination of crushed granite with nominal maximum sizes of 7 and 10 mm. The maximum coarse aggregate size of 10 mm was selected to meet the specification recommended by RILEM for small size of specimens (RILEM TC 50-FMC 1985). A superplasticiser (Rheobuild 1000) was used to improve workability. A General purpose ordinary Portland cement (OPC) conforming to Australian standard (AS 3972) was used for the OPC concrete mixture.

2.2 Mixture proportions

Concrete mixtures were proportioned to investigate the fracture properties of ambient cured geopolymer. Mix variables included the amount of GGBFS as a replacement of fly ash and the amount of alkaline liquid. Five geopolymer concrete (GPC) and one OPC concrete mixtures were used in the experimental work. The mixture proportions of concretes are presented in Table 2. Two sets of mixtures were designed for varying amount of alkaline solution as 40% and 35% of the total binder. The first set of mixtures were designated as A40 S00, A40 S10 and A40 S15 which contained 40% alkaline liquid and 0%, 10% and 15% GGBFS respectively. The other set of mixtures contained 35% alkaline liquid and either 0% or 10% GGBFS. The mixtures are designated as A35 S00 and A35 S10 respectively. The ratio of Na_2SiO_3 to NaOH solution in the alkaline liquid was kept constant as 2.5 for all the geopolymer mixtures.

The slump test was conducted to measure workability of the mixtures. Mixtures having 40% alkaline liquid achieved more than 200 mm slump after mixing which is similar to that obtained in our previous study (Nath and Sarker 2014). Mixtures having 35% alkaline liquid generally show lower workability. Hence, additional water and superplasticiser were used in the mixtures having 35% alkaline liquid to achieve similar slump values of mixtures having 40% alkaline liquid.

2.3 Casting and curing of the test specimens

The beam specimen for fracture test was 600 mm in length and 100 × 100 mm in cross section. The geometric dimensions of all the test specimens were kept constant. A 25 mm deep notch was cast at the mid-section of the beam. Different notch depths were used for fracture tests by different researchers (Gettu et al. 1990; Sarker et al. 2013; Pan et al. 2011) in literature. However, previous studies conducted with different notch-depth ratio revealed comparable results as long as the specimen size remained constant. In this study a notch-depth ratio of 0.25 was used after some trials with 0.25 and 0.50. The smaller ratio of 0.25 was selected to reduce the chance of accidental cracking during de-moulding and handling of the test specimens. It also ensured the ligament area sizable enough to observe the crack propagation in the concrete. The mould was designed to facilitate carving the notch while casting the specimen. Companion cylinder and prism specimens were cast for compressive strength, modulus of elasticity and flexural strength tests.

The geopolymer mixtures were mixed in a laboratory pan-mixer. The premixed alkaline liquid was added gradually to the dry mixture of aggregates and binders (fly ash and GGBFS). The mixing was then continued for 4 to 6 minutes until a consistent mixture was obtained. The fresh concrete mixture was cast in the moulds in two layers. Each layer was compacted using a vibrating table. The moulds with finished concrete specimens were moved to the curing room (18-23 ºC and 70 ± 10% RH) immediately after casting. After 24 hours, the specimens were de-moulded and stored in the same condition (18-23ºC and 70 ± 10% RH) until tested. Note that the specimens were not subjected to heat curing. The GPC specimens without GGBFS (A40 S00 and A35 S00) were de-moulded three days after casting, because of the long setting time required for these mixtures.

To compare with the properties of GPC mixtures, an OPC concrete mixture was designed in accordance with the ACI guideline (ACI 2011.1-91). The OPC concrete specimens were immersed in water after de-moulding on the day after casting. The specimens were removed from water after 28 days and stored in the same condition as the geopolymer samples until tested.

2.4 Test methods

Three-point bending test was conducted to determine fracture properties of the concrete specimens following the RILEM guidelines (RILEM TC 50 – FMC 1985). The beam was simply supported over a span of 500 mm with the notched face down and a single point load was applied at the centre of the beam (Figure 1). To reduce the effect of friction between the loading platen and the specimen, ball bearing support apparatus were used in accordance with the ASTM (C78/C78M-10e) standard. The test was conducted using a closed-loop universal testing machine (Instron Servo Control machine). The specimen was loaded to induce a vertical mid-section deflection at a rate of 0.5 mm/min. This loading rate was selected after several trial tests to ensure the maximum load is reached within 30–60 seconds as recommended in the RILEM guidelines. The load and vertical deflection data were recorded by an automatic data acquisition system at rate of 100 readings per second. The accuracies of the load and deflection data were to 0.001 kN and 0.001 mm respectively. Load was applied until complete failure of the specimen. Three identical specimens were tested for each of the mixtures at both 28 and 90 days. Since the strength of ambient-cured geopolymers continue to develop beyond 28 days, the test was extended to 90 days in order to understand the influence of age on the fracture properties.

Compressive strength test was conducted at the age of 28 and 90 days. Cylinder specimens (100 mm diameter and 200 mm height) were tested at a loading rate of 0.33 MPa/s. Testing for flexural strength was conducted following the Australian

Standard (AS 1012.11-2000). The test involves beam specimens of dimensions 100 mm × 100 mm × 400 mm loaded in pure bending to fail due to flexural stress. Modulus of elasticity of concrete samples was determined according to the ASTM standard (ASTM C 469/C 469M - 10).

2.5 Evaluation of fracture parameters

After the test, the load-deflection graph was plotted with the recorded data. The fracture energy (G_F) was calculated by the work of fracture method using Equation 1 given in the RILEM guidelines (RILEM TC 50-FMC 1985). It is the summation of the work done by the external load calculated by the area under the load-deflection curve, (W_o) and work done by self-weight of the beam.

$$G_F = \frac{W_0 + mg\,\delta_0}{A_{lig}} \quad (1)$$

where W_o = area under the load-deflection curve (N-m), m = mass of the beam between the support (kg), g = acceleration due to gravity (9.81 m/s^2), δ_o = the deflection at the final failure of the beam (m) and A_{lig} = area of the ligament (m^2). The experimental values of fracture energy were compared with some established model equations proposed in the literature for OPC concrete. The CEB-FIP committee recommended a prediction formula as given by Eq. 2 (Bazant and Becq-Giraudon 2002).

$$G_F = (0.0469s^2 - 0.5s + 26)\left(\frac{f'_c}{10}\right)^{0.7} \quad (2)$$

where, s = maximum aggregate size (mm), f'_c = compressive strength of concrete (MPa)

Another equation (Eq. 3) was proposed by Bazant and Becq-Giraduon (2002) following a statistical analysis of 238 test data on fracture energy of OPC concrete of strength and age varying in a wide range. The coefficient of variation of the test to prediction ratios of the results by this equation was found to be 29.9%. The equation takes into account the compressive strength, maximum aggregate size and the water to cement ratio of the concrete. Since geopolymer concrete is different from the usual mixture of OPC concrete, the term liquid to binder ratio of geopolymer mixture, as shown in Table 2, was used as equivalent to the water to cement ratio of OPC concrete. The liquid content was calculated by adding the amount of NaOH solution, Na_2SiO_3 solution and any extra water. Total binder content includes the binders such as fly ash and GGBFS.

$$G_F = 2.5 \alpha_0 \left(\frac{f'_c}{0.051}\right)^{0.46} \left(1 + \frac{s}{11.27}\right)^{0.22} \left(\frac{w}{c}\right)^{-0.30} \qquad (3)$$

where, α_o is aggregates shape factor (1 for round aggregates, 1.44 for angular or crushed aggregates), and w/c is the water to cement ratio of the OPC concrete.

The critical stress intensity factor (K_{IC}) was calculated using Equation 4 (Peterson 1980). It is also known as fracture toughness and relates to the peak load and the geometric dimensions of the beam.

$$K_{IC} = \frac{3P_{max}l}{2bd^2}\sqrt{a_o}(1.93 - 3.07A + 14.53A^2 - 25.11A^3 + 25.8A^4) \qquad (4)$$

where, P_{max} = the peak load, l = the span of beam, b = the width of beam, d = the depth of beam, a_o = the depth of the notch and $A = a_o/d$.

3 Results and discussion

3.1 Mechanical properties

3.1.1 Compressive strength

Mechanical properties of all the mixtures were determined at the same time when the three-point bending tests were conducted. Results of compressive strength, flexural strength and modulus of elasticity are given in Table 3. The compressive strength and modulus of elasticity are also plotted in Figure 2. The 28-day compressive strength of the geopolymer concretes of this study varied from 25 MPa to 46 MPa and increased up to 53 MPa at 90 days. It is clear from the results that the compressive strength enhanced significantly with the increase of GGBFS content in the mixtures designed with 40% alkaline liquid (Figure 2). The improvement of strength due to inclusion of GGBFS followed the same trend as reported in previous study (Nath and Sarker 2014). The increase of strength was also observed when the alkaline liquid was reduced to 35% and no extra water was added (mixture A35 S00). However, mixture A35 S10 showed lower strength than that having 40% alkaline liquid and same additive content of 10% GGBFS (A40 S10). This reduction in strength is caused by the addition of extra water along with superplasticiser in the mixture A35 S10 (Table 2). The additional water reduced the concentration of alkaline liquid which eventually decreased strength. The geopolymer mixtures containing 35% alkaline liquid with or without 10% GGBFS resulted in similar compressive strengths. This result implies that the inclusion of a small amount of GGBFS such as 10% can balance the negative effect of additional water on the strength development of geopolymer concrete.

3.1.2 Flexural strength

It can be seen from Table 3 that flexural strength of geopolymer concrete cured in ambient temperature increased with age for all the mixtures. This is similar to the development of compressive strength with age, as observed in Figure 2. Also, flexural strength increased with the inclusion of GGBFS content up to 10%. A slight decline in the flexural strength was observed for increasing the GGBFS content to 15%. From Table 3 it can be seen that, mixture A35 S10, having additives and extra water in the mixtures, achieved about 30% less flexural strength than that of control geopolymer A35 S00 which had no water added. While mixtures having 35% alkaline liquid only with no extra water achieved higher compressive and flexural strength, addition of water with 35% alkaline activator in concretes having GGBFS have decreased flexural strength. This indicates that the presence of extra water adversely affected flexural tensile strength of ambient cured geopolymer concrete.

When compared with OPC concrete, geopolymer concrete of similar strength (A40 S10) exhibited higher flexural tensile strength than the OPC concrete (Table 3). The result is consistent with that reported for both heat cured (Hardjito 2005; Rangan 2007) and ambient cured geopolymer concretes (Deb et al. 2014).

3.1.3 Modulus of elasticity

Generally, the value of modulus of elasticity varied with the compressive strength and no significant difference is observed due to variation of the mixture proportions. Similar trends were observed at the ages of 28 days and 90 days, as shown in Figure 2. Geopolymer concretes cured in elevated temperature generally reported to have low modulus of elasticity as compared to that of OPC concrete of the same compressive strength (Fernandez-Jimenez et al. 2006; Sofi et al. 2007).

The ambient cured geopolymer concretes of this study also showed similar trends. It can be seen from Table 3 that the modulus of elasticity of geopolymer concretes are relatively less than the OPC concrete of similar compressive strength. For a 40 MPa concrete, while OPC mixture had modulus of elasticity of 30.6 GPa, similar grade geopolymer concrete (A40 S10) achieved a modulus of elasticity of 22.6 GPa at 28 days. This is about 24% less than OPC concrete at 28 days and the difference increased to 29% after 90 days. In a previous study, heat cured geopolymer concrete showed about 22% less modulus of elasticity than OPC concrete (Pan et al. 2011).

3.2 Fracture properties

3.2.1 Load-deflection behaviour

Typical load deflection patterns of fly ash geopolymers containing GGBFS along with 40% alkaline solution, and the OPC concrete are presented in Figure 3. The initial non-linearity of the load–deflection curves were corrected to eliminate distortions caused by the deformation of the specimen at the supports and adjustments at contact planes (Sarker et al. 2013; RILEM TC 50-FMC 1985). Figure 3 shows the load deflection diagrams of different specimens at 28 days and 90 days. As usual, the curve showed a linear upward slope until the load reached cracking limit of the material. It can be seen from the graphs that the slope of the pre-peak curve generally increased for the specimens having higher strength than control concrete (A40 S00). After reaching peak load, the crack initiates which results in a downward post peak curve. The slope of post-peak part of the curve reflects the property of the cracked specimen until breaking. The curvature of post peak curve varied depending on the ductility of the material. The slope gradually decreased with the increase of the compressive strength of the geopolymer concretes. This indicates reduced ductility of the specimens with increasing compressive strength. The control specimen of A40 S00, which had lowest strength, showed greater stretch of the post peak curve before complete failure.

The load-deflection curves of geopolymer concretes are of similar shape as that of OPC concrete. However, the pre-peak slopes of the curve appeared slightly steeper in case of geopolymer specimens. This implies that OPC concrete of similar grade tend to deflect more than geopolymer concretes before initiating the crack. The post peak behaviour is almost similar for OPC and ambient cured geopolymer concretes as indicated by the similar post-peak slopes. This is different from that observed in the study of heat cured fly ash based geopolymer concrete (Sarker et al. 2013). It is reported that, the post-peak load usually dropped faster in the heat cured specimens than in the OPC concrete specimens and showed a steeper slope of the post-peak curve. However, in this study of ambient cured GPC, the post peak slope of load deflection diagram for both GPC and OPC concrete gradually decreased rather than dropping sharply. Geopolymer specimens showed relatively slightly greater stretch of deflection before ultimate failure than OPC concrete at both 28 and 90 days. Hence it can be stated that ambient cured GPC showed more ductile behaviour than heat cured GPC which is comparable to that of OPC concrete.

3.2.2 Peak load

Peak load as a fracture property indicates the maximum load that is required to the separate the surfaces involving in the crack which takes place across an extended crack tip, or cohesive zone (Dugdale 1960). Peak loads of all the specimens are given in Table 4. The average peak loads of ambient cured geopolymer concrete varied in the range of 2.7 to 4.5 kN at 28 days and 3.2 to 5.2 kN at 90 days. Figure 4 shows the variations of average peak load and the flexural strength of the concretes. At both the ages of 28 and 90 days, the peak load varied in the same way as flexural strength of the concrete. Among the geopolymer concretes, mixture A35 S00 showed the maximum peak load as well as flexural strength. The mixture composition mainly influenced the flexural strength which led to the variation of peak load value in three-point bending tests. The OPC concrete has less flexural strength than the geopolymer concrete of equal grade (A40 S10); however, OPC concrete showed similar peak load as compared to similar grade geopolymer concrete. Heat cured fly ash based geopolymer generally showed higher peak load as compared to OPC concrete (Sarker et al. 2013).

3.2.3 Fracture energy

Fracture energy (G_F) was calculated by the work of fracture method (Eq. 1). Results of three-point bending tests are presented in Table 4. Fracture energy of the geopolymer concretes varied in the range of 150 - 232.8 N/m at 28 days and 172.4 - 250.4 N/m at 90 days. The mean fracture energy values of the geopolymer and OPC concrete mixtures are compared in Figure 5. It can be seen that the mixture proportions of geopolymer concrete have influenced the fracture energy. Generally, the fracture energy of geopolymer concretes tends to increase with the increase of GGBFS up to 10% in the mixture. Regardless of alkaline solution content, mixtures having GGBFS as partial replacement of fly ash showed higher fracture energy as compared to the control geopolymers (A40 S00 and A35 S00). Comparing between the controls, mixture A35 S00, which was mixed with 35% alkaline liquid and superplasticiser, showed relatively less fracture energy albeit achieving higher compressive strength than mixture A40 S00. When water and superplasticiser were added in addition to 35% alkaline solution in the mixture, these affected the fracture characteristics. For instance, mixture A40 S10 achieved higher compressive strength and fracture energy (223.1 N/m at 28 day) than those of mixture A35 S10 (197 N/m at 28 days).

Fly ash based geopolymer concrete of similar compressive strength achieved relatively higher fracture energy than OPC concrete. For instance, mixture A40 S10 achieved 26% more fracture energy at 28 days and mixture A40 S15 achieved 37% more fracture energy at 90 days as compared to OPC concrete. Sarker et al (2013) found that the fracture energy of heat cured GPC tends to increase with compressive strength at a higher rate than OPC concrete. The mean 28-day and 90-day fracture energy values of this study and previous results on heat cured GPC (Sarker et al. 2013) are plotted against compressive strength in Figure 6. It is apparent that fracture energy of the ambient cured GPC increase with the increase of compressive strength regardless of the age. The rate of increase is, however, similar to the OPC concrete. It can be noted from Figure 6 that the fracture energy values of ambient cured GPC were higher than those of the heat cured GPC. This is probably due to increased brittleness of heat cured specimens that caused abrupt failure of the concrete after reaching the peak load. As observed in load-deflection curves, the ambient cured specimens of this study showed a gradual post peak progression (Figure 3) rather than abrupt failure and resulted in larger work done (fracture energy).

Figure 6 also compares the fracture energy values obtained from experiment with those calculated using the prediction equations proposed by CEB-FIP (Eq. 2) and Bazant & Becq-Giraduon (2002) (Eq. 3). The experimental values were found to be significantly higher than those predicted using the CEB-FIP equation, whereas the equation of Bazant & Becq-Giraduon predicted values relatively closer to the experiment. However, this equation, which was originally developed from the results of OPC concretes, calculated lower values of fracture energy for geopolymer concrete. As observed in this study fly ash based geopolymer concretes generally show higher fracture energy than that of OPC concrete. Hence the equation of Bazant & Becq-Giraduon (2002) can be used conservatively for preliminary estimate of fracture energy of fly ash based GPC cured in ambient condition.

3.2.4 Critical stress intensity factor

Figure 7 shows the variation of the critical stress intensity factor (K_{IC}) with respect to compressive strength of the studied mixtures of geopolymer and OPC concrete at 28 and 90 days of age. The value of K_{IC} showed a gradual increasing trend with the increase of strength. The geopolymer mixtures followed similar values of K_{IC} as OPC concrete of similar compressive strength. This is different from that reported for heat cured geopolymer which showed higher K_{IC} values as compared to OPC concrete (Sarker et al. 2013). Compressive strength of the mixtures played a significant role on the fracture parameters. However, some of the mixtures, especially those having 35% alkaline liquid, showed different trend which is more related to flexural tensile strength. Hence the values of K_{IC} of different mixtures have been compared to flexural strength (modulus of rupture) in Figure 8. It is evident that the values of K_{IC} followed the same trend of flexural tensile strength development for all of the mixtures. The critical stress intensity at the crack tip is governed by the peak load of concrete, which is also related to tensile strength.

From Table 4 it can be seen that, most of the geopolymer mixtures followed the trend of increasing fracture energy with the increasing value of K_{IC}. However, mixtures A35 S00, which has only fly ash as the binder, 35% alkaline solution and no extra water in the mix, showed comparatively high K_{IC} but less fracture energy at both ages of 28 and 90 days as compared to other control concrete A40 S00 and concretes having GGBFS with fly ash. This is due to its (A35 S00) high flexural tensile strength and increased brittleness. This suggests that the geopolymer concretes which were mixed with 35% alkaline liquid only tend to produce geopolymer gel with relatively low fracture resisting capacity, i.e. low fracture energy but high K_{IC}.

4 Conclusions

This study investigated fracture behaviour of fly ash based geopolymer concrete cured in ambient condition. Geopolymer concretes were prepared with mainly fly ash as the binder and GGBFS as an additive. Fracture properties were investigated by three-point bending test of notched beam specimens. The following conclusions are drawn from the results of the study:

- Inclusion of GGBFS in fly ash geopolymer enhanced compressive strength. Flexural strength increased when GGBFS was added up to 10% of total binder. The flexural strength of geopolymer concretes was higher than the OPC concrete of similar compressive strength. When water was added with 35% alkaline solution to facilitate workability, it caused an adverse effect on the compressive and flexural strengths.
- Modulus of elasticity of geopolymer concrete varied likewise as compressive strength. No adverse effect on the modulus of elasticity was seen for the

presence of GGBFS in addition to fly ash in the mixture. Similar to heat cured geopolymer concrete, the modulus of elasticity of ambient cured geopolymer concrete was less than that of OPC concrete of the same compressive strength.

- The ambient cured GPC specimens showed similar load-deflection behaviour to that of OPC concrete. The ambient cured GPC showed relatively more ductility than the reported heat cured specimens, which is comparable to the OPC specimens. The peak load initiating crack varied with the flexural strength of concrete.
- Generally, the fracture energy and critical stress intensity factor increased with the increase of compressive strength regardless of age. The values of K_{IC} showed the same trend of flexural tensile strength. The fracture energy of concrete having GGBFS as an additive to fly ash was higher than that having fly ash only. Fly ash based GPC achieved relatively higher fracture energy and similar values of K_{IC} as compared to those of OPC concrete of similar compressive strength. Ambient cured GPC resulted in higher fracture energy values than that of the heat cured GPC.
- Geopolymer concretes which were mixed with 35% alkaline solution only tend to produce geopolymer gel with relatively low fracture resisting capacity, i.e. low fracture energy but high K_{IC}. When water was added in the GGBFS-blended mixture with 35% alkaline solution, similar compressive strength, higher fracture energy as compared to control mixture.

Finally, the mixture proportion of geopolymer and curing condition has significant influence on the fracture properties. Fly ash based geopolymer concrete designed for curing in ambient condition can achieve fracture properties comparable to normal OPC concrete.

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6 Compliance with Ethical Standards

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Table 1: Chemical composition of fly ash and GGBFS.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	P_2O_5	TiO_2	LOI*
Fly ash (%)	53.71	27.2	11.7	1.9	-	0.36	0.54	0.3	0.71	1.62	0.68
GGBFS (%)	29.96	12.25	0.52	45.45	-	0.31	0.38	3.62	0.04	0.46	2.39

* Loss on ignition

Table 2: Mixture proportions of GPC and OPC concrete (kg/m^3)

	Coarse aggregate			Binders			Alkaline solutions				
Mix ID	10 mm	7 mm	Sand	Fly ash	GGBFS	OPC	Na_2SiO_3	NaOH	Water	Super-plasticizer	Water/ solid (*w/s*)
A40 S00	651	558	651	400	0	-	114.3	45.7	0	0	0.202
A40 S10	651	558	651	360	40	-	114.3	45.7	0	0	0.202
A40 S15	651	558	651	340	60	-	114.3	45.7	0	0	0.202
A35 S00	655.9	562.2	655.9	400	0	-	100	40	0	6	0.180
A35 S10	655.9	562.2	655.9	360	40	-	100	40	6	6	0.193
OPC	430.4	368.8	921.4	-	-	387.9	-	-	213.4	0	0.55*

* water/cement (*w/c*) ratio for OPC concrete.

Table 3: Strength and modulus of elasticity results

Mixture	**Compressive strength, f_{cm} (MPa)**		**Flexural Strength $f_{ct.f}$ (MPa)**		**Modulus of Elasticity, E (GPa)**	
	28 day	**90 day**	**28 day**	**90 day**	**28 day**	**90 day**
A40 S00	25.6	33.4	4.89	5.91	17.4	20.0
A40 S10	38.3	45.5	5.79	6.47	22.6	23.8
A40 S15	46.6	53.3	5.26	6.12	24.6	25.2
A35 S00	32.5	41.1	6.13	7.68	19.8	22.8
A35 S10	33.3	43.0	4.27	5.52	19.2	22.2
OPC	41.6	50.6	3.68	4.97	30.6	33.4

Table 4: Fracture properties of ambient cured fly ash based geopolymer and OPC concretes at 28 and 90 days.

Mix ID	28 days						90 days					
	Mean f_c (MPa)	**P_{max} (kN)**	**G_F (N/m)**	**Mean G_F (N/m)**	**K_{IC} (MPa-mm$^{1/2}$)**	***Mean K_{IC}* (MPa-mm$^{1/2}$)**	**Mean f_c (MPa)**	**P_{max} (kN)**	**G_F (N/m)**	**Mean G_F (N/m**	**K_{IC} (MPa-mm$^{1/2}$)**	**Mean K_{IC} (MPa-mm$^{1/2}$)**
A40 S00	25.6	2.73	157.7	156.3	15.9	15.7	33.4	3.27	227.1	206.4	16.6	19.4
		2.74	154.9		15.5			3.12	184.7		19.9	
		-	-		-			3.42	207.3		21.6	
A40 S10	38.3	3.72	191.6	223.1	22.5	23.1	45.5	3.69	214.0	234.6	22.0	21.9
		3.61	216.9		22.0			3.60	216.5		20.9	
		4.02	261.0		24.7			3.76	273.2		22.7	
A40 S15	46.6	3.61	231.0	201.3	22.8	21.7	53.3	3.67	201.8	250.5	23.1	25.6
		3.60	200.6		22.4			4.24	305.8		27.3	
		3.55	172.2		19.8			4.37	244.0		26.4	
A35 S00	32.5	4.89	168.1	150.0	28.8	26.6	41.1	5.90	179.4	172.4	30.8	29.5
		4.53	145.9		26.7			5.05	185.0		25.6	
		4.09	136.0		24.3			4.88	153.0		29.0	
A35 S10	33.3	3.33	197.7	197.0	20.6	20.3	43.0	4.12	207.5	175.4	24.0	21.2
		-	-		-			3.07	143.3		18.3	
		3.29	196.3		20.1			-	-		-	
OPC	41.6	3.66	182.3	177.1	21.9	21.5	50.6	4.27	172.9	182.9	25.9	26.1
		3.24	173.2		20.5			4.33	175.1		26.8	
		3.55	175.7		22.0			4.29	200.8		25.7	

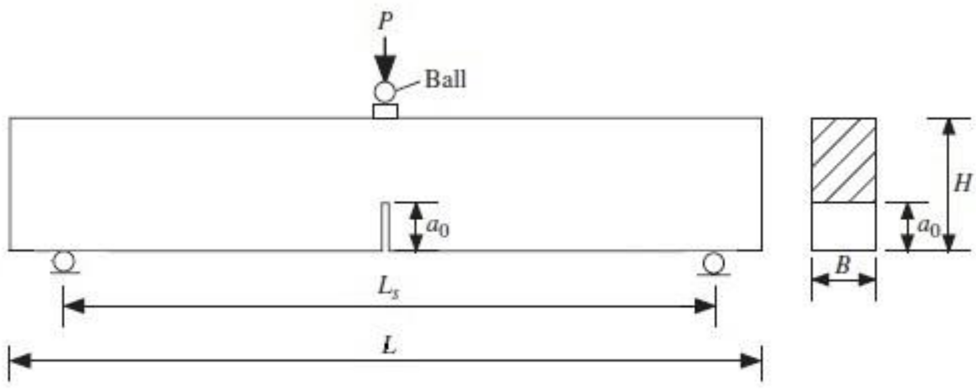


Fig. 1 Schematic diagram of three-point bending test

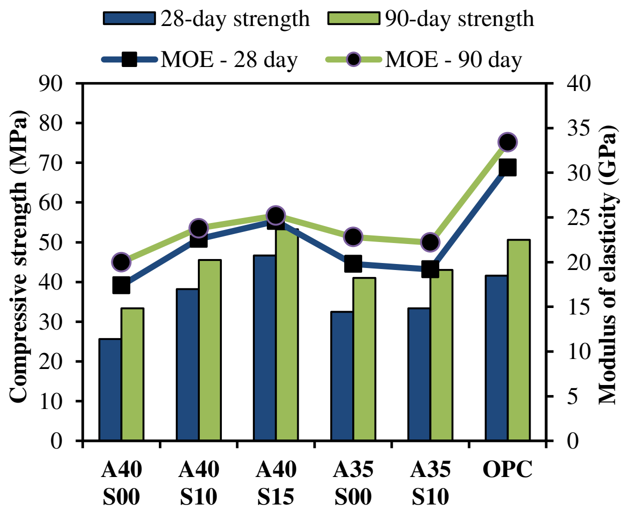
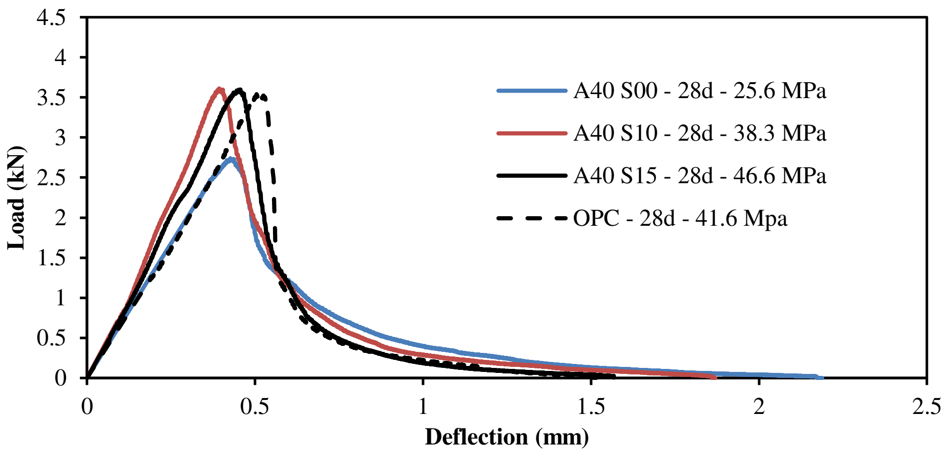
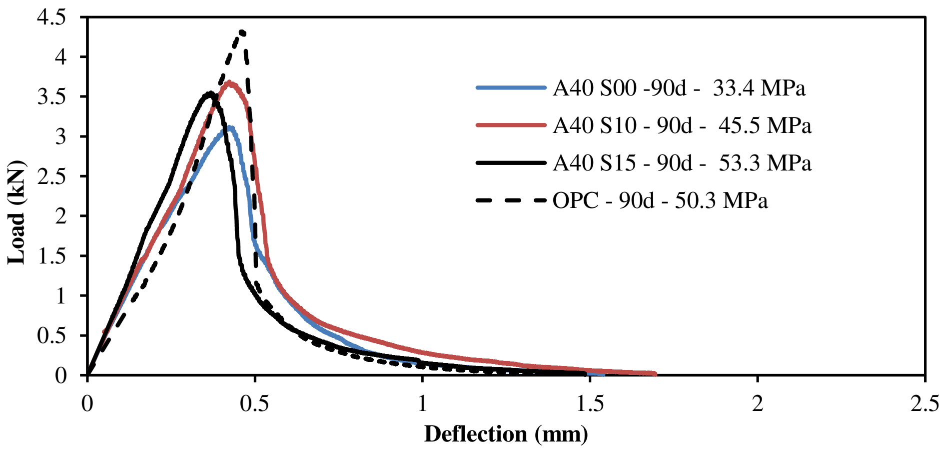


Fig. 2 Compressive strength and modulus of elasticity of geopolymer and OPC concretes



(a)



(b)

Fig. 3 Comparison of the load deflection diagrams of geopolymer concretes and OPC concrete at (a) 28 days and (b) 90 days

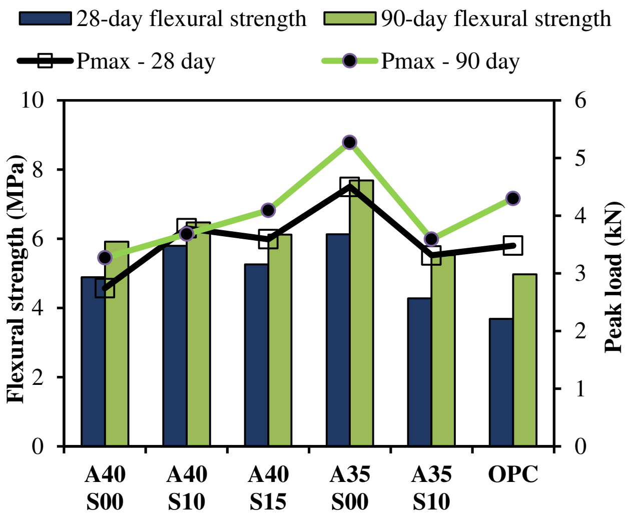


Fig. 4 Relationship of peak load to flexural strength at 28 day and 90 days

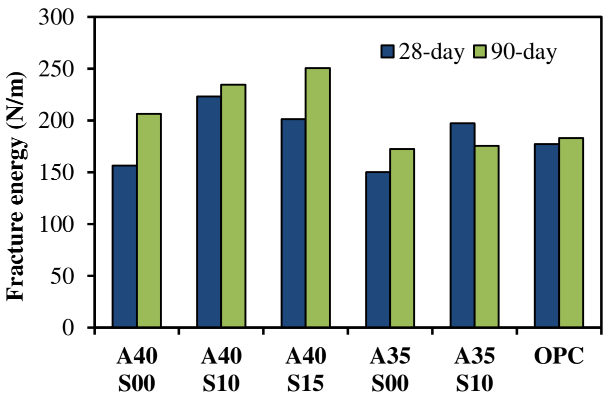


Fig. 5 Fracture energy of geopolymer and OPC concrete at 28 and 90 days

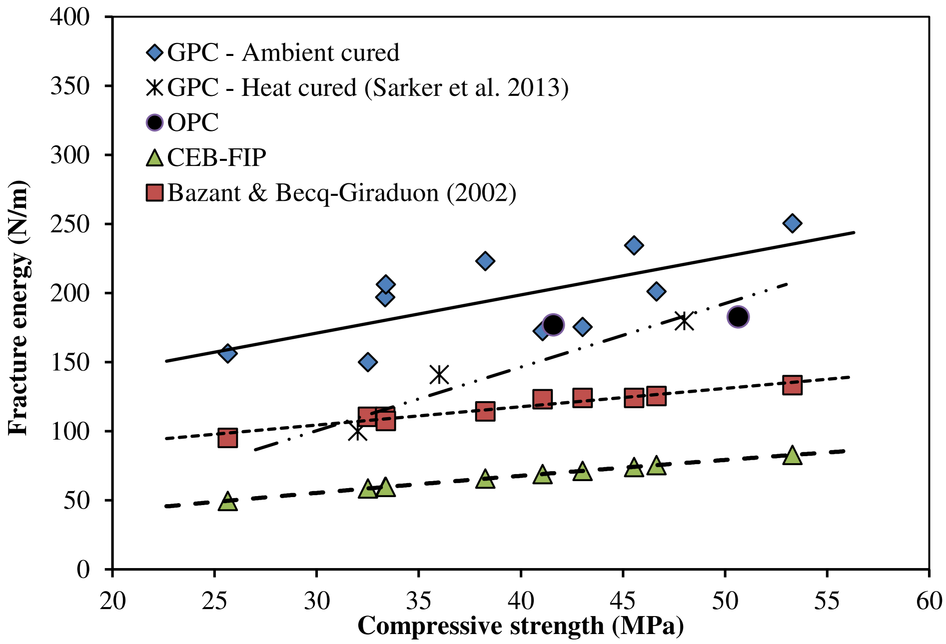


Fig. 6 Relationship of fracture energy and compressive strength

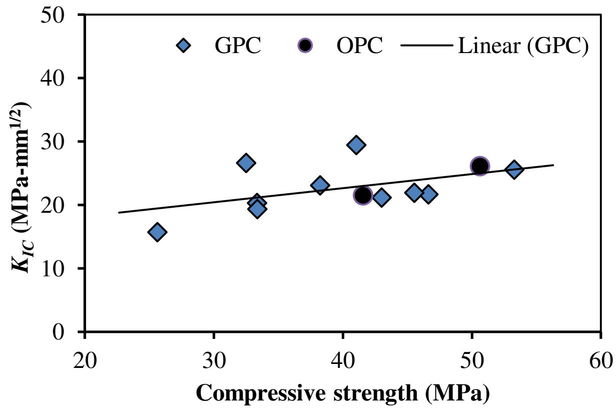


Fig. 7 Relationship of critical stress intensity factor with compressive strength

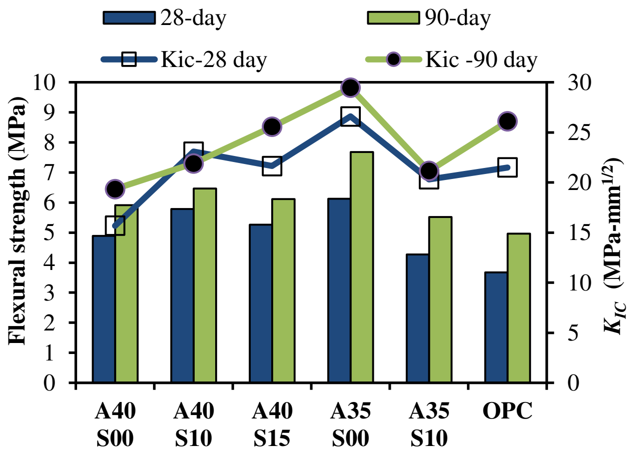


Fig. 8 Relationship of critical stress intensity factor with flexural strength.