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Mechanical and durability properties of fly ash and slag based geopolymer concrete

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Abstract. In this paper, mechanical and short-term durability properties of fly ash and slag based geopolymer concretes (FAGPC-SGPC) were investigated. The alkaline solution was prepared with a mixture of sodium silicate solution (Na_2SiO_3) and sodium hydroxide solution (NaOH) for geopolymer concretes. Ordinary Portland Cement (OPC) concrete was also produced for comparison. Main objective of the study was to examine the usability of geopolymer concretes instead of the ordinary Portland cement concrete for structural use. In addition to this, this study was aimed to make a contribution to standardization process of the geopolymer concretes in the construction industry. For this purpose; SGPC, FAGPC and OPC specimens were exposed to sulfuric acid (H_2SO_4), magnesium sulfate ($MgSO_4$) and sea water (NaCl) solutions with concentrations of 5%, 5% and 3.5%, respectively. Visual inspection and weight change of the specimens were evaluated in terms of durability aspects. For the mechanical aspects; compression, splitting tensile and flexural strength tests were conducted before and after the chemical attacks to investigate the residual mechanical strengths of geopolymer concretes under chemical attacks. Results indicated that SGPC (100% slag) is stronger and durable than the FAGPC due to more stable and strong cross-linked alumina-silicate polymer structure. In addition, FAGPC specimens (100% fly ash) showed better durability resistance than the OPC specimens. However, FAGPC specimens (100% fly ash) demonstrated lower mechanical performance as compared to OPC specimens due to low reactivity of fly ash particles, low amount of calcium and more porous structure. Among the chemical environments, sulfuric acid (H_2SO_4) was most dangerous environment for all concrete types.

Keywords: fly ash/slag based geopolymer concrete (FAGPC)/(SGPC); sulfuric acid; magnesium sulfate; sea water

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1. Introduction

The cement industry is a non-eco-friendly environmental industry due to the continuous emission of CO_2 during the production of raw materials (limestone and clay) depending on the cement production process. The development of alkali activated materials or geopolymer concrete is an up to date study among scientific community. Industrial by-products such as fly ash (FA) and ground granulated blast-furnace slag (GGBFS) are combined with strong alkaline activating solutions such as potassium hydroxide, sodium silicate, sodium hydroxide, and combination of sodium silicate and sodium hydroxide to form a geopolymer concrete with strength similar or higher than ordinary Portlan cement (OPC) concrete (Part *et al.* 2015). The geopolymerization mechanism can be identified with three phases, in the first phase dissolution of oxide materials from fly ash or slag is realized by alkaline solution, in the second phase, gel formation is occurred with transportation and condensation of the dissolved oxide ions into monomers, and in the last stage a three-dimensional aluminosilicate network is composed as a result of polycondensation and polymerization into amorphous to aluminosilicate polymers. The resulting geopolymer materials performs superior chemical and mechanical performance (He *et al.* 2013).

Geopolymer concrete attracts considerable attention among researches in recent years due to its enhanced mechanical strength and durability, thermal and chemical resistance, bond between steel reinforcements and concrete ingredients. (Thokchom *et al.* 2010). Due to these beneficial properties, the geopolymer concrete can be an alternative to ordinary Portland cement (OPC) concrete. The potential usages of the geopolymer concrete are the fiber reinforced composites, fire resistant coatings and waste immobilization solutions for the chemical and nuclear industries (Singh *et al.* 2015). Researchers mostly deal with the production processes of the geopolymer concrete and the effects of manufacturing limitations on physical and mechanical properties of geopolymer concrete. Limited studies have been carried out regarding the durability of geopolymer concretes and the results indicated that geopolymer concretes have shown superior durability performance when exposed to different acid environments compared to OPC concrete (Thokchom *et al.* 2010).

Geopolymer concretes has great potential use in concrete industry due to lack of cement, which requires high amount of energy and CO_2 amounts, lower production costs, energy efficient and environmentally favorable when compared to OPC concrete (Hasanein *et al.* 2011). Compressive strengths over 70 MPa within 24 h and high resistance to chemical attacks allow geopolymer concrete to use in commercial and industrial applications (Petermann *et al.* 2010). Concrete durability has become a critical issue for the future (Mehta and Burrows 2001) as many structures in urban and coastal environments start to deteriorate after 20-30 years exposed to acid, sulfate and chloride attacks, though their design life was at least 50 years (Visitanupong 2009).

Although there are some studies which investigated durability of geopolymer concretes under chemical attacks, either few of them is based on the together use of cementitious materials (fly ash, slag or metaokolin) with OPC concrete or the remaining very few ones were only focused on durability properties without considering mechanical performance of geopolymer concrete. Therefore, the use of the geopolymer concrete in structural designs is still limited due to both lack of standards in design codes and the lack of knowledge especially in durability aspects. In this paper, OPC, SGPC (100% slag) and FAGPC (100% fly ash) specimens were produced with same w/c or alkaline solution/fly ash or slag and aimed to investigate both mechanical and durability properties of geopolymer concretes and the results were compared with OPC concrete to understand the applicability of geopolymer concretes in structural design codes and find the optimum concrete type solution when concretes were exposed to different chemical attacks.

2. Experimental program

2.1 Materials

Two different types of geopolymer concrete (F-type fly ash and slag based) and reference concrete (produced with OPC) were produced to investigate the performance of the geopolymer concretes under chemical attacks. The crush limestone was used as coarse aggregate with a maximum grain size of 10 mm, crushed limestone (≤4 mm) and natural sand used as fine aggregate. The aggregate grading curves were found similar with previous studies (Hardjito and Rangan 2005, Wallah *et al*. 2005). The physical and chemical properties of OPC, FA, and GGBFS were summarized in Table 1.

The alkaline solution was prepared with a mixture of sodium hydroxide solution (NaOH) and sodium silicate solution (Na_2SiO_3). The sodium silicate solution (Na_2O:11.4%, SiO_2: 30.1, water: 57.5% by mass) was obtained from a local supplier. The sodium hydroxide (NaOH) solution was obtained in pellets with 97%-98% purity. The NaOH solids were dissolved in water with 14M concentration, which was considered to be weakest concentration amount of GPC under chemical attack (Kumaravel and Girija 2013). The alkaline solution was ready at least one day before its use. A polycarboxylates based high range water reducing admixture was used as a superplasticizer for workability.

2.2 Mix design and casting and curing of specimens

Several geopolymer trial batches were cast and tested, and the mixes which achieved the best cohesive and workable concrete were chosen as can be seen in Table 2 for detailed analyses. Aggregate content, alkaline solution/slag or fly ash, sodium silicate/sodium hydroxide and curing method affect strength and durability of the geopolymer concrete (Olivia and Nikraz 2012). Aggregate content in the GPC occupied the largest amount (70%) in total weight as in the case of usual concrete. Sodium silicate to sodium hydroxide ratio becomes in the range of 1.5 to 2.5 for economic reasons (Olivia and Nikraz 2012) and it was used as 2.5 in the study. Activator liquids/slag or fly ash ratio was selected as 0.45. The mixes are designed with same w/c and max. aggregate size.

Mixing procedure was as following, dry ingredients; coarse aggregates (SSD condition) and fine aggregates, slag, fly ash, cement (for related mixes) were added into the mixer and mixed for 2.5 minutes. The prepared alkaline solution and superplasticizer added in 1-minute duration and further mixed for 2.5 minute for homogeneity.

Table 1 Chemical composition and physical properties of fly ash, slag, and OPC

Component	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	Loss on Ignition	Specific Gravity	Blaine Fineness (m^2/kg)
Fly ash(%)	2.24	57.2	24.4	7.1	2.4	0.29	3.37	0.38	1.52	2.15	379
Slag (%)	34.12	36.4	10.39	0.69	10.3	0.49	0.97	0.35	1.64	2.79	418
OPC (%)	62.12	19.7	5.16	2.88	1.17	2.63	0.88	0.17	2.99	3-15	326

Table 2 Geopolymer concretes mix ingredients (w/b:0.45)

Materials	Quantity (kg/m^3)		
	FAGPC	SGPC	OPC
Cement	-	-	476
Fly Ash	500	-	-
Slag	-	500	-
Na_2SO_3+NaOH	225	225	-
Water	-	-	214
Coarse Aggregate	1100	1190	1125
Fine Aggregate	550	595	563
Superplasticizer	6	9	3

Slag based GPC (SGPC), fly ash-based GPC (FAGPC) and OPC concretes were cast for the evaluation of different concretes in terms of durability and mechanical aspects. 100×100×100 mm cube specimens were cast for compressive strength test, cylinder specimens with a diameter of 100 mm and a length of 200 mm were produced for splitting tensile strength test and flexural strength test were performed using 100×100×500 mm prismatic specimens. Required compaction was applied to specimens to eliminate the air void. After casting procedure, specimens were covered with plastic bags to minimize alkaline solution from evaporation. Then specimens together with molds were cured in an oven at 70℃ for 48 hours to activate geopolymerization as strength increase was found insignificant beyond 48 hours (Hardjito *et al.* 2005). After oven curing period, GPC specimens were put into room temperature at 23±2℃ in the laboratory till 28th day. OPC specimens were cured in water tank till 28th day.

2.3 Specimens preparation

There is no standard test method available to evaluate the resistance of concretes to chemical attack. ASTM C 267 test method (ASTM C267-01 2012) proposes that specimens should be immersed in water for 24 hours to obtain water saturated specimens before chemical attack. Therefore, specimens were stored in water for 24 hours and initial saturated weights of the specimens were measured. Then specimens were soaked in 5% sulfuric acid, 5% magnesium sulfate and 3.5% sea water solutions for a period of 4 weeks. At the same time, dummy specimens for each different concrete were left in ambient condition at a room temperature of 23±2℃ in the laboratory for 4 weeks for comparison. The chemical resistances of the concretes were evaluated by virtue of visual inspection, change in mass, change in compressive, splitting tensile and flexural strength tests.

2.4 Testing procedures

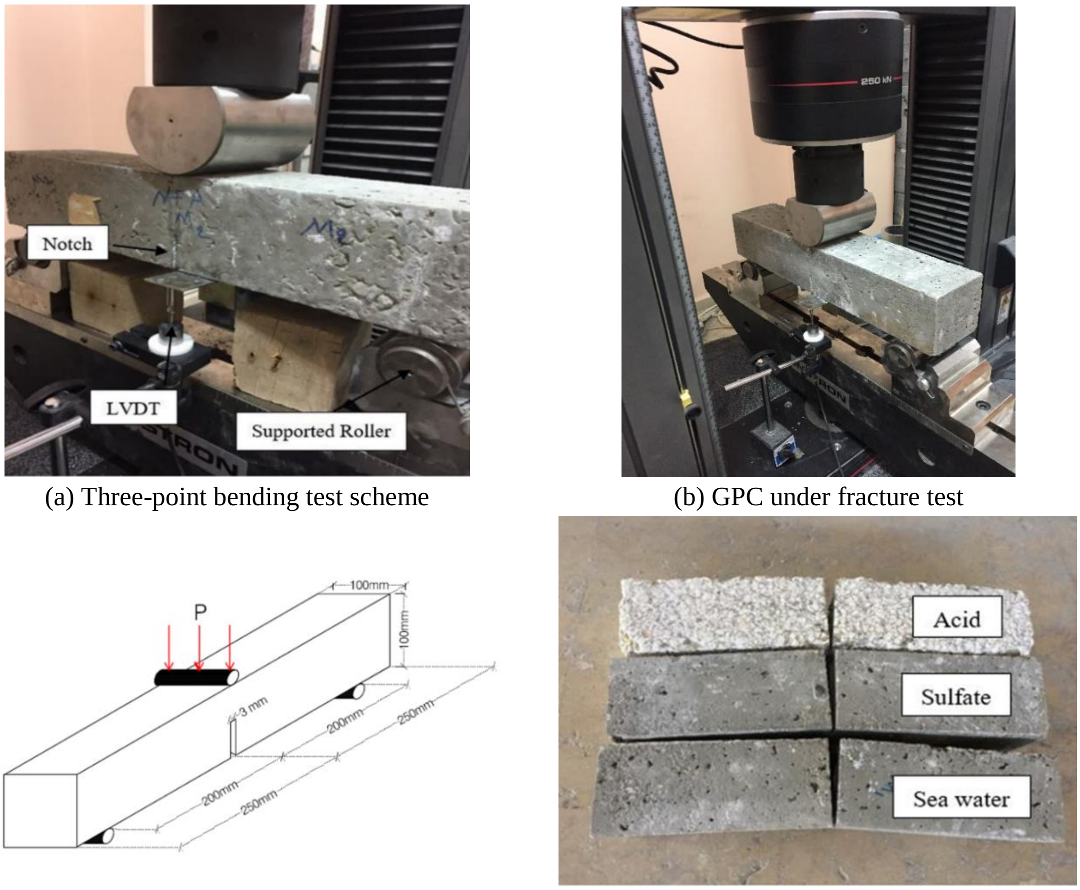
Compressive strength tests on cube specimens were conducted in accordance with ASTM C39 (ASTM C39 2012). Splitting tensile strength tests were executed on cylinder specimens according to ASTM C496 (ASTM C496 1990). Three point bending tests were performed on notched prismatic specimens according to RILEM 50-FMC/198 Committee (RILEM 50-FMC 1985) using

Instron 5500R closed-loop displacement controlled test machine. A linear variable displacement transducer (LVDT) was used to measure displacement at mid-span of the notched prismatic specimens. Notches were composed on the bottom mid-point of the specimens with a 3 mm width and 40 mm height (notch/depth:0.4). Specimens were loaded under displacement control at a rate of 0.02 mm/min. Flexural strength of specimens was calculated using 1st equation (Akcay and Tasdemir 2009)

$$f_{flex} = \frac{3P_{\max} L}{2b(d-a)^2} \tag{1}$$

where $P_{\max}$ is the maximum load (N), L is the span length (mm), b is the width of the beam (mm), d is the depth of beam (mm) and a is the depth of the notch (mm). Three-point bending test set-up details and tested specimens can be seen in Fig. 1.

Fracture energy (G_F) of the prismatic beam specimens were calculated using 2nd RILEM (RILEM 50-FMC 1985) formula



(a) Three-point bending test scheme

(b) GPC under fracture test

(c) Specimen test geometry

(d) Degradation of specimens exposed to chemical solutions

Fig. 1 Test set-up and specimens under three point bending loading

$$G_f = \frac{\left(w_o + mg\delta_s\right)}{A_{lig}} \tag{2}$$

where w_o is the area under the load-displacement curve (N-m), m is the mass of the beam (kg), g is the acceleration caused by gravity (9.81m/s^2), δ_s is the specific displacement (m) and A_{lig} is the area of the ligament (m^2).

Critical stress intensity factor (K_{IC}) was also calculated using 3rd following equation (Peterson 1980)

$$K_{IC} = \frac{3P_{\max} l}{2bd^2}\sqrt{a_0}\left(1.93 - 3.07A + 14.53A^2 - 25.11A^3 + 25A^4\right) \tag{3}$$

where $P_{\max}$ is the peak load, l is the span length, b is the width of specimens, d is the depth of specimens, a_0 is the depth of the notch, and A is the notch depth/specimen depth, respectively.

3. Results and discussion

3.1 Visual inspection

3.1.1 Specimens exposed to sulfuric acid solution

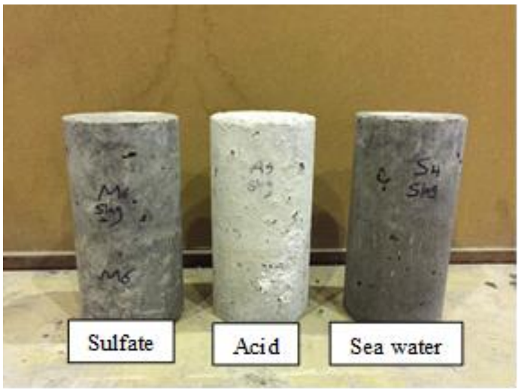
Specimens exposed to 5% sulfuric acid solutions for 4 weeks were given in Fig. 2. It was observed that surface color of the slag based geopolymer concrete (SGPC) and ordinary concrete (OPC) changed from gray to white, while the color of the fly ash specimens remains gray. For SGPC specimens, local very fine micro cracks and little surface erosions were observed at outer surface. For OPC specimens, white layer gypsum crystals were formed; local cracks and intense surface erosions can be visible easily. Moderate surface erosions were observed without color change and gypsum formation in case of FAGPC specimens.

3.1.2 Specimens exposed to magnesium sulfate and sea water (NaCl) solutions

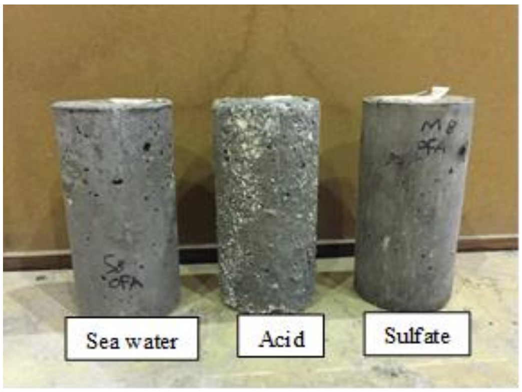
Specimens exposed to magnesium sulfate and sea water solutions were also given in Fig. 2. It can be observed that specimens maintained their initial conditions that no gypsum formation, color change, spalling and cracking was observed on the specimen surfaces. The specimens were observed to remain structurally intact. Similar findings were also found by other researchers (Bakharev 2005, Visitanupong 2009). It can be concluded that sulfuric acid attack seems more hazardous than magnesium sulfate and sea water solutions for both geopolymer and OPC concretes.

3.2 Weight change

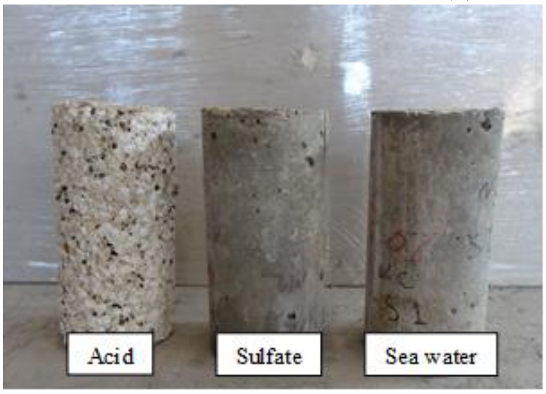
Specimen weights were taken after two weeks and one month later from various chemical exposures. Dummy specimens were also left to compare results with specimens that subjected to chemical solutions. Weight changes for the dummy specimens were measured and the results were given in Fig. 3(a). Weights of the dummy or control specimens indicated that continuous hydration reactions took place that highest weight losses (~3%) were observed for control specimens (Li and Roy 1988, Li and Ding 2003). For geopolymer specimens, weight losses were higher for FAGPC



(a) SGPC specimens



(b) FAGPC specimens

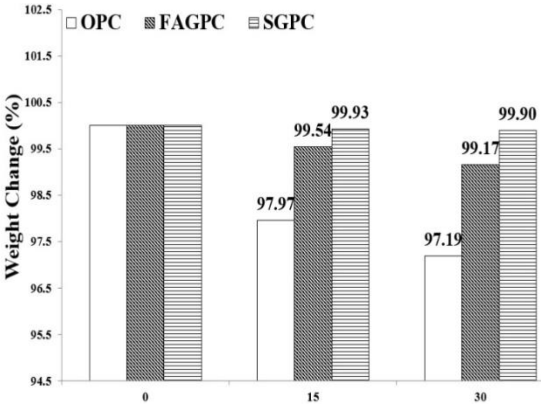


(c) OPC specimens

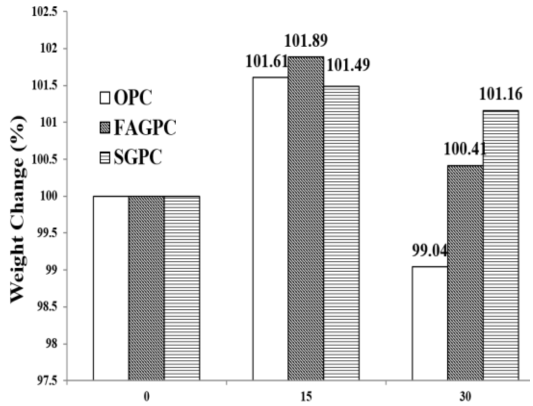
Fig. 2 Visual observation of the specimens exposed to chemical attack

specimens (~0.8%) than the SGPC specimens (~0.1%). It can be concluded that the duration of hydration process was longest in OPC followed by that of FAGPC and then that of SGPC specimens, which can be attributed to oven curing of GPC specimens. Specimens that immersed in sulfuric acid solutions gained weight after two weeks exposure, Fig. 3(b). The gained weights resulted from sulfuric acid solution absorption were 1.61, 1.89 and 1.49% for OPC, FAGPC and SGPC specimens, respectively. Weight gain due to sulfuric acid exposure were also reported in the earlier research (Alii 2007, Suresh Thokchom 2014). However, after 2 weeks, specimens started to lose their gained weights, which could be resulted from both alkali and some material dissolution from concretes into the acidic medium (Thokchom 2014). In case of OPC concrete, sulfuric acid neutralized the hydration products and interfacial transition zone between aggregate and cement was deteriorated and disintegration of the particles from OPC concrete realized (Sanni and Khadiranaikar 2012). The weight loss was measured as 1% for OPC specimens after 1 month of sulfuric acid exposure. An increase in the weight was 0.4% for FAGPC and 1.16% for SGPC, indicating no or negligible weight loss of geopolymer concretes exposed to sulfuric acid solution, due to superior durability performance of GPC.

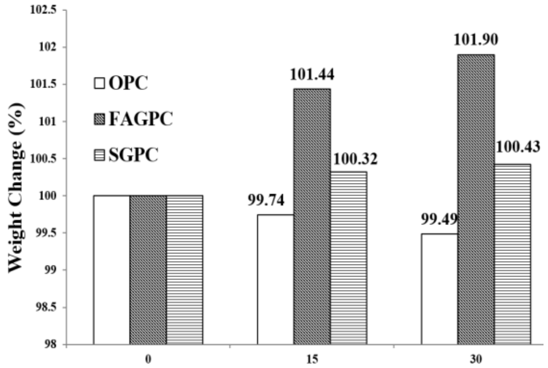
Specimens that immersed in magnesium sulfate and sea water solutions indicated that SGPC and FAGPC specimens gained weight for both 2 weeks and 1 month of exposure. The weights of SGPC specimens increased 0.32% to 0.43% for magnesium sulfate and 0.25% to 0.34% for sea



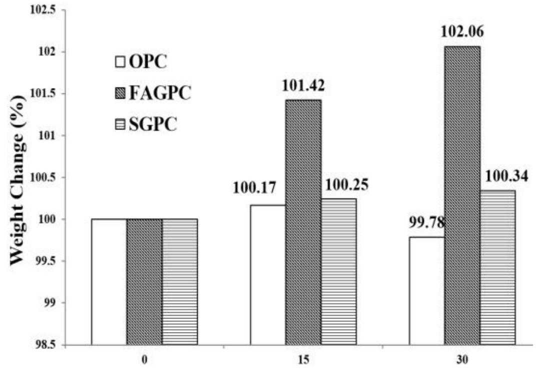
(a) Specimen exposed to ambient environment



(b) Specimens exposed to acid environment



(c) Specimens exposed to sulfate environment



(d) Specimens exposed to marine environment

Fig. 3 Visual observation of the specimens exposed to chemical attack

water solutions; whereas the weights of FAGPC specimens increased 1.44% to 1.90% for magnesium sulfate and 1.42% to 2.06% for sea water solutions after 2 weeks and one-month exposure, respectively. FAGPC specimens were more permeable than the SGPC specimens, which may be attributed to pores resulted from un-reacted fly ash particles. Weight gain due to absorption of magnesium sulfate solution was also reported by Thokchom *et al.* (2010) and Wallah and Rangan (2006). In case of OPC specimens, weight losses of 0.51% for magnesium sulfate and 0.22% for sea water solution were observed. Similar weight loss was also reported by previous study (Sanni and Khadiranaikar 2012).

3.3 Compressive strength

Compressive strength test results for unexposed (control) specimens and specimens exposed to different chemical environments were given in Fig. 4. Numbers in the top of each related graphic data indicates the residual compressive strengths (%) of the specimens after the related chemical exposure. Results indicated that control SGPC specimens demonstrated superior compressive strength performance (~100 MPa) than control OPC specimens (~55 MPa) and FAGPC specimens (~50 MPa). This is the advantage of SGPC with high durability and high mechanical performance. The lowest compressive strength was observed in FAGPC specimens due to the lower activity of

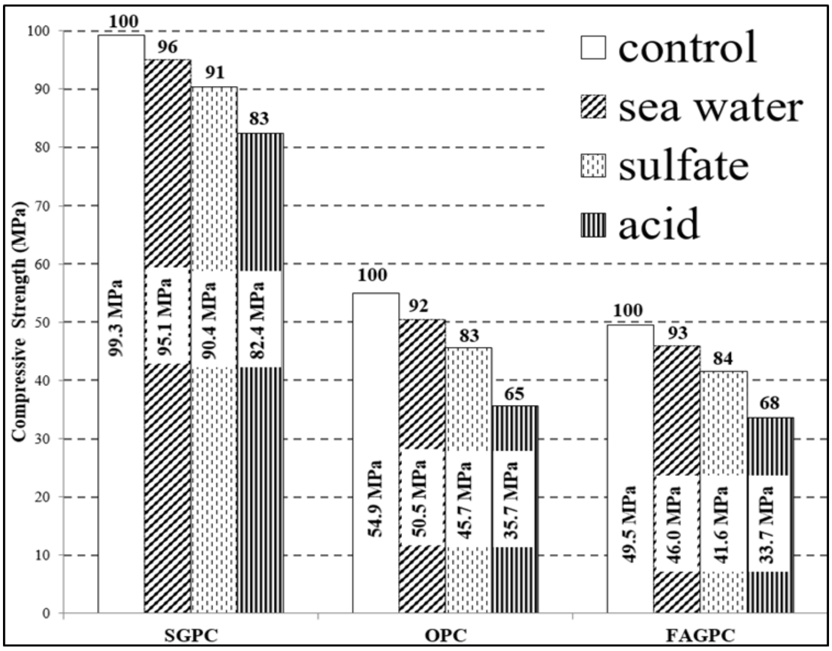


Fig. 4 Compressive strength change of the specimens exposed to different environments

fly ash (Chi and Huang 2013, Patil *et al.* 2014) and low calcium content (Dombrowski *et al.* 2007, Ganesan *et al.* 2013, Komnitsas and Zaharaki 2007). Chi *et al.* studied the effect of slag, fly ash and slag/fly ash combinations on compressive strength in geopolymer concretes and found that compressive strengths of geopolymer concretes increased in the order of fly ash based GPC< OPC<fly ash/slag combination GPC<slag based GPC. Then researchers studied the XRD patterns of the FAGPC (100% fly ash) and found out the effect of low calcium fly ash. Less amount of reactive calcium caused lower amount of calcium silicate hydrate (C-S-H) and the lower amount of calcium in the fly ash is not participated in the calcium silicate hydrate formation (main product that responsible for strength), which explained the low mechanical strength for FAGPC specimens. They also reported that calcium aluminum oxide hydroxide hydrate ($Ca_6Al_2O_6(OH)_632H_2O$) is the main hydration product for FAGPC specimens (Chi and Huang 2013).

Compressive strengths and residual compressive strength (%) of concretes exposed to various chemical environments were also given in Fig. 4. The reduction in compressive strengths for SGPC specimens were 4%, 9% and 17% exposed to sea water, magnesium sulfate and sulfuric acid, respectively. The decline in compressive strength for OPC and FAGPC specimens were 8%, 17%, 35% and 7%, 16% and 32% exposed to sea water, magnesium sulfate and sulfuric acid environments, respectively. Results indicated SGPC specimens showed best mechanical and durability performance, and FAGPC specimens performed better durability resistance than the OPC specimens. FAGPC specimens demonstrated almost similar performance with OPC concrete. However, if the results were investigated in details, it can be seen that FAGPC specimens indicated a slight better performance than OPC under chemical attacks and the performance was found better especially in sulfuric acid environment (5%). It should be remembered that one of the aim of the study was to examine short term severe chemical attack and specimens were immersed to the chemical solutions only for one month. It is expected that further exposure to the solutions, the favorable effect of FAGPC specimens on the durability properties may be seen clearly. Sulfuric acid (5%) and sea water (3.5%) were found as the most dangerous and the least dangerous chemical solution for all concrete types.

The difference between SGPC reaction and FAGPC is that two reactions occur in the case of SGPC and one reaction in the case of FAGPC. Juenger *et al*. (2011) stated that C-A-S-H gel that is highly cross-linked, was formed with a significant bound water content for slag based geopolymer concrete, whereas N-A-S-H gel that includes a very low-level chemical bound water. High bound water generally produces more pore filling capacity that reduces permeability while low bound water causes increased permeability that is resulted in poor durability. In addition, more stable cross-linked aluminosilicate polymer structure is observed in the SGPC specimens (Bakharev 2005).

Among the chemical environments, sulfuric acid seems to be hazardous than sea water and magnesium sulfate environments. The degradation mechanism under sulfuric acid for OPC can be identified that the C-S-H and N-A-S-H decalcifies as sulfuric acid spreads and hence Ca/Si ratio diminishes. The reason of weak OPC to chemical attacks is the high calcium content. Due to the high calcium content in OPC, Ca/Si ratio becomes higher and the free calcium results in deterioration of the cement paste and formation of gypsum and ettringite which can cause expansion, dimensional instability, cracking, spalling and loss of mechanical performance (Ariffin *et al.* 2013, Bassuoni and Nehdi 2007). Bacharev also studied the resistance of geopolymer concrete to acid attack and stated that geopolymer concretes have different deterioration modes. In high performance materials (for SGPC), fissures composed due to disintegration of the aluminosilicate gel in acidic medium, because of the Si-O-Si and Si-O-Al chemical bonds in the amorphous polymer matrix. In low performance materials (FAGPC), aggressive environment composed zeolites and grains which have low intercrystalline bond strength, causing loss of mechanical strength (Bakharev 2005).

In case of sulfate attacks by ions in the soil, ground water and sea water, sulfate ions diffuse into the hydrated cement paste and react with C_3A in the presence of $Ca(OH)_2$ to form ettringite and gypsum, causing expansion and deterioration of concrete (Bondar *et al.* 2015). Brucite ($Mg(OH)_2$) is also formed due to magnesium sulfate attack and brucite retards negative effects of sulfate attacks at early stage. However, decomposition of CSH gel to MSH gel is realized at later stage that causes softening of the binder and causing loss of mechanical strength (Türker *et al.* 1997). For geopolymer concretes, alkalis from geopolymer concrete diffuse into the magnesium sulfate solution and magnesium and calcium diffusion to the subsurface areas was realized to react with the sodium silicate or sodium hydroxide and potassium hydroxides in alkaline solution, causing formation of ettringite and resulting poor mechanical performance (Bakharev 2005). Therefore, fly ash based GPC specimens showed lower mechanical strength and durability characteristics than slag based GPC.

3.4 Splitting tensile strength

Splitting tensile strength results were given in Fig. 5. As in the case of compressive strength, splitting tensile strength increased in the order of FAGPC<OPC<SGPC specimens in the case of the same water or alkaline solution to cement or binder ratio. This is also observed for the other mechanical properties. The reduction in splitting tensile strengths for SGPC specimens were 3%, 8% and 16% exposed to sea water, magnesium sulfate and sulfuric acid, respectively. The decline in splitting tensile strength for OPC and FAGPC specimens were 7%, 15%, 31% and 6%, 14% and

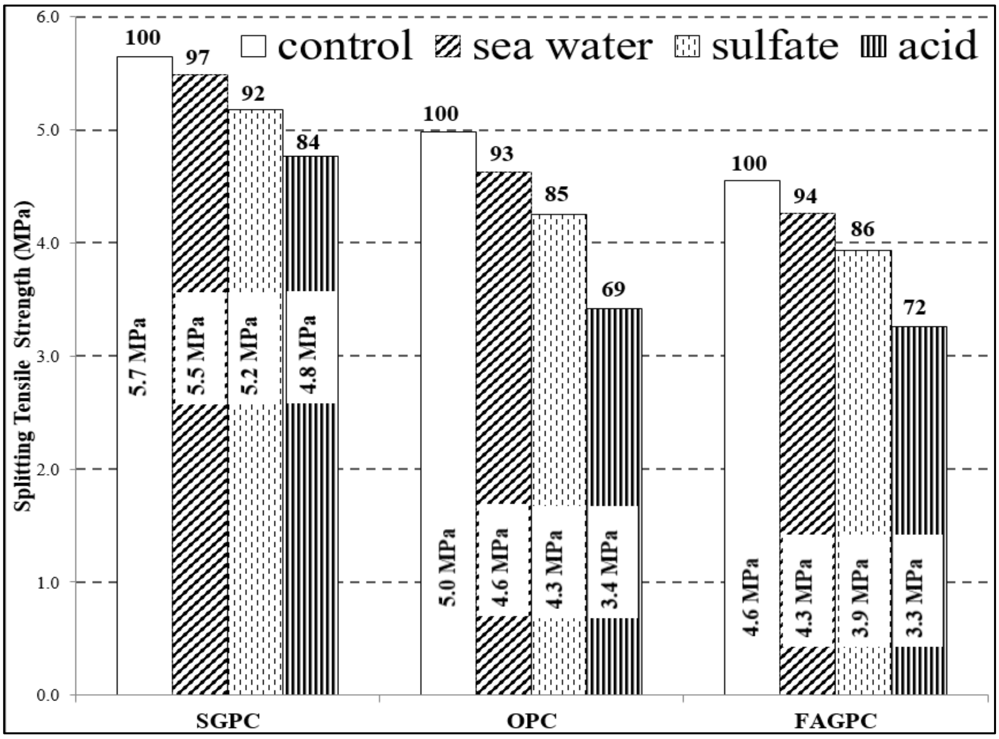


Fig. 5 Splitting tensile strength change of the specimens exposed to different environments

28% exposed to sea water, magnesium sulfate and sulfuric acid environments, respectively. SGPC demonstrated the superior performance due to its more stable cross-linked aluminosilicate polymer structure. Although mechanical strengths of the FAGPC specimens were lower than the OPC specimens, strength losses (%) of OPC specimens were found higher than FAGPC specimens. For example, strength loss of OPC specimens exposed to sulfuric acid was found to be 31 %, while the strength loss was found to be 28% for FAGPC specimens. This may be attributed to low calcium amount in fly ash particles, causing less amount of ettringite and gypsum formation, resulted in lower mechanical deterioration. Splitting tensile strength results indicated that sulfuric acid (5%) was again the most hazardous and sea water (3.5%) was the least hazardous environment for the tensile strengths of the specimens.

For structural design codes and specifications of geopolymer concrete, the paper was also aimed to obtain better relationship between the mechanical strength properties. ACI 363-R92 (ACI 363R-92 1992) and CEB-FIP (Committee Euro 1990) proposed formula (4th and 5th) between compressive strength versus splitting tensile strength.

$$f_{sp} = 0.59 * (fc')^{0.5} \tag{4}$$

$$f_{sp} = 0.301 * (fc')^{0.67} \tag{5}$$

Results showed that the proposed formulas were complied with the experimental test results with an average error of 1.69% for ACI 363-R92 and 0.85% for CEB-FIP model as is seen in Fig. 6. Therefore, these formulas can be also applicable for structural design of geopolymer concrete.

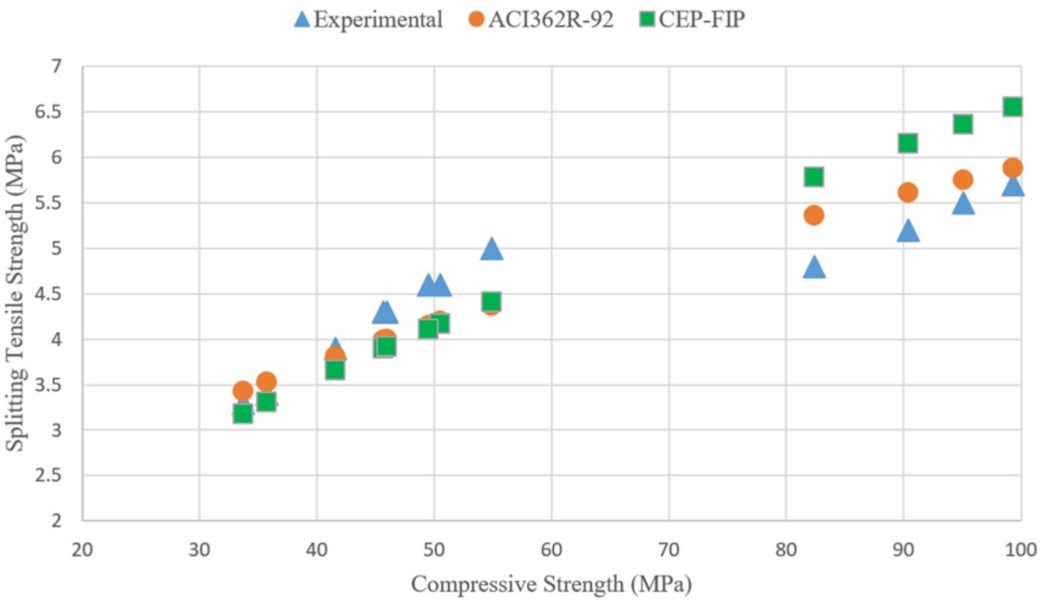
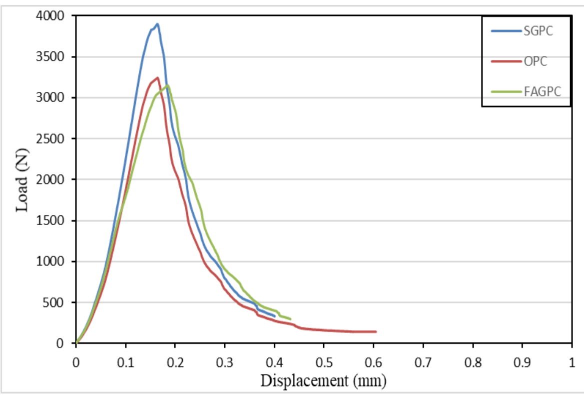
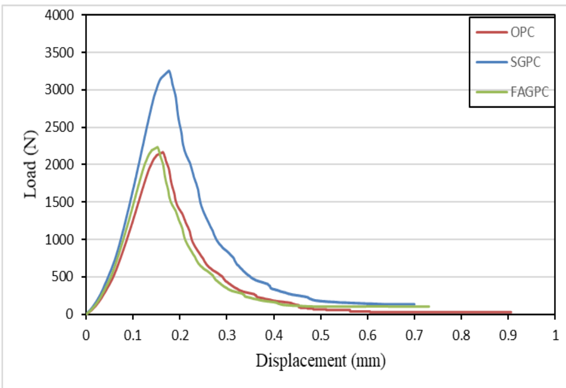


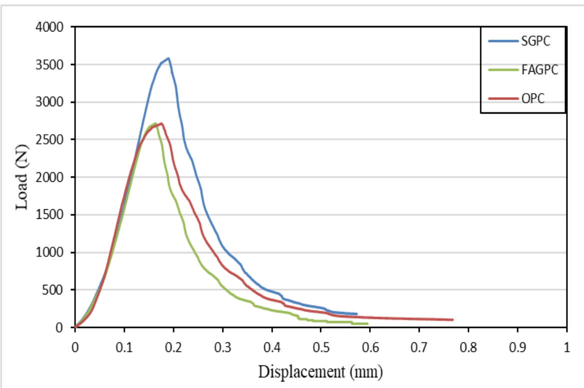
Fig. 6 Compressive strength versus splitting tensile strength relationship



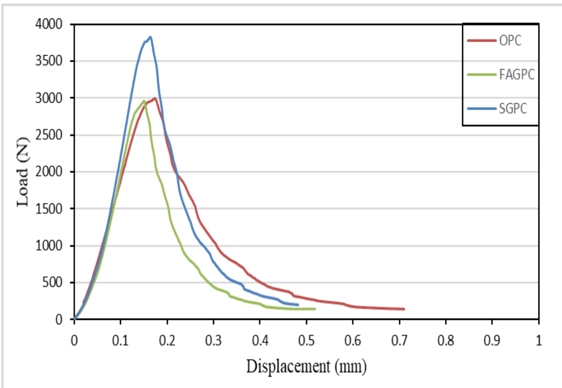
(a) Specimens exposed to ambient environment



(b) Specimens exposed to acid environment



(c) Specimens exposed to sulfate environment



(d) Specimens exposed to marine environment

Fig. 7 Load-displacement curves of test specimens under three-point bending loading

3.5 Flexural strength

Load-displacement curves under three-point bending loading were given in Fig. 7. Strain softening behavior was observed for all specimens after first cracking. SGPC specimens demonstrated highest flexural load capacity than OPC and FAGPC specimens. It was also observed that higher displacement capacities were observed for the unexposed specimens than specimens exposed to various chemical environment, which may be attributed to the poor adherence due to deleterious chemical products/reactions between environments and concrete specimens. Flexural strengths of the specimens were shown in Fig. 8 for various chemical environments. SGPC specimens showed better flexural strength and similar flexural strength and load displacement behavior were obtained for FAGPC and OPC specimens. Sulfuric acid was also seen the most hazardous environment among the tested chemical environments and OPC specimens showed the worst performance than FAGPC and SGPC specimens.

Flexural strength versus splitting tensile strength relationship was also plotted in Fig. 9. High relationship was observed (R^2=0.97) for specimens meaning that flexural strength of geopolymer concrete was estimated using splitting tensile strength of geopolymer concrete data or vice versa. Advantage of GPC is that flexural and splitting tensile strength test results of geopolymer concretes were alike with OPC, indicating geopolymer concretes can be used in structural design.

3.6 Fracture properties

Fracture energies (GF) of the specimens and critical stress intensity factor (K_{IC}) were calculated using 2nd and 3rd equations and the results were given in Table 3 to observe the fracture behavior of

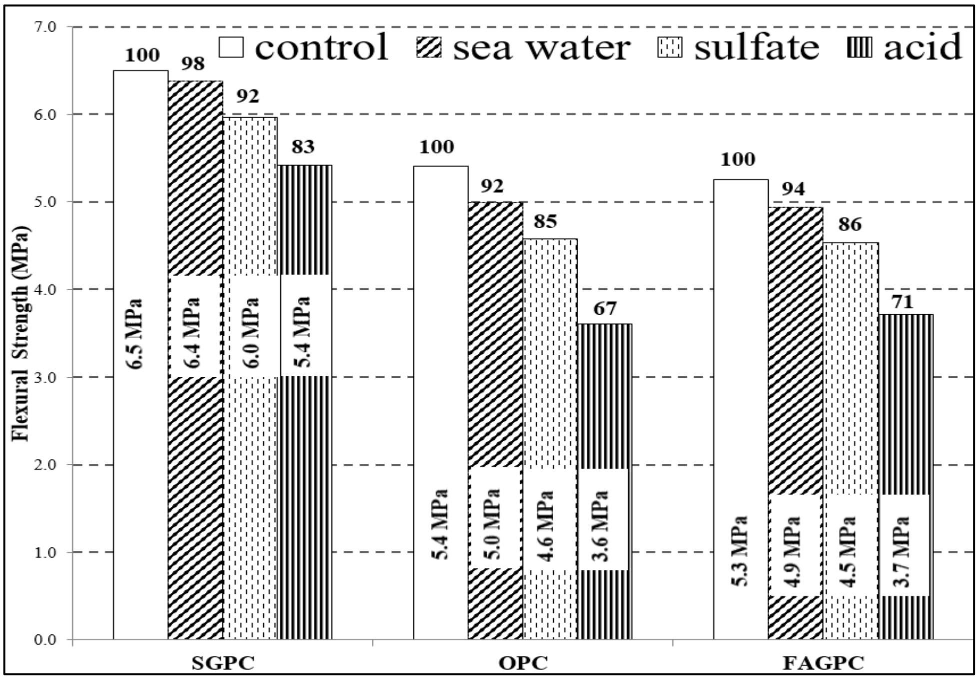


Fig. 8 Flexural strength change of the specimens exposed to different environments

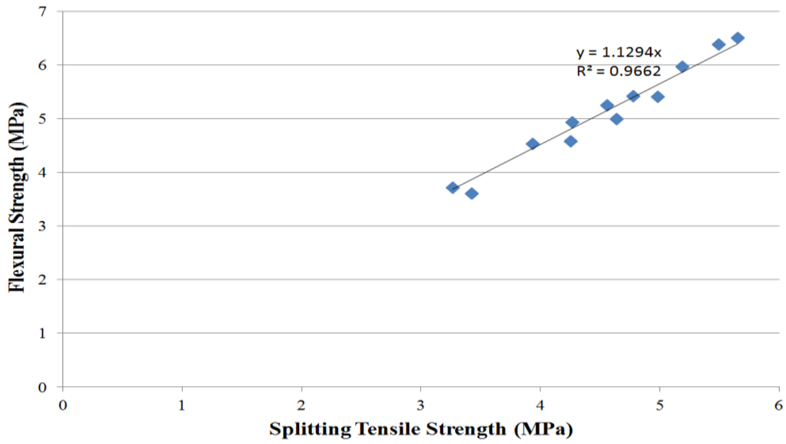


Fig. 9 Flexural strength vs splitting tensile strength relationship

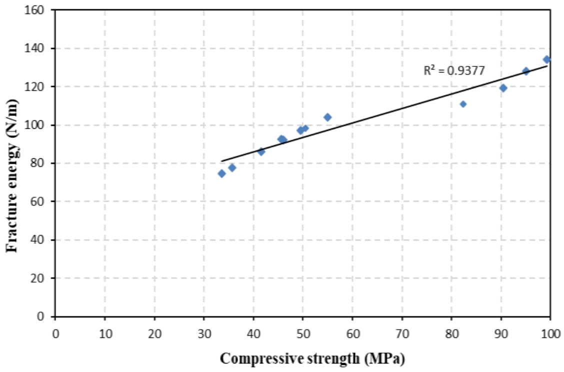
Table 3 Fracture energy and stress intensity factor of specimens under different environments

Environment	Fracture Energy (N/m)			Stress intensity factor (MPa*mm$^{1/2}$)		
	SGPC	OPC	FAGPC	SGPC	OPC	FAGPC
Ambient (Control)	134	104	97	30.8	25.6	24.9
Sea water (3.5%)	128 (4%)	98 (6%)	92 (5%)	30.2 (2%)	23.6 (8%)	23.4 (6%)
Magnesium Sulphate (5%)	119 (11%)	92 (12%)	86 (11%)	28.3 (8%)	21.7 (15%)	21.5 (14%)
Sulphuric acid (5%)	111 (17%)	78 (25%)	75 (23%)	25.7 (17%)	17.1 (33%)	17.6 (29%)

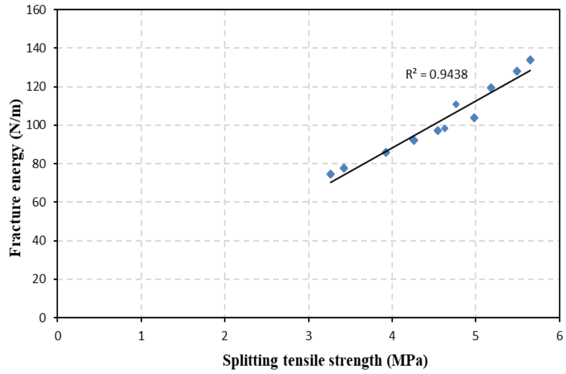
geopolymer concrete under different chemical environments. The stress intensity factor (K_{IC}) refers to the amount of stress concentration near the crack tip when the crack begins to propagate.

Fracture energy and stress intensity factor results indicated that SGPC specimens demonstrated superior fracture performance than OPC and FAGPC specimens. It was also observed that fracture energies of the OPC specimens were higher than FAGPC specimens; however, the fracture energy loss due to chemical environments was lower in the case of FAGPC specimens. This may be attributed to the low calcium amount in the FAGPC specimens. Similar stress intensity factor results were observed for OPC and FAGPC specimens, which may be attributed to the close compressive and splitting tensile strength values of the both concretes.

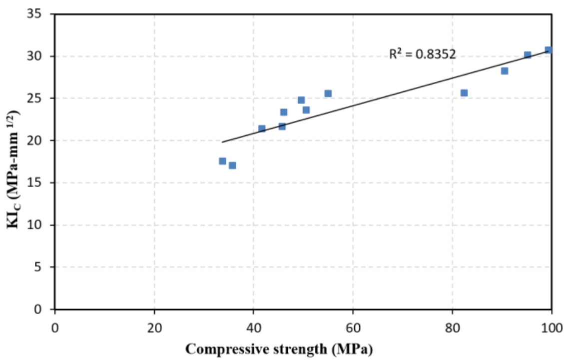
Fracture energy and critical stress intensity factor versus compressive and splitting tensile strength relationships were given for concretes to observe the effect of mechanical strength to fracture properties of the concretes as shown in Fig. 10. Results indicated that fracture energy of the concretes were increased with an increase in both compressive and splitting tensile strengths. It was found that there are good relationships between fracture energy and compressive strength (R^2=0.94) and fracture energy and splitting tensile strength (R^2=0.94) as can be seen in Figs. 10(a)-10(b), respectively. Similar observation that fracture energy of the heat cured FAGPC specimens was increased as compressive strength increased was also reported by Sarker *et al.* (Sarker, Haque, and Ramgolam 2013). In addition to this, critical stress intensity factor (KIC) versus compressive and splitting tensile strength relationships were also investigated in the study and critical stress



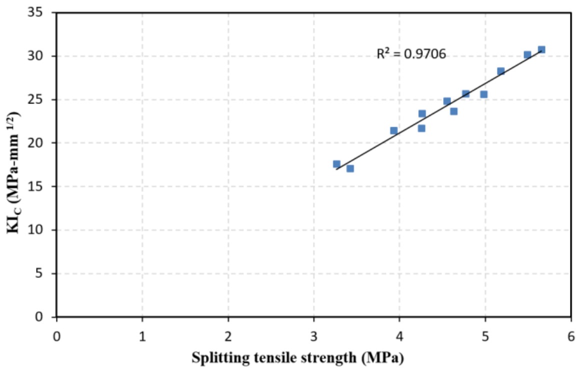
(a) Fracture energy - compressive strength



(b) Fracture energy- splitting tensile strength



(c) Stress intensity factor - compressive strength



(d) Stress intensity factor - splitting tensile strength

Fig. 10 Fracture relationships of specimens under different environments

intensity factor was increased with an increase in both compressive strength and splitting tensile strength. It was found out that there is a good relationship between critical stress intensity factor and compressive strength (R^2=0.84) and there is a perfect relationship between critical stress intensity factor and splitting tensile strength (R^2=0.97) as can be seen in Figs. in 10.c-10.d, respectively. It was concluded that fracture energy depends on both compressive and splitting tensile strength of concrete; however, the effect of splitting tensile strength on critical stress intensity factor (KIC) was found more significant than the effect of compressive strength.

4. Conclusions

In the study, the effects of chemical attacks (5% sulfuric acid, 5% magnesium sulfate and 3.5% sea water) on both mechanical and durability properties of slag based geopolymer concrete (SGPC) and fly ash based geopolymer concrete (FAGPC) were investigated and the results were compared with OPC. In addition to this, the applicability of produced geopolymer concretes to structural use in terms of durability and mechanic aspects was also investigated. The findings were summarized below.

• Visual inspection results indicated that specimens exposed to sulfuric acid solution, SGPC specimens showed little surface deterioration with changed color from gray to white, FAGPC specimens showed moderate surface deterioration without color change and OPC specimens exhibited greatest surface deterioration with color change from gray to white.

• Geopolymer and OPC specimens were visually observed to remain structurally intact and maintained their initial conditions without color change, spalling and cracking when they were exposed to magnesium sulfate and sea water attack. Visual inspection results explained that sulfuric acid attack was determined as the most dangerous chemical environment.

• Weight loss of OPC specimens due to hydration reactions in ambient condition (control specimens) was much more than heat cured FAGPC and SGPC specimens, respectively.

• Weight gain was observed for almost all specimens immersed in chemical solutions during first 15 days of exposure due to solution absorption and expansion occurred by gypsum formation. Weight gain was observed to be higher for specimens exposed to sulfuric acid solution than specimens immersed in magnesium sulfate and sea water solutions.

• However, after one-month exposure to the chemical solution, OPC specimens exposed to all chemical solutions lost weight due to deterioration. Low amount of weight loss observed for SGPC specimens exposed to sulfuric acid and almost similar weights were observed in the case of SGPC specimens exposed to magnesium sulfate and sea water solutions. For FAGPC specimens, weight gain was observed for specimens immersed into both magnesium sulfate and sea water solutions, while weight lost was observed in the case of sulfuric acid attack. Results indicated that SGPC specimens demonstrated the greatest durability against weight change due to attacks.

• Compressive strengths, splitting tensile strength, flexural strength, fracture energy and stress intensity factor results were decreased in the order of sulfuric acid > magnesium sulfate > sea water > control environments, respectively for all concrete types. Sulfuric acid and sea water attacks were observed to be the most and least dangerous environments for all concrete types, respectively.

• SGPC specimens showed superior performance in terms of both mechanical and durability aspects than OPC and FAGPC specimens at same water or alkaline solution to cement or slag/fly ash ratio due to more stable cross-linked alumina-silicate polymer structure of SGPC.

• Although all mechanical strength test results (compressive, splitting, flexural, i.e.) before and after chemical exposure of the OPC specimens were slightly higher than the FAGPC specimens, loss of mechanical strengths due to chemical attack was found to be less on FAGPC specimens, which may be attributed to low calcium amount of the FAGPC specimens.

• Three-point bending test results indicated that both flexural strength and displacement capacities of the both geopolymer and OPC specimens were reduced after chemical exposures.

• Splitting tensile strength results of geopolymer concretes were well predicted by using ACI 363-R92 and CEB-FIP models and both flexural and splitting tensile strength test results of geopolymer concretes were alike with OPC, indicating geopolymer concretes can be used structural design

• It was found from fracture test results that there are good relationships between fracture energy and compressive strength (R^2=0.94) and fracture energy and splitting tensile strength (R^2=0.94); similar good relationships were also observed critical stress intensity factor versus compressive and splitting tensile strength test, indicating OPC concrete can be replaced by geopolymer concretes.

• It can be concluded that SGPC can be used in aggressive environments (sewage, underground structure) due to superior durability to chemical attack as compared to FAGPC and OPC.

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