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Effect of fly ash and GGBS combination on mechanical and durability properties of GPC

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Abstract. Geopolymer is a sustainable concrete, replaces traditional cement concrete using alternative sustainable construction materials as binders and alkaline solution as alkaline activator. This paper presents the strength characteristics of geopolymer concrete (GPC) developed with fly ash and GGBS as binders, combined Sodium silicate (Na_2SiO_3) and Sodium Hydroxide (NaOH) solution as alkaline activators. The parameters considered in this research work are proportions of fly ash and GGBS (70-30 and 50-50), curing conditions (Outdoor curing and oven curing at 600℃ for 24 hours), two grades of concrete (GPC20 and GPC50). The mechanical properties such as compressive strength, split tensile strength and flexural strength along with durability characteristics were determined. For studying the durability characteristics of geopolymer concrete 5% H_2SO_4 solutions was used and the specimens were immersed up to an exposure period of 56 days. The main parameters considered in this study were Acid Mass Loss Factor (AMLF), Acid Strength Loss Factor (ASLF) and products of degradation. The results conclude that GPC with sufficient strength can be developed even under Outdoor curing using fly ash and GGBS combination i.e., without the need for any heat curing.

Keywords: recycled concrete aggregate; waste; strength; workability

1. Introduction

Geopolymers can be formed by treating aluminosilicate materials (such as fly ash, GGBS etc.) with alkaline activators at outdoor and elevated temperature (60-90℃). According to Hardjito *et al.* (2004) sodium activators produce high strength GPC as compared to potassium activators. The commonly used combination of alkaline activators were NaOH and Na_2SiO_3, which binds the loose aggregate in mixture to form geopolymer concrete (GPC) with sufficient strength, durability and low creep (Wang *et al.* 1995). This alkaline solution reacts with SiO_2 and Al_2O_3 in fly ash to form N-A-S-H gel; and calcium in GGBS to form C-S-H gel. The curing conditions, especially temperature significantly enhances the polymerization process (Glukhovsky 1959). The strength and performance of GPC depends on type of alkaline activator, concentration of alkali and curing temperature. Purdon (1940) was probably the first researcher to investigate the alkaline activated slags. Subsequent to this, many researchers performed studies on alkali activated slag and it shows

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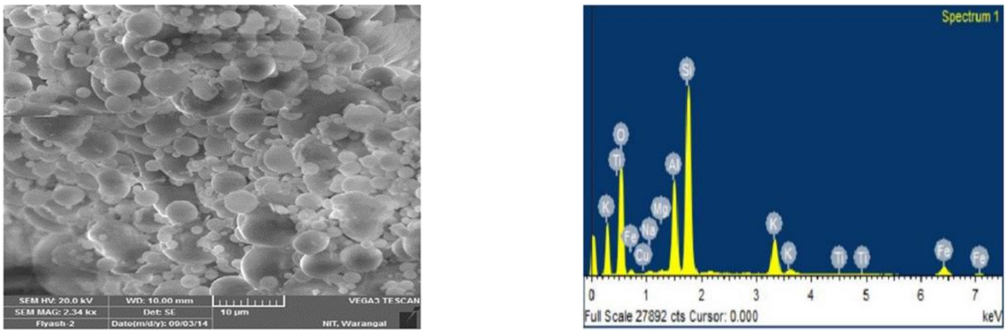
a promise as an alternative binder to OPC. Various authors studied the importance of Na_2SiO_3/NaOH and suggested 2.5 as it leads to attain maximum compressive strength at a constant binder content (Pinto 2004). The use of high alkaline solution as activators to produce artificial cement from by-products such as fly ash and GGBS was introduced by (Davidovits 1978). Later on several investigators (Wang *et al.* 1995, Hardjito *et al.* 2004) study GPC by varying parameters such as strength, durability, workability. The results suggested that geopolymer concrete made by fly ash having good strengths. Higher concentration of alkaline solution and high temperatures results in a strength about 50 MPa (Puertas *et al.* 2000). Though Fly ash activated geopolymers have good performance, it is having some setbacks like setting time, workability, curing regime and strength at ambient temperature (Fernandez-Jimenez *et al.* 2002). High temperatures (60-90℃) are required in order to attain the strength for fly ash based geopolymers. Even though exposing specimens to higher temperatures is possible in laboratory, it would be difficult to maintain higher temperatures while curing at in-situ conditions. So in order to overcome the setbacks, trials are made with alkali activated slag. Even with the alkali activated slag, there is a problem with the setting time and workability (Pradip Nath *et al*. 2014). To improve the workability of fly ash based GPC, naphthalene based super plasticizers can be used (Hardjito *et al.* 2004). Subsequent to this to make common use of GPC as similar to that of OPC, researchers proposed mix proportions (Rangan BV 2008, Anuradha *et al.* 2012). The parameters required to quantify mix proportions are concentration of alkaline solution, water to geopolymer solids ratio, alkaline solution to fly ash ratio (Talha Junaid *et al.* 2015). With the requirement of high performance concrete, the current study is focused on fly ash and GGBS. Though the studies conducted by researchers highlighted the potential of geopolymer concrete made with combinations of fly ash and GGBS to replace high performance conventional concretes (Manjunatha *et al.* 2014, Janardhanan *et al.* 2015), still there is lack of proper mix designs and guidelines for GPC with combination of fly ash and GGBS. Resistance of geopolymer concrete to acid and sulphate attack was studied by (Bhakhrev 2005, Olivia and Hameed 2011) and reported that GPC has better resistance to aggressive environments. Many researchers studied the effect of acids on durability behavior of geopolymer concretes produced by activating GGBS alone or blended fly ash and GGBS which have good resistance than OPC (Blaakmeer 1994, Changgao 1997 and Xincheng 1999). (Rostami *et al.* 1996) developed the chemically activated fly ash which exhibited better resistance to acids than Portland cement concrete. According to (Skvara and Bohunek 1999) the alkali activation through NaOH and Na_2SiO_3 are capable for increasing the reactive substances and properties for fly ash alone or blended fly ash and GGBS. The aforementioned studies indicate the effect of acids of geopolymer concrete. However, the research carried out on varying the amounts of fly ash and GGBS are limited. Thus, the present study seeks to investigate considering the parameters viz. type of binder, binder content, alkaline/binder ratio. The NaOH concentration of 8M and mass ratio of Na_2SiO_3 to NaOH is maintained constant at 2.5 throughout the investigation.

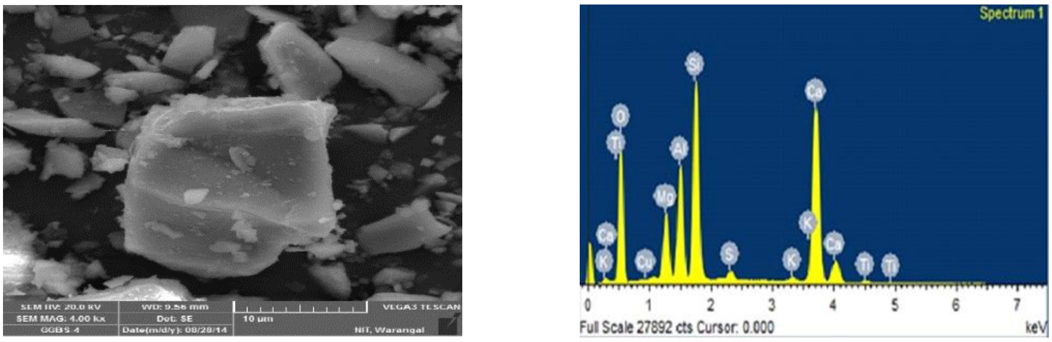
2. Research significance

The available literature suggest that many researchers had carried out works on geopolymer concrete but a proper mix design was not developed till now using both fly ash and GGBS as binders. Hence proper quantification for geopolymer concrete materials is necessary to use GPC with ease for practical applications. It is necessary to make geopolymer concrete because it has enormous potential applications for the construction industry. This study examines the



(a) SEM of fly Ash (b) EDXA of Fly ash

Fig. 1 SEM and EDXA of fly Ash



(a) SEM of GGBS (b) EDXA of GGBS

Fig. 2 SEM and EDXA of GGBS

performance of geopolymer concrete as a structural grade for concrete application, aiming for the optimal percentage replacement of GGBS to meet target strength of GPC20-GPC50. A comprehensive assessment of mechanical and durability characteristics have been evaluated for making geopolymer concrete as a structural grade concrete.

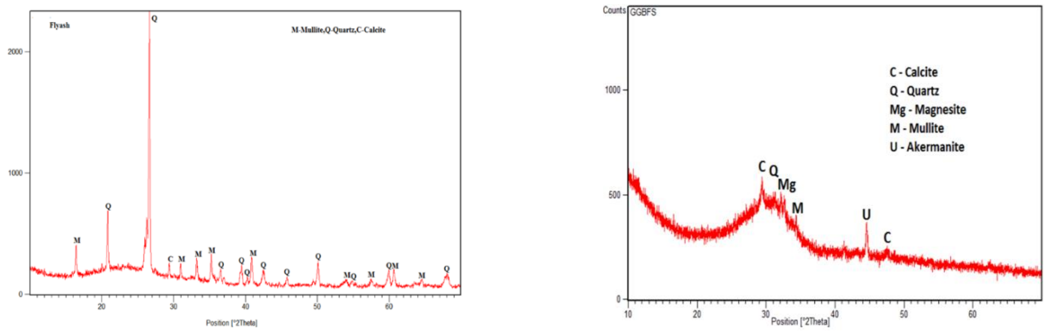
3. Experimental programme

The experimental investigation consisted of finding the fresh state and hardened state properties of geopolymer concrete by casting specimens for GPC20, GPC50 grades. Total of 42 cubes of size 150 mm×150 mm×150 mm, 12 cylinders of size 150 mm dia, 300 mm height and 12 prisms of dimensions 100 mm×100 mm×500 mm were cast and tested for determining mechanical properties such as flexural, compressive and split tensile strengths along with durability characteristics.

3.1 Materials

The materials used in this study were as follows:

3.1.1 Fly ash and GGBS were used as binder materials



(a) XRD pattern of fly ash (b) XRD pattern of GGBS

Fig. 3 XRD pattern of fly ash and GGBS

Table 1 Chemical composition of fly ash and GGBS

Chemical Composition	Fly ash (% by mass)	GGBS (% by mass)
SiO_2	60.11	34.06
Al_2O_3	26.53	20
Fe_2O_3	4.25	0.8
SO_3	0.35	0.9
CaO	4.00	32.6
MgO	1.25	7.89
Na_2O	0.22	NIL
LOI	0.88	NIL

GGBS was obtained from Toshali Cements Pvt ltd, Bayyavaram, India. Fly ash was obtained from NTPC, Ramagundam, India. Chemical composition details are shown in Table 1. The morphology of fly ash and GGBS were examined using Scanning Electron Microscope (SEM) and are shown in Figs. 1 and 2. Specific gravity of fly ash and GGBS were 2.17 and 2.90, respectively. Fly ash particles were spherical in shape and are mainly composed of large percentages of silica and alumina. The shape of the GGBS grains is crystalline and angular form. From the EDAX, it can be observed that GGBS was predominated with calcium and silica compared to other elements. The calcium content of the slag results in raised basicity and increases the compressive strength. The mineralogical characterization of fly ash and GGBS sample were carried out by X-Ray diffraction analysis which is presented in Fig. 3. The XRD image of GGBS depicts glass content as 99%. The higher amounts of glass content helps in increasing the hydraulic activity thus accelerates polymerization process.

3.1.2 Fine aggregate (FA)

The fine aggregate used in the present study conforms to Zone-2 as per BIS: 383-1970. It was obtained from a nearby river source. The specific gravity and bulk density of fine aggregate were 2.65 and 1.45 gm/cc respectively.

3.1.3 Coarse aggregate (CA)

Locally available crushed granite was used as coarse aggregate having a nominal size of 20

Table 2 Mix proportions of geopolymer concrete

Notation	Alkaline/Binder ratio	Binder (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Alkaline Solution (kg/m^3)
$A_1F_{70}G_{30}$	0.45	360	774	1090.8	162
$A_2F_{70}G_{30}$	0.5	360	774	1090.8	180
$A_3F_{70}G_{30}$	0.55	360	774	1090.8	198
$A_4F_{70}G_{30}$	0.6	360	774	1090.8	216
$B_1F_{70}G_{30}$	0.45	420	810.6	966	189
$B_2F_{70}G_{30}$	0.5	420	810.6	966	210
$B_3F_{70}G_{30}$	0.55	420	810.6	966	231
$B_4F_{70}G_{30}$	0.6	420	810.6	966	252
$C_1F_{70}G_{30}$	0.45	450	760.5	972	202.5
$C_2F_{70}G_{30}$	0.5	450	760.5	972	225
$C_3F_{70}G_{30}$	0.55	450	760.5	972	247.5
$C_4F_{70}G_{30}$	0.6	450	760.5	972	270

mm. The aggregates were well graded as per BIS: 383-1970. The specific gravity was 2.8 and the bulk density was 1.5 gm/cc.

3.1.4 Super plasticizer (SP)

Sulphonated Naphthalene formaldehyde based super plasticizer is used for improvement of workability.

3.2 Preparation of alkaline solution

To prepare one litre of 8M NaOH solution, 320 grams NaOH pellets were dissolved in potable water. To achieve the required strength the ratio of Na_2SiO_3 to NaOH was set as 2.5 and the mixed solution was stored for 24 hours (The dissolution of NaOH in water is an exothermic reaction which releases a substantial amount of heat when added in concrete, hence the heat liberated is to be reduced and come down to ambient temperature before it is used for casting).

3.3 Mix proportions

Trial mix proportions were derived by considering the guidelines of Indian Standard mix designs and from design procedures found in literature of GPC (Subhash *et al.* 2015). Binder content (fly ash and GGBS), alkaline/binder ratio, fly ash/GGBS ratio, type of curing and age of curing were considered as parameters in present investigation. Three binder contents (360, 420, 450 kg/m^3) with four alkaline/binder ratios (0.45, 0.50, 0.55 and 0.60) were studied along with 70-30, 60-40, 50-50 as different combinations of fly ash and GGBS. The final mix proportions are presented in Table 2. When fly ash is partially replaced by GGBS, outdoor curing is self-sufficient to attain the required strength (Nath and Sarker 2014). As outdoor curing is the only possible curing method for in-situ casting, it is necessitated to achieve same strength acquired by oven curing. Hence, the present study investigates on elimination of oven curing and attainment of

Table 3 Mix proportion of geopolymer concrete

Mix	Fly ash (Kg/m^3)	GGBS (Kg/m^3)	Fine Aggregate (Kg/m^3)	Coarse Aggregate (Kg/m^3)	Alkaline Solution (Kg/m^3)	NaOH (Kg/m^3)	Na_2SiO_3 (Kg/m^3)
GPC20	252	108	770	1090.8	198	141.42	56.57
GPC50	225	225	761	973	225	160.71	64.28

(a) Outdoor curing (b) Oven curing

Fig. 4 Specimens kept at outdoor and oven Ccring

required target strength by outdoor curing itself with replacement of fly ash by GGBS. Several trials were carried out considering the basic criterion to develop mixes of average cube strength around 20 MPa, 30 MPa, 40 MPa, 50 MPa at 28 days under outdoor curing and at the lower concentration of alkaline solution. Also it has been ensured that all these mixes have medium workability (as per IS 456 2000) at fresh state. The compressive strength of outdoor cured GPC specimens was compared with that of oven cured specimens.

A, B, C represents 360, 420, 450 kg/m^3; F and G represents Fly ash and GGBS contents.

In the present investigation, a series of laboratory experiments were performed to determine the optimum mix proportions of concrete with minimum binder content. The GPC20 grade was developed by taking alkaline solution to binder ratio of 0.55 and binder (Fly ash+GGBS), 360 kg/m^3 with fly ash to GGBS ratio 70:30. Similarly for developing GPC50 grade, the alkaline solution to binder (Fly ash+GGBS) is taken as 0.5 with binder content 450 kg/m^3 and fly ash: GGBS was taken as 50:50. After certain trial mixes and testing of cast specimens, a final mix proportion is shown in Table 3.

3.4 Casting and curing of geopolymer concrete

The individual dry materials were weighed and mixed using a rotating drum type pan mixer of 100 kg capacity. The alkaline solution and Sulphonated Naphthalene formaldehyde based super plasticizer of required dosage was added after uniform mixing of dry materials. Proper homogenous mixing would be ensured by continuous mixing for 5 to 7 minutes and fresh property test was conducted to find the workability of GPC. This concrete was transferred into concrete moulds (150 mm×150 mm×150 mm) followed by table vibration for a period of 45 seconds and left to set for 24 hours. The specimens were de-moulded 24 hours after casting and cured in both outdoor and oven. For outdoor curing, specimens were left outdoor (Temperature-35±2℃ and relative humidity-75%) up to specified age of testing (7 and 28 Days). Temperature and humidity control is not necessary for outdoor cured specimens whereas in the case of oven curing, the de-moulded specimens were kept in oven at a temperature of (60℃ for 24 hours) and the specimens were left to outdoor temperature until age of testing. The compressive strength test was carried out on GPC specimens at age of 7 and 28 days.

3.5 Properties of hardened concrete

3.5.1 Compressive strength test

Compressive strength was determined by testing the concrete cubes of size 150 mm as per IS 516:1999 and the results are given in Table 4. In order to assess the compressive strength of GPC20 and GPC50, specimens were tested at the ages of 7 and 28 days for both outdoor and oven curing.

3.5.2 Split Tensile strength (f_{split})

The split tensile strength was determined by testing the cylindrical specimens as per IS 516:1959 in a 3000 KN capacity compression testing machine. The results were shown in Table 5.

3.5.3 Flexural strength (f_t)

To determine the flexural strength, prisms were tested under two point loading as per IS 516:1959. The values of flexural strength for GPC mixes are shown in Table 6.

3.5.4 Water sorptivity

The absorption of water and transmission by capillary action, called 'sorpitvity', can be measured based on the increase in weight of specimens at the end of a standard interval of time (Hall 1989). Sorptivity tests were conducted on specimens for both the outdoor and oven curing. Cubic specimens (150×150×150 mm) cured under different conditions were sealed with wax on three sides to allow water transmission only from the bottom portion and weighed before the test. The specimens were kept in water in such a way that height of water is about 5 mm. The specimens were weighed, under saturated surface dry condition, at the end of 10, 20, 30, 40, 50, 60 min and then at intervals of 30 min. Hall's method was used to conduct this test (Hall 1989).

$$\frac{\Delta w}{A * d * \sqrt{t}} = S \qquad (1)$$

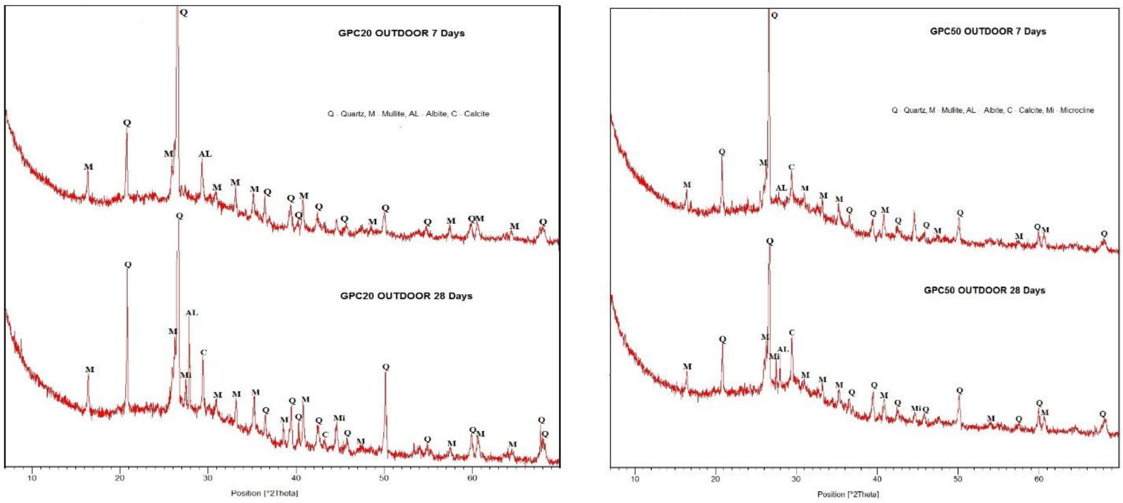
Where S = the Sorptivity coefficient of the specimen (mm/min$^{0.5}$).
d = density of water (1gm/cm^3), t = time (min),
ΔW = the amount of water adsorbed in (kg),
A = the cross-section of specimen that was in contact with water (m^2).

4. Results and discussions

4.1 Compressive strength

Table 4 Compressive strength of geopolymer concrete

Grade of Concrete	Density (kg/m^3)	Compressive Strength (MPa)			
		Outdoor Curing		Oven Curing	
		7 days	28 days	7 days	28 days
GPC20	2430	25.7	29.5	26.1	32.0
		26.7	30.7	31.6	33.6
		29.7	33.2	29.9	36.2
	Average	27.4	31.1	29.2	33.9
		Outdoor Curing		Oven Curing	
		7 days	28 days	7 days	28 days
GPC50	2540	48.7	57.0	55.0	59.8
		49.8	56.6	54.0	58.7
		51.0	58.5	51.2	61.9
	Average	49.8	57.4	53.4	60.1



(a) XRD Pattern of GPC20 (b) XRD Pattern of GPC50

Fig. 5 XRD Pattern of GPC20 and GPC50

Compressive strength of GPC depends on many factors such as binder content, amount of alkaline content and aggregate used in the mix. Several trial mixes were carried out and tested. Based on experimental results two mixes were chosen. Table 4 shows the values of compressive strength of GPC for different ages (7 and 28 days). There was an increase in compressive strength of outdoor as well as oven cured GPC with an increase in GGBS content in the mix. The presence of calcium is found to be critical to attain strength for GPC which was enhanced with C-A-S-H gel formation. The observed compressive strength after 28 days for GPC20 and GPC50 are about 31 MPa and 57 MPa respectively.

XRD for GPC specimens cured at outdoor condition 7 and 28 days for both the grades GPC20 and GPC50 are shown in Fig. 5. From XRD patterns, it is evident that some dissolvable minerals such as quartz and Mullite have remained in all the products. The peak (between 26° and 30°) observed in the XRD patterns of the fly ash and GGBS based GPC shows that the geopolymer material has both semi-crystalline and amorphous structure, and that of the reaction products between 26° and 30° with relatively smaller intensities indicates that the geopolymer material has almost complete amorphous structure. They show that the geopolymers for both the grades have a diffuse hump at about 26°-30°. By comparing the patterns of both the grades, no significant change was observed in GPC when partial replacement of fly ash with GGBS (30% and 50%) in outdoor condition.

4.2 Effect of curing on compressive strength

The effect of outdoor and oven curing on compressive strength of GPC were investigated in this study. The oven cured specimens have relatively higher compressive strength compared to outdoor cured specimens. The strength gain is more because the polymerization process is generally accelerated in the higher temperature than outdoor. In terms of practical application, it is very important to cure at outdoor temperature. With the exposure of outdoor curing the maximum strength gain is about 57 MPa for GPC50 where as in the GPC20 grade for outdoor curing the strength gain is about 31MPa for 8M. Outdoor curing produced satisfactory results without exposure to the oven curing with addition of GGBS. Hence, oven curing can be eliminated for GPC made with replacement fly ash with GGBS. With increase in GGBS content in mix and by varying the alkaline activator solution there is rapid increase in compressive strength up to 7 days and the strength continued to increase up to 28 days. The mix having 50% GGBS content in the total binder content achieves more strength than that of mix prepared with a GGBS content of 30%. The increase in strength of fly ash and GGBS based GPC is due to presence of calcium content. This increase in compressive strength due to the presence of soluble calcium, accelerates the hardening process Subhash *et al.* (2013).

4.3 Effect of age on strength of concrete

The 7 days strength and 28 days strength relation for GPC is very important. The work is done to estimate the strength of GPC at 7 and 28 days. The compressive strength of GPC depends mainly on curing regime, type of binder content and molarity of alkaline activator solution. The compressive strength of the oven cured specimens for 7 days curing is more than the strength of outdoor cured specimens. Similarly, the strength the oven cured specimen is almost double than that of the outdoor cured specimen after 28 days curing. The early strength within 7 days is very active and later on the gaining in strength was reduced. The initial curing temperature influences the polymerization process. Degree of heating also plays a vital role in accelerating the strength attainment of GPC irrespective of grade of the concrete. The gain of strength is faster at early age compared to that later age. This was observed in both types of curing, the gain of strength for oven cured GPC is higher compared to that of outdoor cuing. The early rate of strength gain within 7 days is high and later on the gaining in strength was not seen much as in conventional concrete. This aspect can be observed from the ratio of 28 day to 7 day compressive strength. This ratio ranged from 1.04 to 1.35 for outdoor cured samples. The ratio of 28 day to 7 day compressive strength of oven cured sample showed a range of 1.06-1.32. This clearly indicates that compressive strength attainment beyond 7days is very slow compared to conventional concrete as for conventional concrete this ratio is 1.50.

Table 4 Split tensile strength for geopolymer concrete

Grade of Concrete	Split Tensile Strength (MPa)	
	Outdoor Curing	Oven Curing
GPC20	2.5	2.7
	2.1	3.0
	2.1	2.6
Average	2.2	2.7
	Outdoor Curing	Oven Curing
GPC50	2.7	3.0
	2.6	3.3
	3.0	3.5
Average	2.8	3.3

4.4 Split tensile strength

The outdoor and oven cured specimens at the age of 28 days are presented in Table 5. The split tensile strength of GPC for 28 days were in the range of 1.92-3.25 MPa for outdoor and oven curing for grades GPC20 and GPC50 respectively. This shows that outdoor curing at room temperature itself is sufficient for GPC specimens to gain its split tensile strength. This appears due to the strong bond of the geopolymer gel to the aggregate particle. The split tensile strength of GPC specimens cured under outdoor gained sufficient strength with the inclusion of GGBS for fly ash in the mix. With increase in GGBS content there is an increase in tensile strength was observed. For GPC, the increase in strength may due to the continuous formation of N-A-S-H and C-A-S-H gels Pradip Nath *et al.* (2014). An empirical equation was developed using the experimentally obtained compressive and Splitting Tensile strength values of fly ash and GGBS based concrete for both outdoor and oven curing and is shown in Eqs. (2) and (3) respectively. For conventional concrete the relation between the compressive and tensile strength is $0.7 * \sqrt{f_{ck}}$ but here the value is less compared with the conventional concrete.

$$f_{split} = 0.353 * \sqrt{f_{ck}} \quad (2)$$

$$f_{split} = 0.427 * \sqrt{f_{ck}} \quad (3)$$

Where f_{split} is the splitting tensile strength and f_{ck} is compressive strength.

4.5 Flexural strength

It can be observed from Table 6 that the flexural strength of oven cured specimens have higher strength than outdoor cured specimens due to the fast polymerization process. Flexural strength of outdoor cured geopolymer concrete 2.3 MPa for GPC20 where as for the oven cured specimens it was about 2.6 MPa. With increase in the GGBS content there is an increase in the flexural strength of GPC. The GGBS content plays a significant role for the formation of C-A-S-H gel in the mix which further leads to increase in strength of GPC. This gel formation is responsible for the

Grade of Concrete	Flexural Strength (MPa)	
	Outdoor Curing	Oven Curing
GPC20	2.5	2.5
	2.4	2.6
	2.0	2.7
Average	2.3	2.6
	Outdoor Curing	Oven Curing
GPC50	3.6	4.4
	3.3	4.1
	3.7	3.8
Average	3.5	4.1

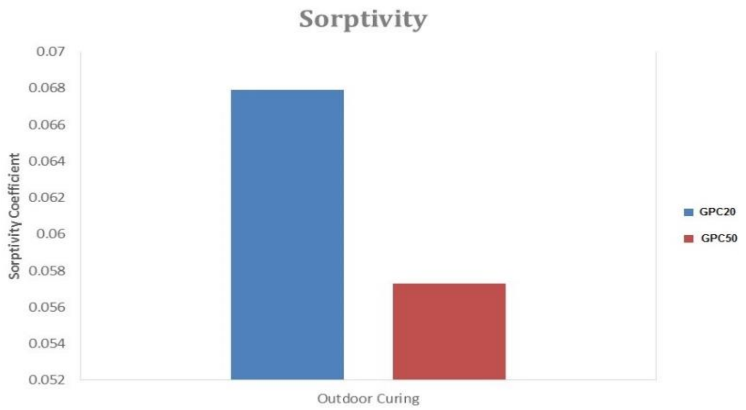


Fig. 6 Sorptivity of ambient-cured geopolymer concrete at 28-days for GPC20 and GPC50

strength contribution. The relation between the compressive strength and flexural strength is shown in Eqs. (4) and (5).

Outdoor Curing

$$f_t = 0.421 * \sqrt{f_{ck}} \tag{4}$$

Oven Curing

$$f_t = 0.441 * \sqrt{f_{ck}} \tag{5}$$

4.6 Sorptivity test

Volume of voids present in concrete can be indirectly measured using sorptivity test. The low sorptivity value of GPC is also an indication of disconnected fine pore structures in the matrix. The effect of slag content had a positive effect on pore structure resulting in lower sorptivity value. From the experimental values (Fig. 6), the rate of water absorption was found to be decreasing with increase in GGBS content. With increase in GGBS content in the mix the pore structure

Table 7 Ultrasonic pulse velocity of geopolymer concrete at 28 days

Grade of Concrete	Ultrasonic pulse velocity (km/s)	
	Outdoor Curing	Oven Curing
GPC20	2.9	2.56
	3.5	2.74
	3.4	2.79
Average	3.27	2.7
	Outdoor Curing	Oven Curing
GPC50	3.2	3.23
	4.0	2.94
	3.6	3.25
Average	3.6	3.14

becomes more compact and homogenous which eventually reduces the sorpitvity. Pap worth and Grace (1985) recommended sorptivity values to determine the quality of GPC. Since the obtained sorptivity values are less than 0.1 mm/min 0.5, these GPCs consisting 30% and 50% GGBS can be rated as “Very Good”.

4.7 Ultrasonic pulse velocity (UPV)

The UPV test is used to determine the quality of concrete. The UPV values for GPC20 mix was found to be 3.26 km/s for outdoor cured specimens where as for the oven cured specimens it is in the range of 2.70 km/s where as for GPC50 there is little rise in the values compared to that of GPC20. Whitehurst classified fly ash based geopolymer concrete as excellent, good, doubtful, poor and very poor for UPV values of 4.5 km/s and above, 3.5-4.5, 3.0-3.5, 2.0-3.0 km/s and below 2.0 km/s, respectively. High UPV values is an indication of good quality concrete. The presence of voids has been recognized to have an influence on the UPV transmission. The measured 28-days UPV values for all GPC specimens are shown in Table 7. For the samples, velocities at Outdoor curing are found within 3.0 to 3.5 km/sec and these can be treated as of good quality and the oven cured specimens conformed to the poor quality. Compared with the conventional concrete the quality of the concrete is less in geopolymer concrete. There is no proper guidelines for the geopolymer concrete. Here the microstructure is quite different compared with the conventional concrete. In geopolymer concrete for the attainment of strength polymerization process plays a prominent role.

4.8 Acid attack test

The performance of GPC specimens subjected to acid attack by immersing concrete cubes in Sulphuric Acid (H_2SO_4) was evaluated. Being alkaline in nature, cubes are likely to be affected during contact with sulphates. After specified age of curing (28 days) the initial mass of cubes were recorded just before the specimens were immersed in 5% H_2SO_4 solution.

4.8.1 Resistance of GPC for sulphate attack

Fig. 7 Visual of specimens subjected to H_2SO_4 of GPC20 and GPC50 after 56 days

The resistance to sulphate attack of geopolymer concrete was studied by immersing specimens in 5% Sulphuric acid. The mass loss of the specimens was observed for 7, 14, 21, 28 and 56 days and the strength loss was studied for 7, 28 and 56 days.

4.8.2 Visual appearance

There were no signs of cracking, disintegration or change in external appearance in the GPC specimens as shown in Fig. 7. Only, a trace amounts of white deposits were observed on the surface of concrete specimens. This is true for both grades GPC20 and GPC50. The deterioration of surface of the GPC specimens was observed to increase with increase in immersion period. It was also observed that there was no change in dimensions due to sulphate attack, leaching formation was minimum for both the grades of GPC.

4.8.3 Change in the mass of the specimens subjected to sulphate attack

The change in mass of GPC specimens with age compared to initial mass of specimens were calculated

The ratio of change in mass of specimen to the initial mass, called Acid Mass Loss Factor (AMLF), after removing the deposits was calculated. Durability is inversely proportional to AMLF of the concrete.

$$\text{Acid Mass Loss Factor} = \frac{\text{Change in Mass}}{\text{Initial Mass}} X100 \tag{6}$$

The acid mass loss factor values were depicted in Fig. 8. The mass loss of specimens exposed to the sulphuric acid solution was observed up to 56 days. The mass loss of specimens increased with an increase in immersion period. At 7 days, both GPC20 and GPC50 slowly lost mass of about 0.93% and 1.25% respectively. This increase in mass loss continued up to 56 days. It indicates continuous penetration of sulphuric acid solution in addition to formation of reaction product gypsum due to interaction of geopolymer material with 5% sulphuric acid Thokchom *et al.* (2011). GPC50 has more calcium content compared to GPC20, which leads to increase in formation of gypsum. This newly formed reaction product gypsum causes internal voids, which is responsible for mass loss in GPC50. Also presence of more paste in GPC50 allows the acid to

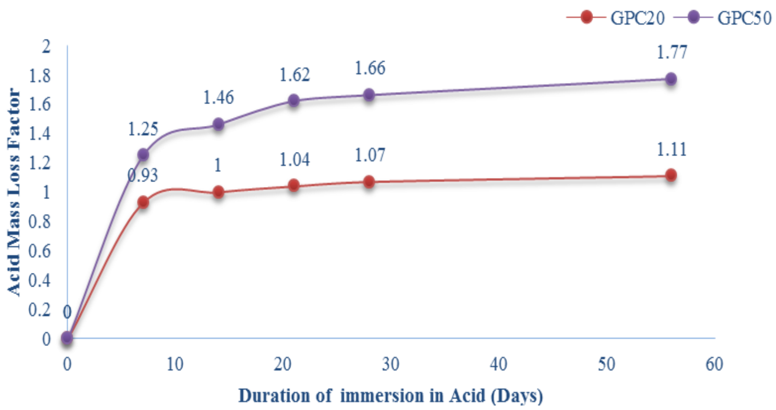


Fig. 8 Acid mass loss factor vs. Duration of immersion in acid

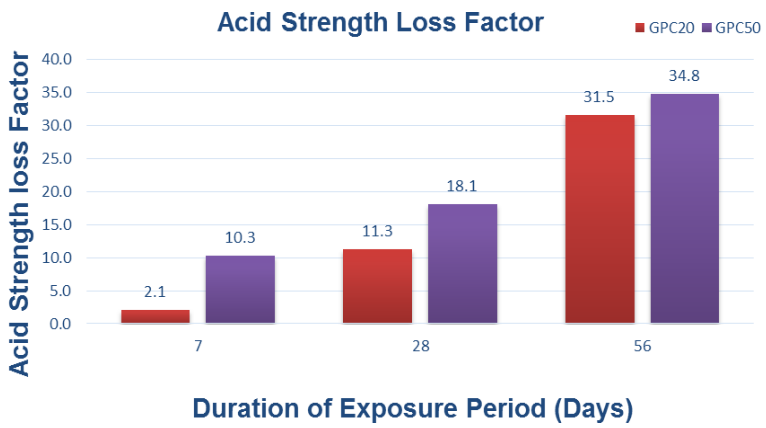


Fig. 9 Acid strength loss factor vs. Duration of immersion in acid

react and resulting in increased voids which interlink among themselves causing reduction in strength. This may be the reason for more mass loss in GPC50 when compared to GPC20. From Fig. 8, it can be observed that AMLF of GPC20 is less than GPC50 therefore GPC20 is more durable than GPC50.

4.8.4 Acid strength loss factor for specimens exposed to H_2SO_4

The ratio of change in strength of specimen to the initial strength, called Acid Strength Loss Factor (ASLF), was calculated.

$$\text{Acid Strength Loss Factor} = \frac{\text{Change in Strength of Specimen}}{\text{Initial Strength}} \text{X100} \qquad (7)$$

In general, the compressive strength decreases gradually with increase in exposure period. The same effect was observed for GPC20 and GPC50 up to 56 days. The ASLF for GPC50 is more compared to GPC20 as shown in Fig. 9. The decrease in the strength may due to the reaction of sulphuric acid (H_2SO_4) with calcium present in the GGBS in presence of water forming gypsum ($CaSO_4 \cdot 2H_2O$) and also reduces the pH value of concrete. C-A-S-H is unstable at low pH value and calcium reacts with H_2SO_4 in presence of water and forms gypsum Prinya Chindaprasirt

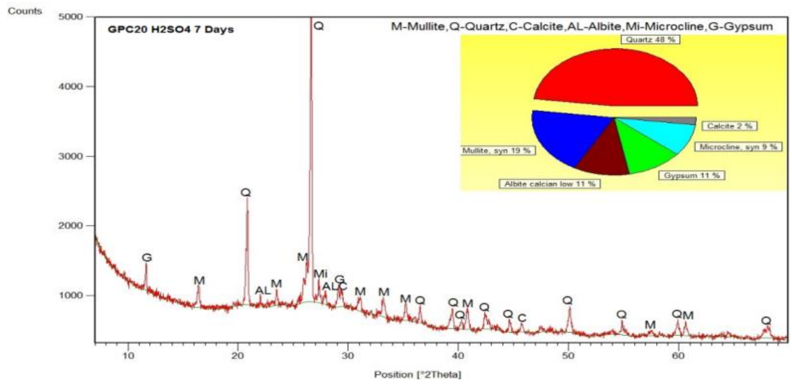


Fig. 10 XRD analysis for specimens subjected to H_2SO_4 for 7 days (GPC20)

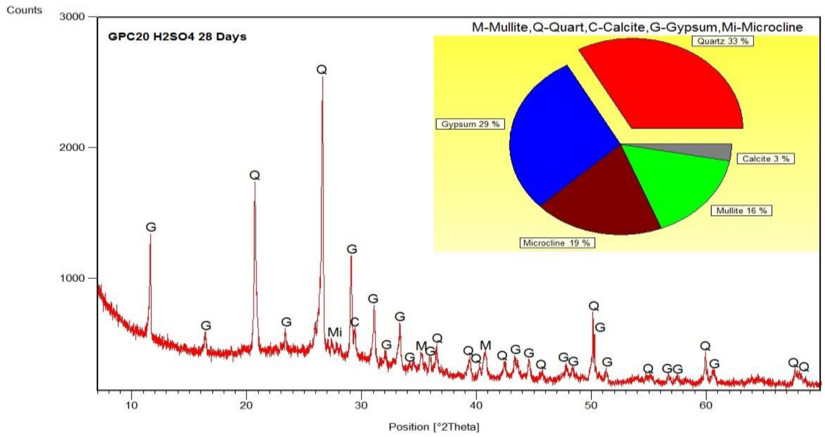


Fig. 11 XRD analysis for specimens subjected to H_2SO_4 for 28 days (GPC20)

(2012). The percentage loss of strength for GPC20 and GPC50 after 56 days exposure is around 31% and 35% respectively. When exposed to acid environment, the increase in loss of strength in GPC50 may be due to increased GGBS content. This strength loss can be attributed to declassification of alumino-silicate bondage (C-A-S-H) gel and increase in gypsum content which can be observed using XRD analysis.

4.8.5 XRD analysis of GPC specimens subjected to H_2SO_4 solution

X-ray diffractograms with their different percentages of mineralogical variation when the specimens are exposed to sulphuric acid is shown in Figs. 10-12. From the study XRD analysis show that some dissolvable ingredients Mullite and Quartz remain in all GPC samples. The broad peak (between 26° and 30°) observed for GPC20 and GPC50 exposed to the sulphuric acid indicates that GPC has a crystalline phase. A crystalline phase of albite was still visible in the samples exposed to acid for 7 days. A quantity of microcline was still visible in the samples exposed to acid for 56 days. When the specimens are immersed in H_2SO_4 solution, declassification of aluminosilicate bondage occurs leading to formation of gypsum causing loss of strength. The percentage of gypsum formation in GPC20 increases with increase in immersion period from 11%, 29% to 47% for 7, 28 and 56 days.

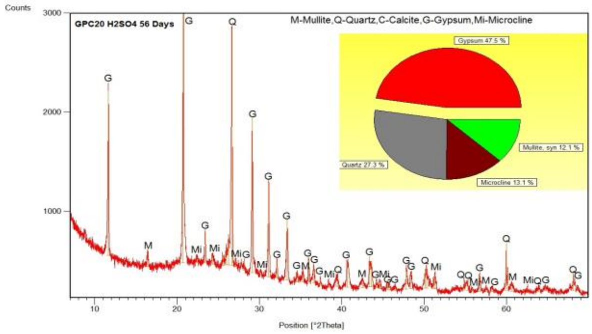


Fig. 12 XRD analysis for specimens subjected to H_2SO_4 for 28 days (GPC20)

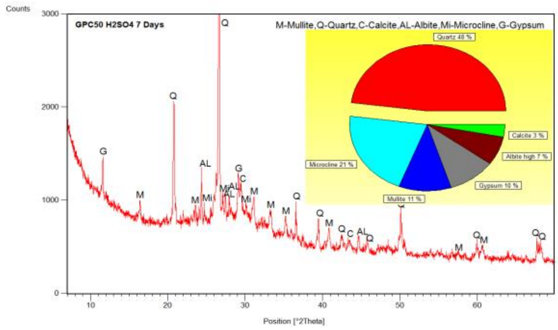


Fig. 13 XRD analysis for specimens subjected to H_2SO_4 for 7 days (GPC50)

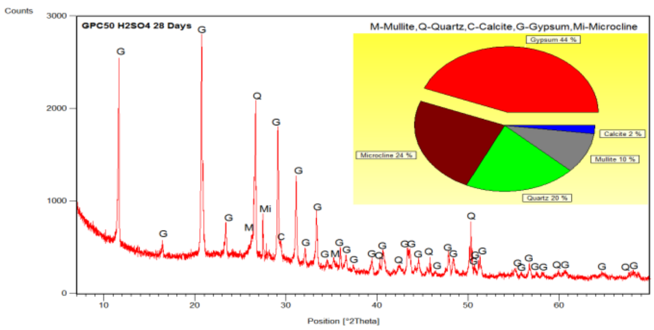


Fig. 14 XRD analysis for specimens subjected to H_2SO_4 for 28 days (GPC50)

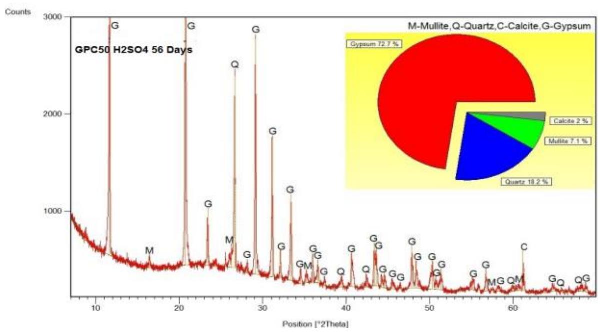


Fig. 15 XRD analysis for specimens subjected to H_2SO_4 for 56 days (GPC50)

After exposure to the sulphuric acid, the percentage of gypsum formation is increased with increase in age which is observed from Figs. 13-15.The gypsum formation in GPC50 more compared with GPC20. For 28 and 56 days the percentage of gypsum is about 46% and 52%. The reaction product Albite was visible for GPC50 for 7 days of exposure. The N-A-S-H type of phase was poorly observed with increase in the exposure period. This observation shows the decomposition of C-A-S-H phase in GPC has supplied the calcium required for the formation of gypsum Gadsden (1975), Farmer (1974).

5. Conclusions

• Oven curing can be eliminated by using a suitable combination of fly ash and GGBS to achieve a required compressive strength of geopolymer concrete.

• The strength of geopolymer concrete increased with increase in percentage GGBS content in the mix.

• Method of curing plays an important role in attaining the strength of Geopolymer Concrete.

• XRD analysis helps to identify the amorphous phases in GPC and these phases are responsible for the contribution of strength. The minerals (Albite and Microcline) identified using XRD analysis are responsible for increase in strength in GPC.

• The rate of water absorption was found to be decreasing with increase in GGBS content in GPC which eventually reduces its sorptivity.

• GPC50 has more calcium content compared to GPC20, which leads to the increased formation of gypsum in the matrix, which results in formation of internal voids. These internal voids results in decrease in strength and increase in mass loss.

• Higher the GGBS content, the strength degradation is more. Similar pattern was observed in GPC50 when compared to GPC20. This degradation of strength is due to formation of gypsum within the structure as observed in XRD analysis.

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