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RESEARCH PAPER

Investigation on the Study of Durability Characteristics and Endurance of Phosphate-Admixed Geopolymer Concrete Incorporated with Copper Slag

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Abstract

In order to avoid the deleterious impact on carbon dioxide emission from the production of cement, an alternative binding material by synthesizing the pozzolanic precursor (rich in Si, Al) is activated with the reagents of alkali/acidic medium through the exothermic process of geopolymerization. Geopolymer concrete (GP) is recognized as an alternative promising material to the conventional cement concrete. This research aims in investigating the performance of the physical-durability characteristics of the GPC produced from the natural mineral phosphate deposits, which is pulverized and utilized as one of the precursors along with the most endorsed prime materials, fly ash and ground granulated blast furnace slag. This combination had a leading chemical composition of Ca, Si, and Al which creates a sturdier internal dense matrix from the polymerization process to produce the oligo-silates gel structure, and this poly-condense forms the reticulation networking with the final product of geopolymer solidification. Based on the test results obtained in the aggressive environment exposure conditions, this concrete proved to counterpart the conventional OPC by enduring the acidic, sulphate and chloride environments and also able to withstand thermal exposure condition with minimal crumbling.

Keywords Geopolymer concrete · Phosphate · Copper slag · Ambient curing condition

1 Introduction

Sustainable concrete is progressively appealing attention, since the fabrication of ordinary Portland cement consumes a large amount of energy and resource, and emits lot of carbon dioxide (Ding 2016). The emission of greenhouse gas is quite alarming and immediately requires an alternate material to substitute cement in the construction industry (Kannapiran 2013). Also, the process of OPC production gulps down the confined natural resources of limestone's and coals as a fuel for calcination (Aly 2019). To overcome this serious issue, world researchers are aiming to produce a new and eco-friendly concrete with low carbon foot print. In this effort, an innovative green geopolymer technology was developed due to its outstanding performances as the geopolymer construction composites with nine times lesser emissions of CO_2, and with lower energy consumption (Davidovits 2015), and exhibits low carbon footprint, with excellent strength, durability, freeze–thaw, thermal, etc., also vowing with a sustainable construction materials (Luhar 2019). Previous researches have reported that the properties of GPC (Hardjito 2004) such as the tensile strength, modulus of elasticity, Poisson's ratio are similar to those of PCC, signifying the compatibility between PCC and geopolymer concrete. Additionally GPC possess low permeability, effective bonding with cement paste and mortar; also it is excellent anti-corrosive material (Zhang 2010). Geopolymer is inorganic polymers developed by the chemical reaction amongst the alumina and silica-rich source materials and alkali activators through the process of geopolymerization in an alkaline medium (Ganjian 2009) using low operational energy; GPC are amorphous polymers and synthetic minerals belonging to alumino silicates as zeolites. In the polymerization process, the reactions polysialates, polysialate siloxo and polysialate disiloxo are formed (Davidovits 1994). The chemical designation of geopolymer based on silico-aluminates is, poly(sialates) are silicon-oxo-aluminate, poly(sialates) are chain and ring is

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formed and cross-linked through a sialates Si–O–Al bridge and the polymers with fourfold coordination with oxygen in Si^{4+} and Al^{3+} (Kannapiran 2013). The basic mechanism for the formation of geopolymer binder consists of three stages associated with the dissolution of Si and Al from the precursor, gelation and condensation forming a three-dimensional network of silico-aluminates (Rickard 2011). The gels stimulate the final structure of GPC and control the ionic transport. Recently, numerous studies have reported the utilization of industrial wastes materials, i.e. flyash and GGBS as the potential precursor for the geopolymer synthesis (Timakul 2016). Profuse amount of fly ash present in the landfill creates health hazards and pollutes the surrounding environments by contaminating air, soils, surface and subsurface water (Luhar 2021). Apart from it, GGBS is a highly cementitious with calcium silicate hydrates compound that enhances and promotes concrete to increase in compressive strength when mixed with fly ash. Fly ash has desirable amount of silica, irrespective of main source materials like fly ash and GGBS (Chidambaram 2019). But fly ash alone as a source material in GPC shows poor results under ambient curing temperature (Jawahar 2016). The molarity of sodium hydroxide assists the strength development. In the coupling of alkaline activator and precursor of the preference with the past researches, sodium silicate gives better activation with GGBS (Bakharev et al. 1999) and sodium hydroxide is more preferred for flyash inclusion as binder in GPC (Memon and Nuruddin 2011). The major dissimilarity with OPC and GPC mix design is binder; instead of C–S–H gel formation, the Si–O–Al bonds are developed from the precursors used in the production of GPC, additional materials if included there is a need to find the chemical reactions of the constituent materials in the polymerization process using the microstructural studies. Alternatively, the utilization of river sand as a fine aggregate in concrete production is high, and the demand increases with the increase of the infrastructural developments, results in the depletion of natural sand and affects the ecological imbalance. To overcome this serious issue, some researchers identified some alternative fine aggregates, namely copper slag (Singh 2015). The performance of flyash-based GPC incorporated with full replacement of copper slag showed better results in the mechanical properties (Mahendran 2016). But limited durability study on flyash and GGBS combination of GPC incorporated with copper slag.

There is no systematic study on the durability of GPC in the presence of RPP and Flyash + GGBS is available in the literature. The slabs of the highway pavements in the saline regions are attacked by the sulphate compounds, whereas the structures in the marine environments are deteriorated by the chloride compounds and the surroundings of the food processing industries are affected by the acid produced. So this paper attempts to investigate the role of RPP on the durability properties of slag-ash-based GPC in aggressive environment particularly in 5% sulphuric acid solution, 5% sodium chloride solution and 5% sodium sulphate solution. Apart from it, investigation on the thermal performance of GPC, water absorption and NDT was analyzed.

1.1 Research Significance

In the existing exploration on geopolymer concrete, there is an insufficient knowledge in optimizing the combination of precursors particularly flyash, GGBS and RPP combinations. So far many researchers have considered several factors, like varying the molarity, super-plasticizer dosage, alkaline liquids to binder ratio, etc., to achieve a reasonable conclusion. This study is an attempt to optimize the binder combination at 12 molarity and 14 molarity of sodium hydroxide dosage using precursors as GGBS + RPP and Flyash + GGBS + RPP along with the full replacement of copper slag, instead of depleting river sand as fine aggregate. The durability performance of the GPC admixed with industrial waste and natural rock powder (RPP) was determined, and performing mixes were arrived and enhanced results were found.

1.2 Materials

Rock phosphate powder from local dealer was used as one of the precursor. Low calcium flyash class F (ASTM C618-17 2017) from Tuticorin thermal power plant with bulk density = 1.047 g/cc and the chemical analysis is depicted in Table 1, whereas GGBS brought from JSW was used in this research. The specific gravity of RPP, fly ash and GGBS is 3.1, 2.14 and 2.7, respectively. From the locally available quarry, coarse aggregates of 20 mm and 10 mm with the specific gravity of 2.65 were used. The fine aggregate was replaced either fully or partially with copper slag brought from sterlite industries, Tuticorin. The chemical composition of copper slag is given in Table 2. Heavy metals leaching test of copper slag under aggressive conditions was referred from the previous studies conducted as per ASTM D-5233-1995d;

Table 1 Chemical analysis of fly ash (Indhumathi 2019)

Sl no	Composition (%)	XRF determined
1	SiO_2	49.2
2	Al_2O_3	18.3
3	Fe_2O_3	2.3
4	SO_3	0.25
5	CaO	1.3
6	Na_2O	0.22
7	LOI	0.6

Table 2 Chemical composition of copper slag (Vinotha 2019)

Composition	Fe_2O_3	Fe_3O_4	SiO_2	CaO	S	Cu	Al_2O_3
% by mass	55–60	< 10	27–33	1–3.5	0.2–1.5	< 1	< 3

Table 3 Heavy metals leaching under aggressive conditions (Brindha 2010)

Sl no	Constituents	Leaching (ppm)
1	As	0.923
2	Ba	0.25
3	Cd	Nil
4	Co	Nil
5	Cr	Nil
6	Cu	11.64
7	Mn	0.05
8	Mo	Nil
9	Ni	0.1
10	Pb	Nil
11	Se	Nil
12	Sr	0.05
13	Zn	0.99

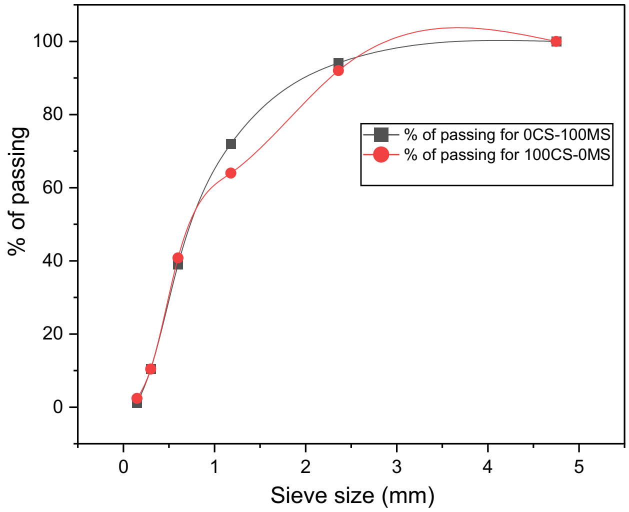


Fig. 1 Sieve analysis of fine-aggregate in Zone II (confirmed as per IS: 383-1970)

the constituents present are expressed in ppm; the results are presented in Table 3. The sieve analysis of fine-aggregate with the combination of copper slag/M-sand as 0/100 and 100/0, respectively, found to be in Zone II confirmed as per IS: 383-1970, and the results are illustrated in Fig. 1. For control specimen C1, M-sand with fineness modulus of 2.45 and specific gravity of 2.6 was used for the GPC mixes. The combination of Na_2SiO_3 and NaOH solution in 12 molarity and 14 molarity was used as the alkaline liquid. The sodium hydroxide was in the white coloured pillet form brought in the commercial grade with 99% purity, whereas the highly viscous sodium silicate solution in commercial grade having specific gravity of 1.48 gm/cc was used for the production of GPC.

1.3 Mix Design

From the past studies on GPC, the mix design in this research was followed by Rangan (2008), considering the parameters by fixing the alkaline liquid ratio as 2, alkaline liquids to binder as 0.35 and water content from 12 to 14% of binder with 12 molarity and 14 molarity of sodium hydroxides. The aggregates were fixed between 75 and 80% of entire mass of GPC, with fine aggregate of 35%.

1.4 Mixing Sequence, Casting and curing

The mixing sequence of GPC is represented in Fig. 2. To determine the mechanical, durability and non-destructive test (NDT), the standard size of 150 × 150 × 150 mm cube was cast for the mix proportion described in Table 4. For sorptivity test, disc samples of size 100 × 50 mm were cast to measure the capillary rate of water absorption. The specimens were tested after the 28 days of ambient curing.

2 Test Programs

The geopolymer concrete cube specimens were test for the resistance to aggressive environmental conditions such as acidic, sulphate/saline, marine conditions. After the curing periods of the cube samples, a set of three specimens from each mix are sorted and immersed in the separate container filled with 5% of sulphuric acid solution, 5% sodium sulphate solution and 5% of sodium chloride solutions. The containers were left undisturbed for the duration of 90 days and 180 days. Later on, the samples were removed, dried and analyzed for mass loss, strength loss and visual observations. Electrical muffle furnace was used to examine the thermal resistance of GPC cubes for 400 °C and 800 °C for 2-h duration. The typical crack pattern, colour change, strength and mass loss are discussed in Sect. 6.3.2. In order to determine the sorption of the proposed GPC, cylindrical specimens of dim 100 × 200 mm were cast and sliced to the required dimension of 100 × 50 mm disc, and three set of each mix was observed for the surface capillary suction, for the optimum sorptivity coefficient. The water absorption percentage was obtained through the standard procedure of ASTM

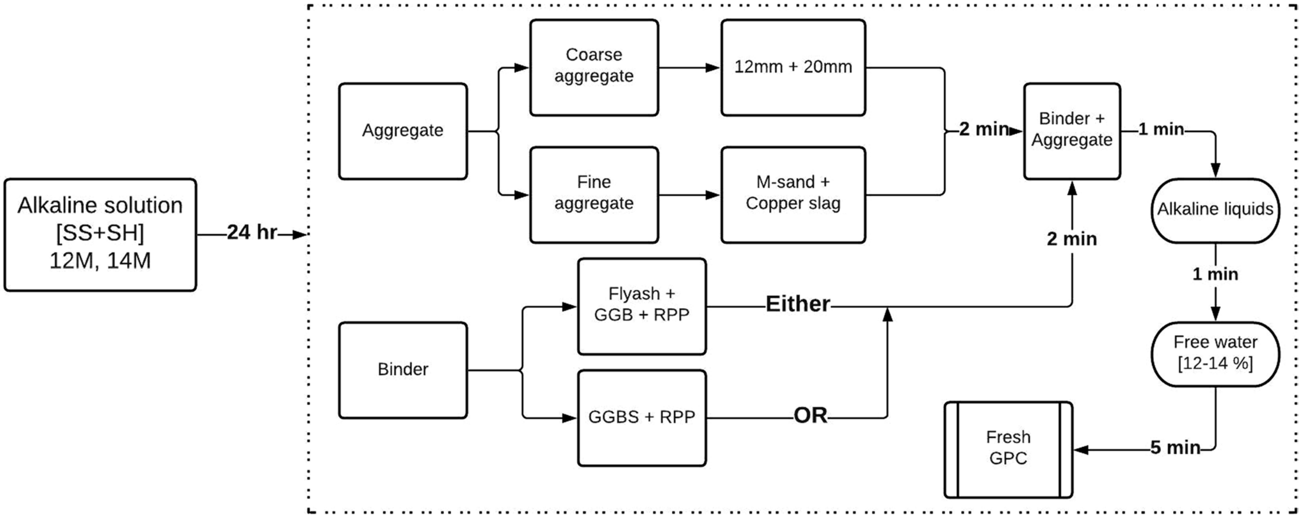


Fig. 2 Flowchart on the mixing sequence of GPC production

Table 4 Mix proportions on varying binder percentage

Sample ID	Molar concentration	% of RPP w.r.t. Flyash	% of GGBS w.r.t. Flyash	W/B
C	12	0	30	0.35
C1	14	0	30	0.35
GR	12	30	70	0.35
GR1	14	30	70	0.35
FGR	12	30	35	0.35
FGR1	14	30	35	0.35

C642-1360 °C for oven-dried cube samples are immersed in water for 24-h duration, later on removed to find the absorption percentage of the samples.

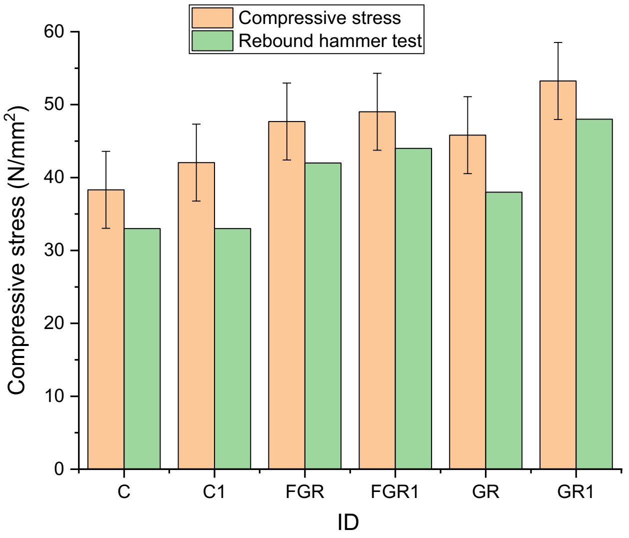


Fig. 3 Graphical representation of compressive stress and rebound number

3 Results and Discussion

3.1 Compressive Stress and Rebound Hammer Test

Figure 3 represents the compression and rebound hammer relationship of GPC with various combinations of precursors'. Destructive test (DT) compressive strength was tested in the UTM, and average was taken from the three samples. Similar dosages of another set of samples were cast for non-destructive test (NDT) by performing rebound hammer test. On comparing the overall results of DT and NDT, the rebound hammer test results were insignificantly lesser than the compression stress results by DT. The average compression of peak stresses was found with the GGBS + RPP-admixed GPC with 53 MPa at 14 molarity of alkaline solution, followed by the FA + GGBS + RPP-admixed GPC of FGR1 with 49 MPa. The compressive stress of the proposed mix followed the usual trend of increase in the compressive stress with the higher concentration of molarity. Thus, the results variation of DT and NDT had an approximation of 10–15% difference in the RPP-admixed GPC.

3.2 Durability Studies

3.2.1 Acid Resistance

The geopolymer concrete cube specimens after the curing period were immersed in 5% sulphuric acid for 3 months and 6 months. The concentration of acid solution was based on the practical application of construction materials as in the industries, sewage pipes, mining's, etc. The compressive strength results of GPC samples exposed to sulphuric acid solution are represented in Fig. 4. The visual examination after the immersion of the samples for 6 months, was observed that the surface of the samples FGR, FGR1 was leached with the lessening in colour and the aggregates were exposed at the sides as shown in Fig. 7a. But the control samples C, C1 and GR, GR1 does not show any surface disintegration and colour change. The control samples C and C1 consist of low calcium class F Flyash, which is less soluble in the acidic solution (Bakharev 2005). The change in mass was quite insignificant for both 3-month and 6-month samples. The 3-month acid-exposed specimen was found with a significant weight reduction, samples FGR and FGR1 which had a weight loss of 1.53%, whereas GR and GR1 loss of 0.6% and control samples persisted with same mass before and after immersion. The interaction of acid solution and GPC, causes replacement of exchangeable Na cation in the polymers by hydrogen ions or hydrogen. Exposing GPC to a strong acid results in the breakage of Si–O–Al bonds and increases the number of Al–OH and Si–OH groups and results with the silicic acid ions in the solution and therefore leads in the mass loss of the geopolymer concrete specimens when exposed for higher concentration of acid solution for the longer period (Breck 1974). There was a gradual increase in the overall mass of the specimens exposed for 6 months in the acid solutions. Sulphuric acid is more aggressive and results with severe delamination and de-polymerization. The products of de-polymerization precipitate as zeolites or gel, to increase the overall weight of the specimen (Bakharev 2005). The 14 molarity samples persisted its mass without and increment or reduction, whereas the 12 molarity specimens with FA + GGBS + RPP-admixed ID FGR had a negligible increase in the overall mass as 0.01% and GGBS + RPP combined precursor GR with 0.06% and Control C with 0.01%. The development of change in mass of the samples is depicted in Table 5. The compressive strength reduction of 14 molarity samples of FGR1 and GR1 is 17% and 39.6%, respectively, on the 3 months and 35.78% and 45.3% reduction on 6 months, respectively. This reduction of compressive strength is higher than the usual trend of control specimen C which is 1.3% on 3 months and 26.01% on 6 months. Similarly C1 with 14 molarity had 12.5% reduction on 3 months and 32.1% reduction on 6 month. Therefore, the residual compressive strength declined as the molarity is increased, whereas the control samples performed well enough than RPP-admixed concrete under higher concentration of alkaline solution. The 12 molarity FGR and GR sample performed well after the exposure of sulphuric acid solution for 3 months. It was found that FGR has 47% of improved compressive strength after immersion and GR has 32.4% increment. This could be due to the chemical reaction which improved the compression behaviour. Since this specimen had surface disintegration and colour change and expected to give reduced compression result, in contrast it performed well than before immersed samples. So the FGR and GR can be recommended for the utilization as the construction materials in the food processing industries, mining, etc.

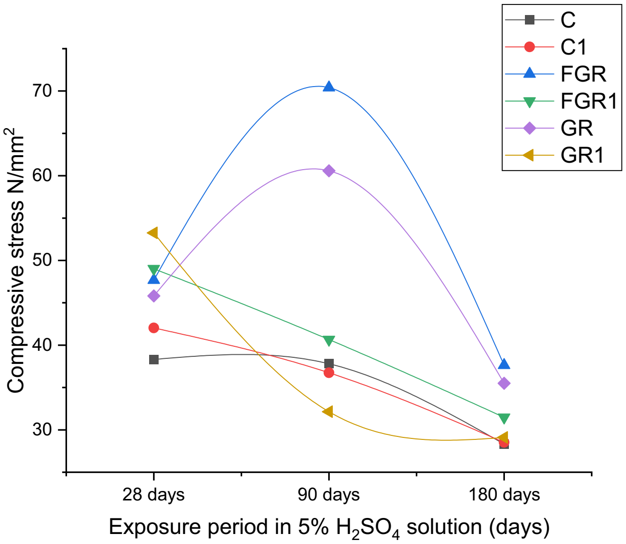


Fig. 4 Residual compressive stress of 5% sulphuric acid-exposed specimens

Table 5 Variation on mass (Kg) of the cube after immersion in acid, sulphate and chloride solution for 3 and 6 months

ID	3 months acid		6 months acid		3 months Sulphate		6 months Sulphate		3 months chloride		6 months chloride	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
C	8.46	8.46	8.30	8.40	8.44	8.54	8.40	8.54	8.88	9.00	8.06	8.2
C1	7.90	7.88	8.26	8.42	8.42	8.48	8.82	8.92	8.68	8.78	8.84	8.98
FGR	9.48	9.34	9.68	9.67	9.38	9.46	9.36	9.40	9.54	9.62	10.02	10.12
FGR1	9.14	9.00	9.96	9.96	9.62	9.66	9.30	9.38	9.28	9.32	9.60	9.68
GR	9.84	9.78	9.38	9.44	9.88	9.92	9.52	9.58	9.78	9.84	9.4	9.42
GR1	9.72	9.66	9.64	9.64	9.68	9.72	10.34	10.38	10.06	10.12	9.6	9.64

3.2.2 Sulphate Resistance

The slabs of highway pavements in the saline region are usually attacked by the compounds like Na_2SO_4 and $MgSO_{4}$-based sulphate compound. The ability to sustain the sulphate environment of the GPC admixed with RPP and industrial waste materials was assessed from the immersed cubical specimens of dimension 150 × 150 × 150 mm in the 5% sodium sulphate solution for 90 days and 180 days, and the results are depicted in Fig. 5. The sodium sulphate will react with the concrete microstructure and will disintegrate the concrete surface by reacting with the calcium present in the materials used, and this deteriorates the crystal matrix and de-polymerizes the internal structure and reduces the strength. From the visual inspection, colour change was observed in the 180-day immersed samples of reference specimens C and C1, as shown in Fig. 7b. This may be due to the reaction of calcium hydroxide with the sodium sulphate solution, resulting with the products calcium sulphate. The chemical solution reacts through the porous medium of the GPC and reacts with the polymerized products, resulting with the rapid attack, and reduces the overall performance of the structure. Compared to the overall specimen, the mass loss and the increment in compression strength results were observed in the 12 molarity activator solution and RPP-admixed GPC. In the samples FGR and GR, mass loss was 0.85% and 0.4% for 90 days exposed in the 5% of sodium sulphate solution. The evolution of the compressive strength was 50% increment for FRG and 51% increment for the GR samples. The 14 molarity mix samples FGR1 and GR1 were found to be 0.55% and 0.41% of mass loss and reduction in the compression results of 7.39% and 23.45%, respectively, for 90-day immersion. For 180 days of immersion in the Na_2SO_4 solution 25% and 48% reduction in the strength and mass loss up to 0.86% and 0.38%, thus with higher molarity it does not have the ability to sustain in the sulphate environment and cannot prevent the reaction with the calcium present in the materials, resulting in the reduction in strength, mass and surface disintegration. The 12 molarity activator with the RPP-admixed GPC performs better under the aggressive sulphate environment, and this can be due to the stable structure of the aluminosilicate formed as the polymeric structure resulting in the densely packed internal particles resisting the solution entering the specimen and delays/prevents the concrete from the deterioration (Muhammad 2014).

3.2.3 Chloride Resistance

Resistance to chloride penetration is highly concentrated for the durability of concrete research, which promotes the corrosion of the embedded reinforcement of the structural members and reduced the performance. The compression strength results of GPC samples soaked in 5% sodium chloride solution are depicted in Fig. 6. The performance of the control samples for 90 days and 180 days was observed with the increase in the mass up to 1.3% and 1.7% for C with 12 molarity, whereas 1.1% and 1.6% for C1 with 14 molarity of sodium hydroxide solution. With the increase in the molarity, the absorption rate was slightly reduced due to the denser matrix which reduced the porous structure of the concrete internal structure. But the compression behaviour was found with 2% and 17.5% reduction in 90 days and 180 days for C and C1 with 26% and 50% reduction in the compressive strength. Similarly, flyash-admixed concrete was observed with the white patches on the surface with the salt deposits

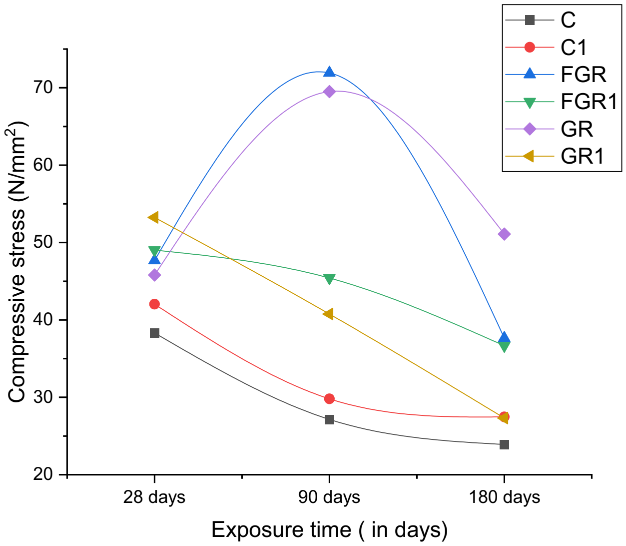


Fig. 5 Residual compressive stress of 5% sodium sulphate-exposed specimens

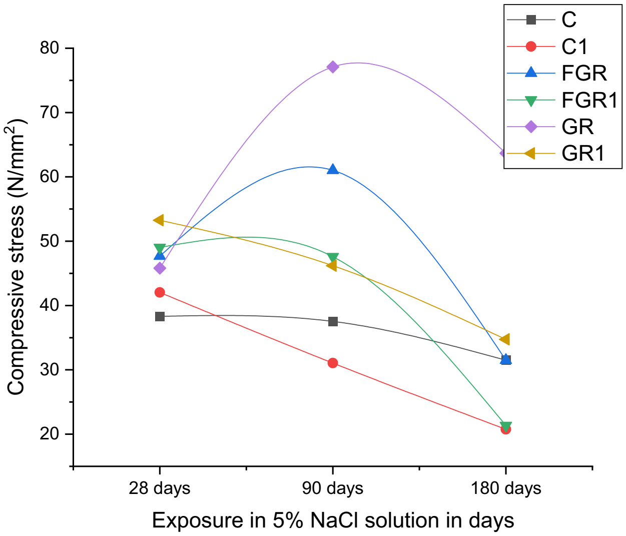
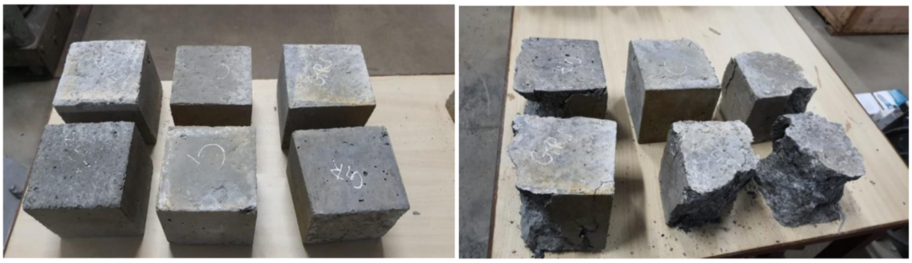


Fig. 6 Residual compressive stress of 5% sodium chloride-exposed specimens

Fig. 7 **a** Samples exposed for 6 months immersed in 5% of sulphuric acid. **b** Samples exposed for 6 months immersed in 5% of sodium sulphate. c Samples exposed for 6 months immersed in 5% of sodium chloride

(a) Samples exposed for 6months immersed in 5% of sulphuric acid

(b) Samples exposed for 6months immersed in 5% of Sodium sulphate



(c) Samples exposed for 6months immersed in 5% of Sodium chloride

in both FGR and FGR1, but not in other samples immersion in 5% of NaCl solution. FGR and FGR1 followed the similar trend of reference sample behaviour in increment of compressive stress and mass by 0.8% and 0.9% in FGR and 0.4% and 0.8% in the FGR1. The compressive strength in FA + GGBS + RPP-admixed GPC in 12 and 14 molarity activator solution was found with the increment up to 27% on 90-day exposure and gradually reduced up to 33% on 180 days of exposure in the NaCl solution (Fig. 7c). During the first soaking period of 90 days the compressive stress increased and on further immersion the strength is reduced; this strength fluctuation was found in the 12 molarity samples, rather than that the 14 molarity samples were found with the gradual reduction in the compressive strength with the prolonged soaking period in the chloride solution. The strength reduction is due to the chloride ion penetrating inside the concrete and the diffusion in it (Roy 1993). Thus the resistance to this chloride ingression rate into the concrete matrix will reduce with the age of the concrete, thereby resulting in the chloride refinement and biding in the porous medium/matrix of the microstructure. Modifying the microstructure with the additional reaction products can resist the chloride ingression into the GPC (Chandani 2016). The performance of GGBS + RPP-admixed GPC with the activator of 12 and 14 molarity of sodium hydroxide dosage was observed with the difference in mass up to 0.6% and 0.2% on 90 and 180 days of 5% NaCl exposure for GR and 0.6% and 0.5% on 90- and 180-day immersion for GR1. The compressive strength for GR and GR1 in 90 days was increased up to 68% and reduced for GR1 up to 13%, respectively, similarly, 39% increment for GR in 180-day exposure and 35% reduction for GR1 specimens. From the overall performance of chloride resistance of RPP-admixed GPC with various precursors' was found with the gradual reduction in the compressive strength for 14 molarity samples, with insignificant mass gain. But the 12 molarity samples were found with the fluctuation in the compressive stress, increment in 90-day immersion and decrement on the further immersion due to the effect of chloride ingression in the concrete.

3.2.4 Sorptivity

The sorptivity test was conducted as per the ASTM C 1585–04, to determine the surface capillary suction of specimen exposed to Ca $(OH)_2$ solutions in a uni-direction (Fig. 8). The water ingression of exposed surface of immersed unsaturated GPC specimen is dominated by the surface absorption, during the initial period of contact with the solution. Specimens with lower sorption yield with higher compression results by reducing the pore radius inside the concrete. The RPP with 30% of binder was selected for sorptivity test, and the sorptivity coefficient of the samples is given in Table 6. From the results, the coefficient of water sorption of the mixes with flyash + GGBS + RPP, i.e. FGR and FGR1 with 12 and 14 molarity, respectively, is 0.65×10^{-8} mm^2/s and 0.19×10^{-8} mm^2/s. The decrease in sorption with the increase in molarity was due to the increase in polymerization process, and the reaction products create a denser matrix with the improved internal particle packing and reduce the pores. The finer particles of flyash have a specific surface area of 480 m^2/kg and reduce the interconnecting voids by lowering the capillary pores (Saha 2018). While comparing the GGBS and RPP specimens of GR and GR1, the sorption coefficient was 0.18×10^{-8} mm^2/s and 0.13×10^{-8} mm^2/s.

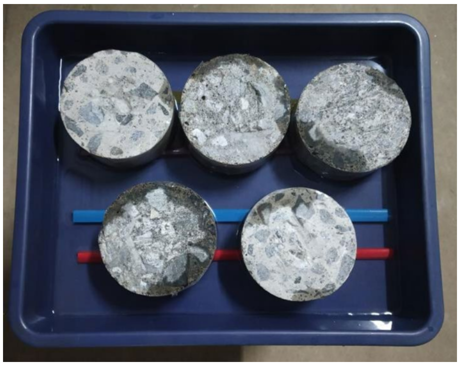


Fig. 8 Test setup of sorptivity test

Table 6 Results on the coefficient of capillary water suction

ID	Sorptivity coefficient × 10^{-8} mm^2/s
C	1.38
C1	2.1
FGR	0.65
FGR1	0.19
GR	0.18
GR1	0.13

3.3 Physical Properties of GPC

3.3.1 Water Absorption

The water permeability of GPC specimen with the inclusion of RPP admixed with industrial waste materials (flyash + GGBS) at 28 days is shown in Table 7. The coefficients of immersed water absorption percentage of GR and GR1 were approximately 0.63% and 0.6%, whereas the reference mixes C and C1 had 1.7% and 1.43%, respectively. FA admixed had water absorption of 1.43% and 0.84%, slightly higher than GGBS + RPP-based GPC. From this it can be ascribed to the pore distribution differences and dense internal matrix structure formed inside the crystallized zeolite gel from the pozzolanic reaction of RPP in GPC with copper slag replaced concrete. These results associate RPP in GPC with copper slag as filler incorporates with lower permeability.

3.3.2 Elevated Temperature

The residual compression results of 28-day ambient cured specimens are illustrated in Fig. 9. All the mixes were exposed for 2-h duration at room temperature, 400 °C and 800 °C, respectively (Fig. 10). The specimens observed with slight colour change on its surface with visible minor cracks when exposed to 400 °C and more superficial cracks at 800 °C. At each temperature range, the specimens exhibited with a typical crack pattern, change in colour and mass loss of the specimen. The strength loss was observed in G6 at 800 °C and can be due to the pozzolanic effects and the reaction within the internal bonds, which resulted with disintegration, and the colour change is due to the Fe in copper slag tending to react. On increasing the temperature to 400 °C and 800 °C, the internal moisture present in the pores evaporates. When the pore waters of GPC reach above > 100 °C of normal water boiling point, it forcefully tries to escape outside the specimen and forms superficial microcracks on the surface. Till 400 °C all the specimens observed with improved compressive strength, and in future scope those mixes can be recommended for oven curing conditions. The crystallization of the RPP in GPC contributes to

Table 7 Physical property of optimized mix in GPC

ID	Water absorption %	UPV Km/s
C	1.7	4.043
C1	1.43	4.28
FGR	1.43	4.58
FGR1	0.84	3.65
GR	0.63	4.58
GR1	0.60	4.75

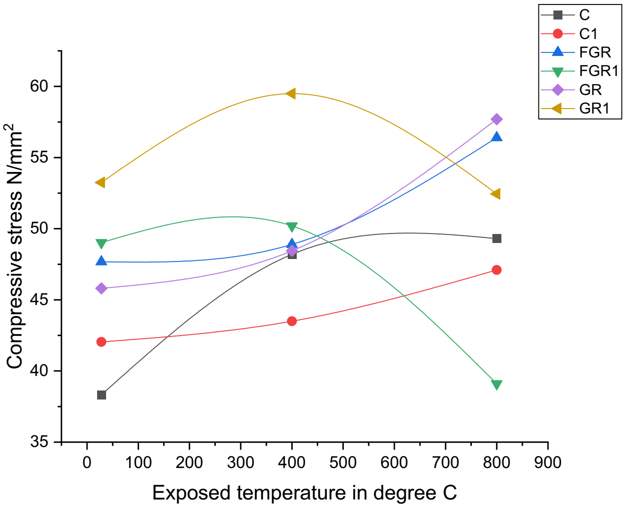


Fig. 9 Specimens exposed to 800 °C in oven

the higher compressive stress on the elevated temperature. At 800 °C, specimens were observed with extensive cracking and surface spalling. On further increasing the temperature can result with strength loss and the microcracks at the surface can be encountered by using microfibers.

The inclination in temperature will affect the integrity of the GPC specimen. The compressive strength increases with the increase in temperature, by attaining a peak stress of 59.5 MPa at 400 °C. However, GGBS+RPP combined mix GR and GR1 with 12 and 14M, respectively, had an insignificant variation with the molarity. GR1 was recorded with 11.7% increase in the compressive strength for 400 °C exposure, but 1.5% strength reduced on 800 °C. The strength loss can be influenced by the thermal strain between the matrix and aggregate (Daniel 2010). But the 12 molarity GR was found with 5.7% increment in the compressive strength at 400 °C and 25.9% at 800 °C. Similarly, FGR and FGR1-based GPC under 12 and 14 molarity had an insignificant evolution in the compressive strength, and 12 molarity mix FGR obtained 2.5% and 18.2% improvement in the compression results after the exposure of 400 °C and 800 °C, respectively. But the 14 molarity mix FGR1 had a rise of 2.4% and dip of 20.23% with the reference mix. Thus for GGBS+RPP and FA+GGBS+RPP-based GPC performs well with 12 molarity of activator solution with higher thermal gradient and can be further recommended for heat curing regime for better strength.

Fig. 10 Graphical representation of residual compression results on elevated temperature

3.3.3 Ultrasonic Pulse Velocity

The velocity propagation of ultrasound pulse velocity is measured by direct transmission method to establish the homogeneity inside the concrete, and any presence of crack or voids are indicated along with the flaws in the microstructure. From the results in Table 7, the UPV values of the GR1 mix proportions found to be higher velocity with minimum time to transmit with the velocity of 4.75 km/s, and similar trend of higher UPV value can be observed in the compressive strength test results. This might attribute to the fact that with the increase in compressive strength the matrix gets denser and lowers the voids, thereby leading to higher UPV values. If the velocity is higher, then the quality of the concrete is good in terms of homogeneity, density with higher elastic modulus and uniformity. Therefore the UPV of geopolymer concretes admixed with the industrial waste materials are indicated as ‘excellent and good’.

4 Conclusions

The exploration on geopolymer concrete using RPP and industrial waste materials has been investigated. With the inclusion of RPP as a precursor, the insoluble property reduces the penetration and enhances the strength by retaining the density inside the matrix with the higher molarity and reduces the pore connectivity, which leads to the disintegration of the matrix. The following conclusions are drained from the test results obtained:

1. RPP-admixed GPC had peak compressive stress up to 53 MPa for GR1 samples. On comparing the rebound hammer test results with the destructive test, the variation was up to 15% reduction with the results obtained in the GPC produced.
2. Geopolymer concrete incorporated with RPP yields higher resistance to acid and sulphate environment in 12 molarity specimens with lesser mass loss and strength loss. FGR and GR had an increase in compression results after 90 days of exposure to the sulphuric acid with 47% and 32.4%, respectively. Similarly for

sulphate-exposed environment the mix FGR and GR had a rise in compressive strength with 50% than the control mixes.

3. On examining the pore structure of GPC with sorptivity and water absorption, the finer particle enhances the pore filling and reduces the water sorption; the lowest sorption rate was obtained in mix GR1 with 0.13×10^{-8} mm^2/s. The immersed water absorption percentage of GR was found with the reduction of 62.9% with the reference sample C.
4. Enhancement in strength and weight loss was observed in the elevated temperature for GR1 mix up to 400 °C at 59.5 MPa, and on increasing to 800 °C the strength reduces with 25.9% of the reference samples.
5. The minimum travelling time of the ultrasonic pulse inside the cubical specimens of GPC mix of GR1 was found with maximum velocity of 4.75 km/s. Higher UPV value results with higher compression results and furnishes improved durability.

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