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Research Article

Durability Studies on Fly Ash Based Geopolymer Concrete Incorporated with Slag and Alkali Solutions

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This study explores the durability of green cementitious material of geopolymer concrete. Geopolymer concrete is produced from the polycondensation reaction of aluminosilicate materials (fly ash, Ground Granulated Blast furnace Slag (GGBS)) with alkaline activator solutions. Geopolymer concrete has excellent mechanical properties and its production requires low energy and results in low levels of CO_2 emission. Due to the high demand for river sand, manufactured sand is used as a replacement material in geopolymer concrete under ambient curing conditions. In this study, the durability of G30 grade geopolymer concrete has been investigated using tests acid resistance, water absorption, sulphate resistance, Rapid Chloride Penetration Test (RCPT), and rate of absorption (Sorptivity) test. The sulphuric acid, sodium sulphate, and water absorption tests were carried out at 28 days, 56 days, and 90 days for both the geopolymer and the conventional concrete. The reduction percentage in water absorption and compressive strength loss was found to be better in geopolymer concrete than in conventional concrete. Geopolymer concrete's chloride penetrability and rate of absorption were analogous to conventional concrete. Regression analysis for geopolymer and conventional concretes in the rate of absorption test showed a good relationship between absorption and the square root of time.

1. Introduction

In the cement industry, the production of the clinker by heating calcium carbonate ($CaCO_3$) in a rotary kiln requires a lot of energy. The process also releases a large quantity of carbon dioxide into the atmosphere due to the complex chemical reactions (Intergovernmental Panel on Climate Change [IPCC] Guidelines). As per the account of 2005, the global carbon dioxide emission is roughly 28.3 gigajoules per tonne (Gt/y), out of which the production of cement accounts for about 1.8 gigajoules per tonne (Gt/y) [1]. The cement production industries contributed roughly 7% of the worldwide carbon dioxide emission [2]. This ecological impact needs to be reduced by using cement production in a lesser manner. Finding eco-friendly and environmentally substitute materials instead of ordinary Portland cement is the main way to curb the discharge of CO_2. Incorporating waste byproduct materials as cement replacement in concrete is the main alternative for Portland cement concrete [3]. The source materials such as GGBS, rice husk ash, fly ash, and silica fume, which is affluent in silica and alumina ar, are geopolymer concrete, a newly emerged material and one of the possible substitutes materials for cement to be used in the building material in the construction industry. A huge quantity of industrial byproduct materials of fly ash (FA) and Ground Granulated Blast furnace Slag (GGBS) is generated from thermal power plants during the burning of coal and iron production from a ground blast furnace in steam or water [4]. This waste byproduct material creates disposal and storage problems. Based on global statistics data, the unutilized and packed landfill quantity of fly ash is 176 million tonnes, and that of GGBS is 200 million tonnes [5]. Several researchers have employed fly ash as the main base material for replacing the cement in geopolymer concrete for manufacturing railway sleepers [6] and concrete columns [7]. A few studies have also been carried out using other materials like GGBS [8], rice husk ash [9], silica fume [10], and metakaolin [11] in geopolymer concrete.

Baburao et al. studied the durability of ordinary Portland cement concrete containing varying amounts of manufactured sand that replaced natural sand and inferred that 70% replacement by manufactured sand showed good durability properties [12]. Farooq et al. developed a multilayer feed-forward neural network model for finding the durability properties of high-performance concrete and concluded that 10% metakaolin + 10% silica fume + 20% bottom ash replacement of cement showed good performance in terms of strength as well as durability properties [13]. Kumar et al. replaced the coarse aggregate, fine aggregate, and cement with the concrete of oil palm shell manufactured sand and GGBS. They inferred that oil palm shell concrete with 40% GGBS replacement showed enhanced compressive strength in the long term [14]. Thangapandi et al. investigated the strength and durability of conventional concrete incorporated with manufactured sand instead of natural sand. The results revealed that 60% replacement of natural sand with m-sand showed optimum percentage for both strength and durability of the conventional concrete [15].

Sallehan et al. examined the mechanical and durability properties of Recycled Concrete Aggregates (RCA) in a treated way under different curing conditions such as normal water curing, open-air environment, and seawater exposure conditions. The authors concluded that seawater exposure caused a detrimental effect on the compressive strength of untreated RCA compared to normal water curing and open-air environment curing conditions. RCA showed poor porosity and permeability in the open-air environment curing conditions [16]. Dimitriou et al. inferred that recycled aggregate concrete showed improved strength and durability properties compared to the natural aggregate [17]. Ortega-lópez et al. studied fibre-reinforced Electric Arc Furnace (EAF) slag under wet-dry tests, as well as freeze-thaw, sulphate, and industrial environments. They proved that fibre-reinforced EAF slag exhibited better durability [18]. Nath and Sarker studied the durability of high-strength concrete containing a high volume of fly ash and observed that the high-strength concrete mixes showed less shrinkage and ion permeation and rate of absorption at 28 days. Even after six months, the rate of absorption and chloride iron permeation were lower [19]. Saha partially replaced cement with fly ash in conventional concrete and inferred that the concrete containing fly ash exhibited lower chloride permeability and water rate of absorption. Later, drops were observed with increasing curing time [20]. Bakharev investigated the durability properties of geopolymer concrete (fly ash) with an alkali activator solution immersed in acetic acid solutions and discussed the parameters of weight loss, compressive strength, and others [21]. Simatupang valuated class F and class C fly ash-based mortar characteristics on alkaline activated material when immersed in 10% sulphuric acid solution for 65 days [22]. Yong et al. stated the procedure for the rate of absorption test and obtained a 0.109 mm/min 0.5 rate of absorption value for lightweight OPS geopolymer concrete [23].

However, only limited studies are available on rapid chloride penetration and rate of absorption tests on fly ash and slag-based geopolymer concrete under ambient curing conditions using manufactured sand. In the present investigation, a more sustainable green geopolymer concrete is produced by replacing GGBS with fly ash and river sand with manufactured sand under ambient curing conditions. While previous investigations have dealt with the mechanical properties, validation, modulus of elasticity, and impact resistance test, this research focuses on the durability properties of geopolymer concrete under ambient curing conditions such as sulphuric acid and sodium sulphate, water absorption, rapid chloride penetration test, and rate of absorption tests. The research work aims to study the influence of slag content using alkali activator solutions on the durability properties and compare the performance of geopolymer concrete with that of ordinary Portland cement concrete.

2. Materials and Mix Proportions

2.1. Materials. Geopolymer concrete is a member of a family of inorganic polymers that do not use Portland cement as a binder for making concrete. Its properties are mainly formed by reacting an alkaline liquid with an aluminosilicate source material (rich in silica and alumina). This study used calcium class F fly ash and GGBS fly ash, which were procured from North Chennai Thermal Power Plant station and Astra Chemicals, respectively. The chemical constituents of fly ash and GGBS used for this research are given in Table 1. Coarse aggregates of sizes 8, 12, and 20 mm were used. Manufactured sand and natural sand were used as fine aggregate. The aggregates (fine and coarse) were used in Saturated Surface Dry (SSD) conditions. The specific gravity values of coarse aggregate, river sand, and m-sand are 2.73, 2.66, and 2.72, respectively.

Alkali solutions of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) in the ratio of 2.5 were used. Sodium silicate solution was used in the ratio of SiO_2/Na_2O by mass of 2.0, and an 8M concentration of NaOH solution was used. A superplasticizer (naphthalene based) was used in the geopolymer concrete.

A three-dimensional polymeric chain is formed during the polymerization process by the fast chemical reaction on silicon-aluminium minerals under alkaline conditions with the formula (empirical) $Mn[\text{-}(SiO_2)z\text{-}AlO_2]n.wH_2O$, where M is an alkali cation such as K^+ or Na^+, w is the water content, z is the Si/Al molar ratio, and n is polymerization degree [24]. The schematic form of geopolymerization is shown in Figure 1.

2.2. Mix Proportions of Geopolymer and Conventional Concrete. Twenty geopolymer concrete mixes were studied for optimizing G30 geopolymer concrete, and comparison studies were carried out with five conventional concrete

Table 1: Chemical constitution (in %) of fly ash and GGBS.

Constituents	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O	K_2O	SO_4	LOI[a]
Fly ash	63.32	26.76	2.49	5.55	0.29	0.0004	0.0002	0.36	0.97
GGBS	35.05	12.5	34.64	0.3	6.34	0.9	0.6	0.38	0.26

[a]Loss of ignition.

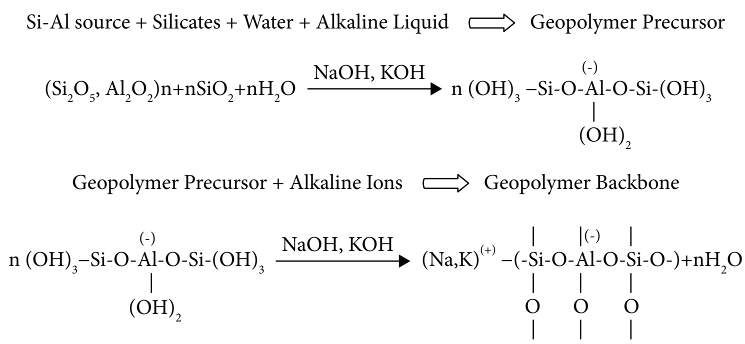


Figure 1: Schematic form of geopolymerization.

mixes as per IS 10262 [25]. This investigation's geopolymer concrete mix proportion is 1 : 2.22 : 3.86 : 6.95 by mass of alkaline activator solutions, aluminosilicate binder, fine aggregate, and coarse aggregates. The ratio between the alkaline activator solutions and the binder was 0.45. The quantity of the superplasticizer (Conplast SP430) used was 1% of the binder content (GGBS and FA) in the geopolymer concrete. For geopolymer concrete, river sand was partially or fully replaced with m-sand.

In the mixing process, fine and coarse aggregates were first mixed in Saturated Surface Dry (SSD) conditions in a mixer machine. Then, the binder contents were mixed with the aggregates. The mixing was continued for about 3 minutes. The already prepared alkali-activated solution was poured into the mixer machine, and the mixing was continued for about 4 minutes. Finally, the superplasticizer was added to the mixture until the concrete appeared homogenous and had the desired consistency. The geopolymer concrete was poured into the moulds in a new state. After demoulding the specimens, the samples were cured under ambient temperature for 28 days. The mechanical properties of the geopolymer and the conventional concrete can be found in previous studies.

Based on the mechanical properties of the prepared geopolymer concrete mixes, three concrete mixes that achieved G30 grade were chosen, and their durability-related properties were investigated and compared with conventional concrete. The mechanical properties were validated using MATLAB software using the Levenberg-Marquardt training algorithm. The mechanical properties of the geopolymer concrete (binder (80% fly ash + 20% GGBS) and 100% replacement of river sand with manufactured sand) and conventional concrete are shown in Table 2.

The stress-strain curves for the conventional and geopolymer concrete from an average of the three values and the failure patterns of these types of concrete tested under uniaxial compression are shown in Figure 2.

The mixed proportions of the G30 grade of geopolymer concrete studied for durability are given in Table 3. For comparative analysis, a mixed proportion of conventional concrete is also provided.

The proportions of coarse aggregate, superplasticizer, and alkali-activated solutions used in the geopolymer concrete mixes were 1189 kg/m^3, 3.8 kg/m^3, and 171 kg/m^3, respectively. The coarse aggregate and water used in the conventional concrete mix were 1189 kg/m^3 and 171 kg/m^3, respectively. From Table 3, it is observed that G20M0 indicates that the mixes have 20% GGBS, 80% fly ash, and 0% manufactured sand. In the same way, G20M100 indicates 20% GGBS, 80% fly ash, and 100% manufactured sand in the mix.

3. Microstructural Analysis and Experimental Procedures

3.1. Scanning Electron Microscopy (SEM) with Energy-Dispersive X-Ray Spectroscopy (EDX) Analysis. The Scanning Electron Microscope equipped with an Energy-Dispersive X-ray spectrometer was used to characterize the microstructure of the geopolymer concrete. The SEM measurements were performed using EVO 18 research microscope and LaB6 filaments electron source to find the surface morphology of the concrete mixes.

The images were obtained at a resolution of 8 kV. The samples were evaluated in the system vacuum technique. The SEM images of fly ash and GGBS are shown in Figures 3(a) and 3(b), respectively. The SEM image of m-sand is shown in Figure 3(c). The results showed that fly ash and GGBS have high silica and alumina content. Fly ash particles are viewed as spherical, while GGBS is granular, and m-sand is angular in shape.

3.2. Experimental Procedures

3.2.1. Acid Resistance Test. The testing requirements include preparing a curing tank separately by mixing 5% concentrated sulphuric acid solution with the required water level to immerse the specimens. The tanks are made isolated from other laboratory areas as the handling of acids needs care.

Table 2: Mechanical properties of geopolymer concrete and conventional concrete.

Mechanical properties	Geopolymer concrete (GC)	Conventional concrete (CC)
Compressive strength (MPa)	40.35	38.95
Split tensile strength (MPa)	3.32	3.17
Flexural strength (MPa)	4.69	4.46
Modulus of elasticity (GPa)	19.10	22.19

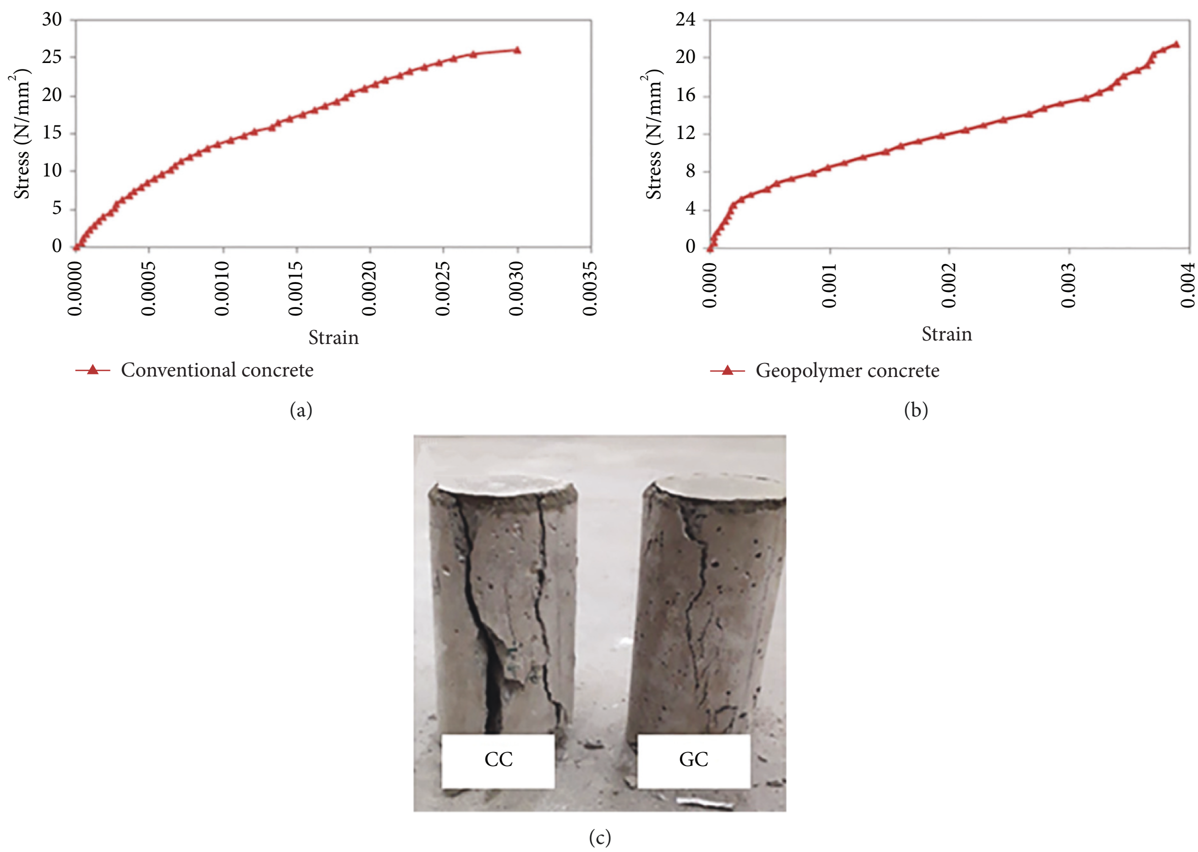


Figure 2: Stress-Strain curve for (a) conventional concrete and (b) geopolymer concrete. (c) Failure patterns of CC and GC were tested under uniaxial compression.

Table 3: Details of mix proportions of concrete specimens.

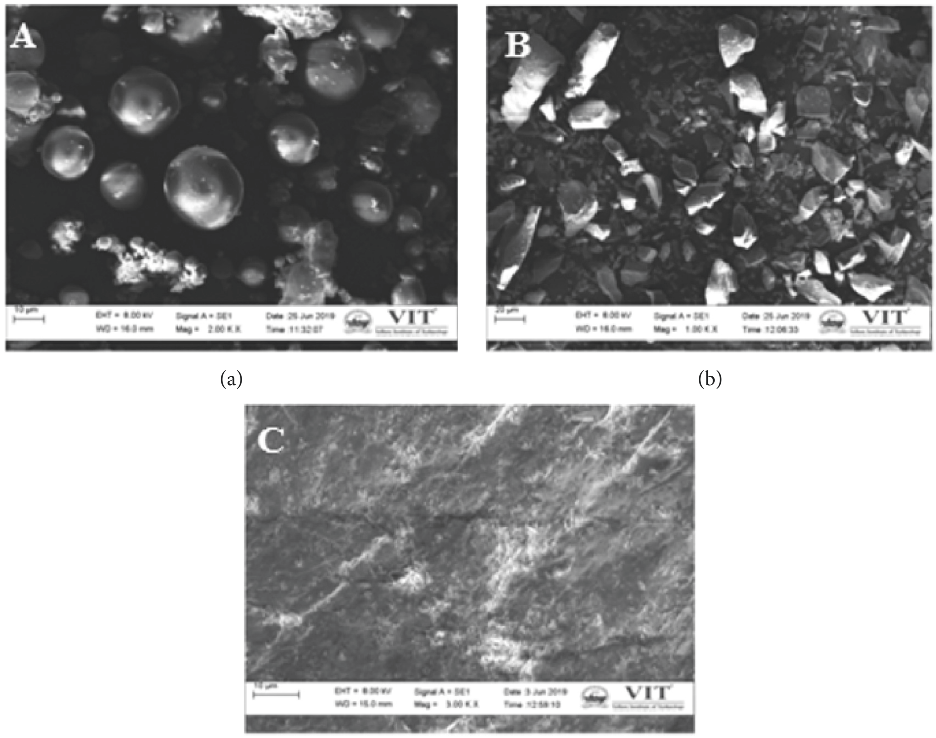
Mixes	ID	Fly ash	GGBS	Cement	M-sand	River sand
G20M0	GC1	304	76	—	0	660
G20M50	GC2	304	76	—	330	330
G20M100	GC3	304	76	—	660	0
C100R100	OPC	—	—	380	0	660

All units are in kg/m^3.

The specimens are to be placed with care inside the proposed area without splattering the acid solution. Nine specimens each for GC1, GC2, GC3, and OPC were tested for the acid tests as per the procedure given in ASTM C 642 [21]. Initially, the ambient cured geopolymer concrete samples cured for 28 days of size 150 mm × 150 mm × 150 mm were cast to conduct an acid resistance test. After 28 days, water cured conventional concrete cube samples were taken out from the water curing tank. After cleaning, the weights of the cube samples were recorded as W_1. The cube samples were then immersed in 5% sulphuric acid solution with a minimum of 30 mm depth of acid present above the top surface of the concrete specimens. Three samples were taken out from the containers after 28 days, 56 days, and 90 days to carry out the testing. Variation in compressive strength and mass has been recorded before and after immersion. The cube specimens were washed with tap water and weighed using a digital weighing balance with an accuracy of 0.1 mg. The average weight of cube samples was noted as W_2. The variation in mass was calculated as shown in the following equation:

$$\%\ \text{weight loss} = \left[\frac{\text{Initial weight}\ (W_1) - \text{Final weight}\ (W_2)}{\text{Initial weight}\ (W_1)}\right] \times 100. \tag{1}$$

3.2.2. Sulphate Resistance Test. The acid attack test was followed by sulphate curing to understand the resistance of the specimens towards sulphate attack. The specimens were



(a) (b) (c)

Figure 3: SEM images of (a) fly ash, (b) GGBS, and (c) M-sand.

immersed in a solution made of 5% sodium sulphate powder and the required quantity of water to immerse them fully. Unlike acid curing, sulphate curing does not require special handling equipment as it does not cause harm directly. The sulphate intrusion into the specimen was determined by measuring the loss in weight and compression values of the immersed specimens after the proposed curing periods of 28 and 56 days. Nine specimens each for GC1, GC2, GC3, and OPC were tested for sulphate resistance test as per the procedure given in ASTM C 642 [26]. The ambient cured geopolymer concrete cube samples cured for 28 days were subjected to an acid resistance test. After 28 days, water-cured conventional concrete cubes were taken out from the water curing tank. After cleaning the surfaces of the cubes, they were placed in a 5% sodium sulphate solution. The containers were closed to minimize the evaporation and falling of dust particles. The new solutions were maintained every month to regulate the pH value of the solution. The solutions were stirred every week to avoid deposits at the base of the containers. Three samples were taken out from the containers after 28 days, 56 days, and 90 days to carry out the testing. Variations in compressive strength and mass were recorded before and after immersion. The cube samples were tested in a compression testing machine.

3.2.3. Water Absorption Test. Water absorption was determined by measuring the hike in weight recorded over an oven-dried sample when immersed in water for 24 hours. The surface water was removed before measuring the weight. The ratio of the increase in weight to the weight of the dry sample expressed in percentage is termed absorption. Nine specimens each for GC1, GC2, GC3, and OPC were tested for water absorption test as per the procedure specified in ASTM C 642 [9]. The saturated weights of the cube samples measured after being taken from the water curing tank are denoted as W_s. The drying process was continued in the oven at a temperature of 105°C. The drying process was stopped when the difference between two successive measurements was small. The dry weights of the samples were recorded as W_d. The absorbed water was calculated using the following equation:

$$\text{Water Absorption} = \left[\frac{W_s - W_d}{W_d}\right] \times 100, \tag{2}$$

where W_s is weight of the samples at fully saturated condition (kg) and W_d is weight of samples at oven-dried condition (kg).

3.2.4. Rapid Chloride Penetration Test (RCPT). Concrete structures are mainly affected by chloride penetration in seawater and groundwater having high concentrations of chloride salts. The Rapid Chloride Penetration Test is fast and is the main indicator of chloride ion penetration into the concrete structures. The RCPT test was performed per the procedure given in ASTM C 1202-1997 [16]. Concretes of sizes of 100 mm diameter × 50 mm thickness were sliced from the top portion of the cylinders with 100 mm diameter × 200 mm height. After the curing period, the samples were tested for chloride permeability. Before testing, the samples were dried to ensure that they were free of moisture. The samples were preconditioned as per standards, wherein two halves of the samples were sealed in the container. One container side was packed with 0.3 N sodium hydroxide solution and linked to the anode terminal. In contrast, on the other side, 3% sodium chloride solution was poured and the cell was connected to the cathode terminal. The dried samples were subjected to 60-volt electric potential for about 6 hours and the current passing was recorded every 30 minutes. The RCPT test setup is shown in Figure 4.

Figure 4: Test setup for RCPT test.

3.2.5. Rate of Absorption. The rate of absorption (Sorptivity) characteristic is a concrete's ability to absorb or transmit water through the capillary action like a homogenous material. Water was used as a test fluid for carrying out the rate of absorption test. The procedure for the rate of absorption test was adapted from [26, 27]. The arrangement for the rate of absorption (Sorptivity) test is shown in Figure 5. ASTM C1585 Standard was considered for rate of absorption test (Sorptivity) [27].

The 100 mm cube samples cured for 28 days were used for the rate of absorption test. Ambient cured samples were dried in an oven at a temperature of 105 ± 5°C for about 48 hours until no variation in sample weight was achieved. After that, the samples were cooled at room temperature. The nonabsorbent solutions were prepared using resin and Methyl Ethyl Ketone Peroxide (MEKP) as the catalyst and Cobalt Octoate (CO) as the promoter. The sides of the cube samples were coated with the already prepared nonabsorbent solutions to avoid the penetration of water through the sides of the cube samples. The prepared tubes were positioned in a tray such that the bottom of the cube samples got in touch with the water to a height of 5 mm. The samples were taken from the tray, wiped off with dampened tissue, and then weighed using a weighing balance with 0.1 mg accuracy every 10 minutes.

Since the square root of time increases, the water absorption (cumulative) will also increase. The rate of absorption has been calculated using the following equation:

$$I = s_t^{0.5}, \tag{3}$$

where S is rate of absorption (mm), t is elapsed time (minutes), and absorption, $I = \Delta w/\mathrm{Ad}$, Δw = difference between the mass of the sample after 30 minutes of capillary suction of water and the mass of the oven-dried sample (grams). A is surface area of the sample and d is density of water.

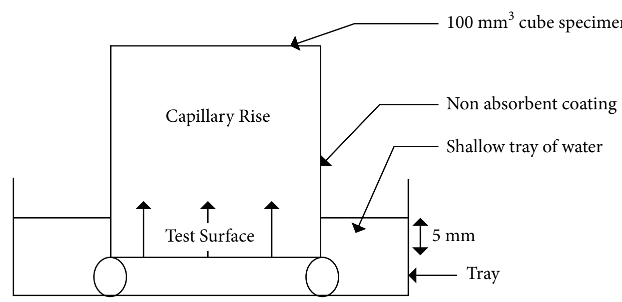


Figure 5: Arrangement for the rate of absorption (Sorptivity) test.

4. Results and Discussions

4.1. Scanning Electron Microscopy (SEM) with Energy-Dispersive X-Ray Spectroscopy (EDX) Analysis of Geopolymer Concrete. The SEM images and the EDX spectra of the geopolymer and conventional concrete samples are shown in Figures 6 and 7. These microstructural images of the samples GC3 (G20M100) and OPC (C100R100) of geopolymer concrete were obtained at 28 days.

While using GGBS in fly ash-based geopolymer concrete, calcium aluminosilicate hydrate (C-A-S-H) is a reaction product when calcium compound rises in geopolymer concrete [28]. Meanwhile, in ordinary Portland cement concrete, calcium silicate hydrate (C-S-H) gel is the reaction product. The density and homogeneity could be improved by adding the fine particles as an additive in geopolymer concrete.

4.2. Acid Resistance. The weight loss in percentage and compressive strength for GC1, GC2, GC3, and OPC concrete mixes at 28 days, 56 days, and 90 days are presented in Figure 8 and Tables 4 and 5.

From Figure 8(a), it is observed that the percentage weight loss of all the concrete mixes increases with the curing period. The percentage of weight loss between 28 days and 90 days of immersion for the GC1, GC2, and GC3 mixes is lower when compared to that of the OPC. The percentage of weight loss in geopolymer concrete is low due to sodium content and the low permeability of the solution when compared. The test results implied that the GC1, GC2, and GC3 specimens showed better resistance to acid attack when compared with OPC × geopolymer concrete possessing strong resistance to acid attack due to the generation of calcium aluminium silicate gel (C-A-S-H) and sodium aluminosilicate gel (N-A-S-H). The OPC concrete is highly susceptible to acid attack due to the formation of calcium silicate hydrate gel (C-S-H) gel [2PC].

The compressive strength reductions for GC1, GC2, GC3, and OPC concrete mixes for 28 days, 56 days, and 90

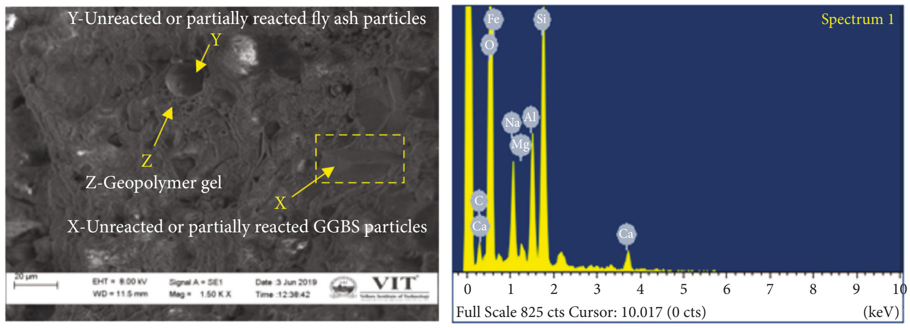


FIGURE 6: SEM image and EDX spectrum of mix GC3 (G20M100).

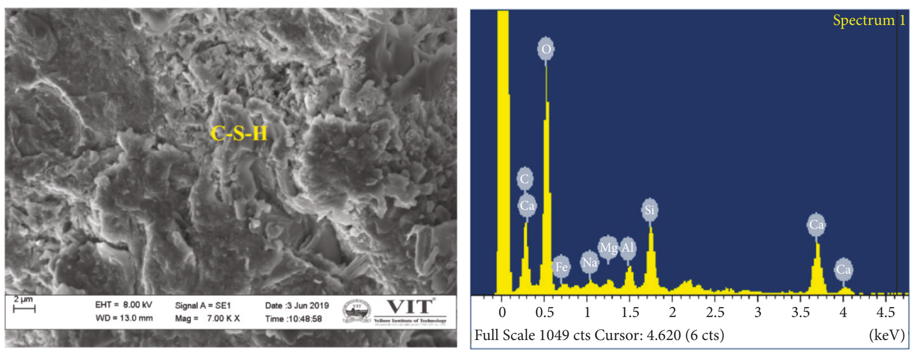


FIGURE 7: SEM image and EDX spectrum of mix OPC (C100R100). X: unreacted or partially reacted GGBS particles. Y: unreacted or partially reacted fly ash particles. Z: geopolymer gel.

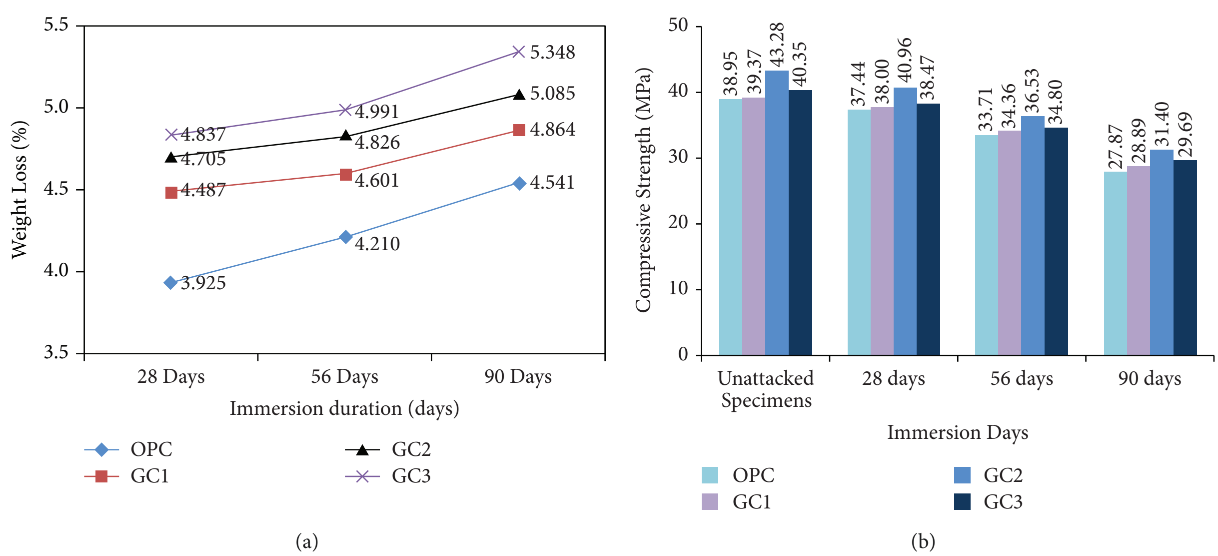


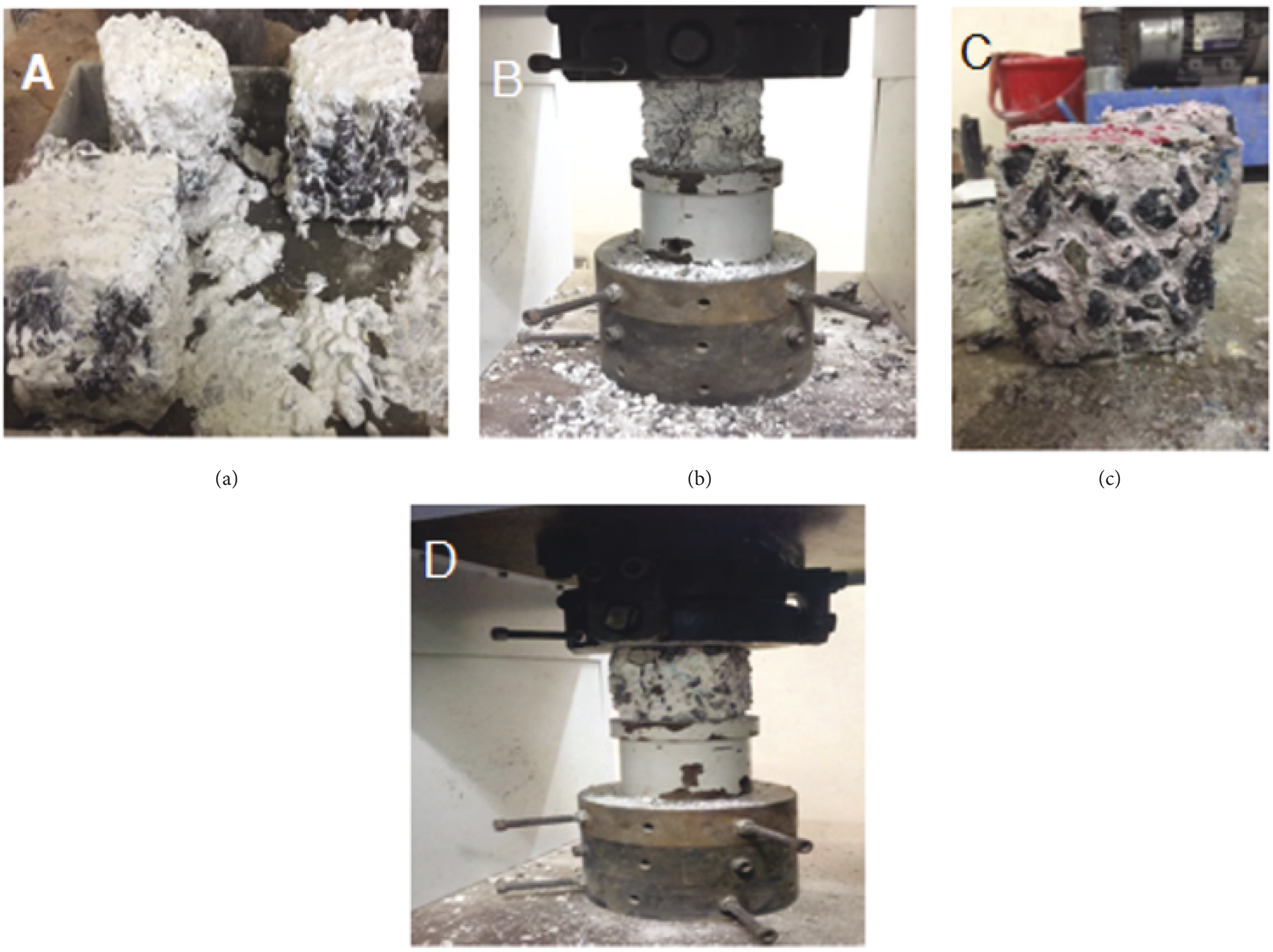
FIGURE 8: Variation of (a) percentage weight loss and (b) compressive strength after the acid test as a function of curing period.

TABLE 4: Weight loss in the geopolymer and OPC concrete mix percentage after the acid test for different curing periods.

Mix ID	28 days	56 days	90 days
OPC	37.44	33.71	27.87
GC1	38.00	34.36	28.89
GC2	40.96	36.53	31.40
GC3	38.47	34.80	29.69

TABLE 5: Compressive strength values of the geopolymer and OPC concrete mixes after the acid test for different curing periods.

Mix ID	Unattacked specimens	28 days	56 days	90 days
OPC	38.95	37.44	33.71	27.87
GC1	39.37	38.00	34.36	28.89
GC2	43.28	40.96	36.53	31.40
GC3	40.35	38.47	34.80	29.69



(a) (b) (c) (d)

Figure 9: (a) Cubes of the conventional mix (OPC) after removal from acid curing; (b) compressive testing of acid cured conventional cube specimen; (c) cubes of geopolymer mix (GC-3) after removal from acid curing; (d) compressive testing of acid cured geopolymer cube specimen.

days are presented in Figure 8(b). It is noted from Figure 8(b) that the compressive strengths for the mixes OPC, GC1, GC2, and GC3 were 27.87 MPa, 29.09 MPa, 31.40 MPa, and 29.69 MPa, respectively, at 90 days. The equivalent percentage losses in compressive strength were 25.56%, 23.45%, 23.34%, and 22.82%. The test results revealed that OPC experienced maximum strength loss, whereas GC1, GC2, and GC3 experienced minimum strength loss. The compressive strength loss was in the order of OPC > GC1 > GC2 > GC3. The decalcification of C-S-H was detected, which, alongside the dissolution of calcium hydroxide, results in a very porous corroded layer and a decrease in compressive strength. On the other hand, the decalcification of the C-A-S-H type gel in geopolymer concrete results in a dense highly siliceous layer that is more resistant to acid attack [29]. Cubes of the conventional and geopolymer concrete mixes after removal from acid curing and compressive testing are shown in Figure 9.

In an acidic environment, geopolymer concrete's better performance than conventional concrete is attributed to the lower calcium content in fly ash, since geopolymer concrete does not depend on lime-like ordinary Portland cement concrete. Geopolymer concrete does not allow ingress of sulphuric acid, since it does not have a transition zone. Hence, geopolymer concrete has a higher durability factor [30].

4.3. Sulphate Resistance Test. The weight loss in percentage and compressive strength for GC1, GC2, GC3, and OPC concrete mixes at 28 days, 56 days, and 90 days are presented in Figure 10 and Tables 6 and 7.

From Figure 10(a), it is noted that the percentage weight loss of all mixes increases with the curing period. The percentage of weight loss is higher in OPC concrete than in geopolymer concrete during 28 days and 90 days of immersion in a sulphate solution. When geopolymer concrete samples were immersed in sulphate solution, the transmission of sulphate ions caused by the disintegration of siloxane bonds (-Si-O-Si-bonds) decreased the Si/Al atomic ratio and leaching of Si in the geopolymer gel structure.

Compressive strength reductions for GC1, GC2, GC3, and OPC concrete mixes at 28 days, 56 days, and 90 days are

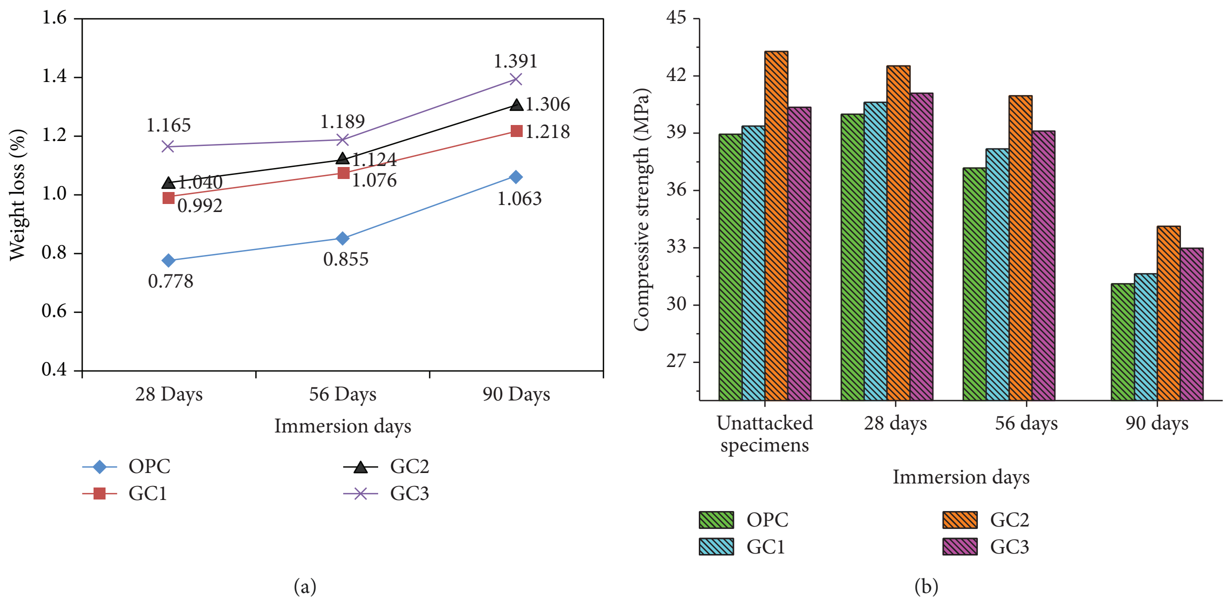


Figure 10: Variation of (a) percentage weight loss and (b) compressive strength after sulphate test as a function of curing period.

Table 6: Weight loss in percentage of the geopolymer and OPC concrete mix after sulphate test for different curing periods.

Mix ID	28 days	56 days	90 days
OPC	0.778	0.855	1.063
GC1	0.992	1.076	1.218
GC2	1.040	1.124	1.306
GC3	1.165	1.189	1.391

Table 7: Compressive strength values of the geopolymer and OPC concrete mixes after sulphate test for different curing periods.

Mix ID	Unattacked specimens	28 days	56 days	90 days
OPC	40	37.18	31.11	40
GC1	40.62	38.18	31.64	40.62
GC2	42.52	40.96	34.13	42.52
GC3	41.09	39.11	32.98	41.09

presented in Figure 11(b). The compressive strengths of OPC, GC1, GC2, and GC3 mixes were 31.11 MPa, 32.44 MPa, 34.13 MPa, and 32.98 MPa, respectively. The equivalent percentage losses in compressive strengths were 22%, 20%, 19.73%, and 19.73%. The test results indicated that OPC experienced maximum strength loss, whereas GC1, GC2, and GC3 experienced minimum strength loss. Figure 11 shows the compressive testing of sulphate cured conventional and geopolymer concrete cube specimens. The authors reported that low calcium fly ash concrete showed higher resistance to sulphate attack [31]. It was also reported that AAS concrete has better sulphate resistance than OPC [32]. The compressive strength of geopolymer concrete had a minimum deteriorating effect due to sulphate ions $(SO_4)^{-2}$ [33]. It could be observed that the presence of GGBS additives led to the minimum strength loss in geopolymer concrete (fly ash-based) compared with conventional concrete.

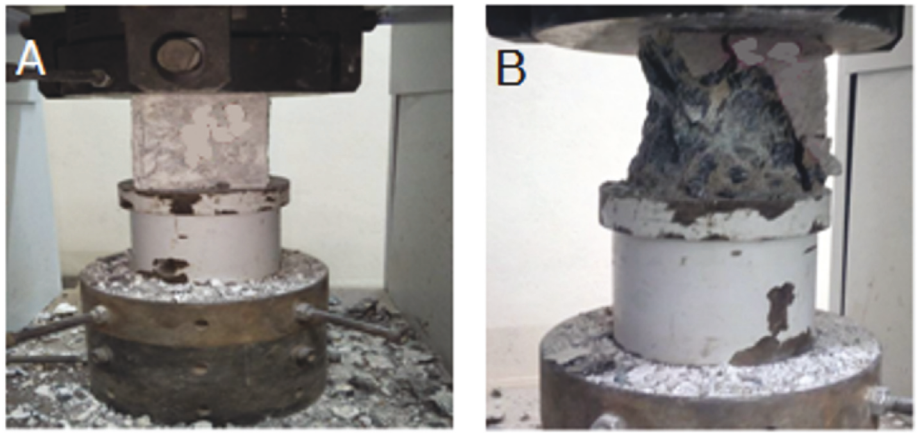
4.4. Water Absorption Test. The water absorption percentages for GC1, GC2, GC3, and OPC concrete mixes at 28 days, 56 days, and 90 days are presented in Figure 12 and Table 8.

It is noted from Figure 12 that the increase in the percentage of water absorption for geopolymer concrete is lower than that for OPC concrete. The percentage loss in water absorption is taken between 28 days and 90 days. The percentage loss in water absorption for geopolymer concrete decreases from 28 days to 90 days compared to control concrete. The authors found that the fine slag particles fill the pores, leading to lower water absorption values for alkali-activated fly ash blend with slag (AAFS) binders compared to ordinary Portland cement concrete [34].

4.5. Rapid Chloride Penetration Test. The Rapid Chloride Penetration Test (RCPT) value indicates chloride penetration (permeability) into the concrete specimens. It is expressed as the total charge passing in the coulomb during the test period. The RCPT values for GPC and OPC concrete mixes are given in Table 9. The total charge passing through the concrete specimens of geopolymer concrete and conventional concrete at 28 days is shown in Figure 13. The average values for the three specimens for each mix were also obtained.

It is observed from Figure 13 that the penetration level of chloride in the geopolymer concrete falls under the “low level” against the “very low level” in ordinary Portland cement concrete. Cl^- ion penetration was reduced when the FA content increased in the concrete mixtures. Hence, FA concrete showed better resistance to Cl^- ion.

4.6. Rate of Absorption Test. The rate of absorption (Sorptivity) measurement is usually performed for short periods. Hall (1989) suggested that two hours is sufficient for performing the rate of absorption measurements. Martys (1997)



(a) (b)

Figure 11: Compressive testing of sulphate cured (a) conventional and (b) geopolymer concrete cube specimens.

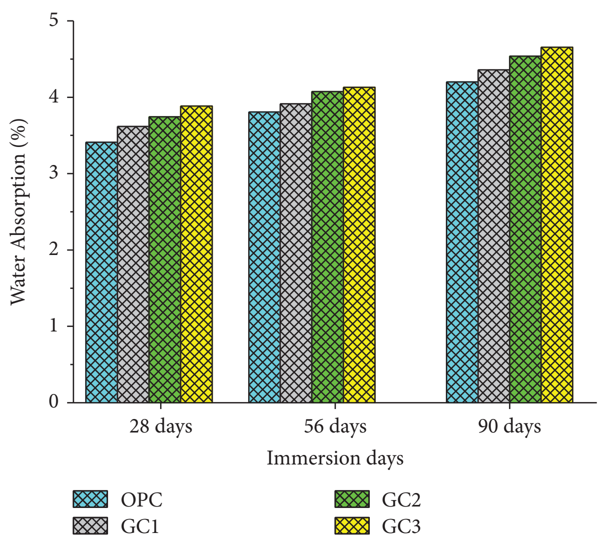


Figure 12: Water absorption percentage as a function of curing period for different concrete mixes.

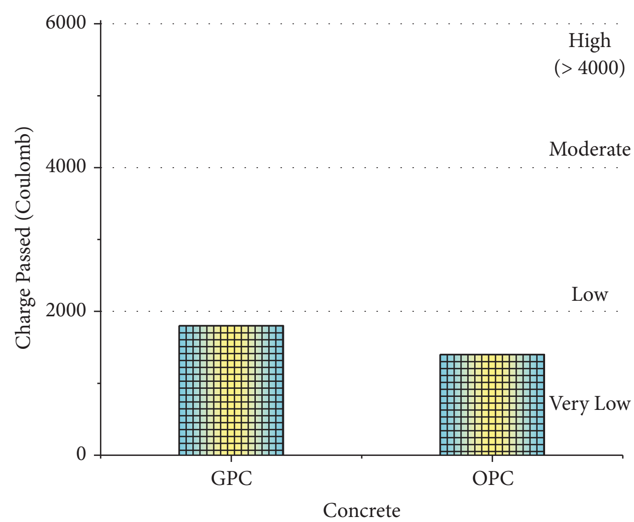


Figure 13: Rapid Chloride Permeability Test results for GPC and OPC mix.

Table 8: Water absorption percentage for different concrete mixes at different curing periods.

Mix ID	28 days	56 days	90 days
OPC	0.778	0.855	1.063
GC1	0.992	1.076	1.218
GC2	1.040	1.124	1.306
GC3	1.165	1.189	1.391

Table 9: RCPT values for different concrete mixes.

Mix ID	Charge passing (coulombs)	Charge passing (coulombs)
GPC 1	1206	
GPC 2	1676	1662 (avg)
GPC 3	2104	
OPC 1	758	
OPC 2	873	847 (avg)
OPC 3	911	

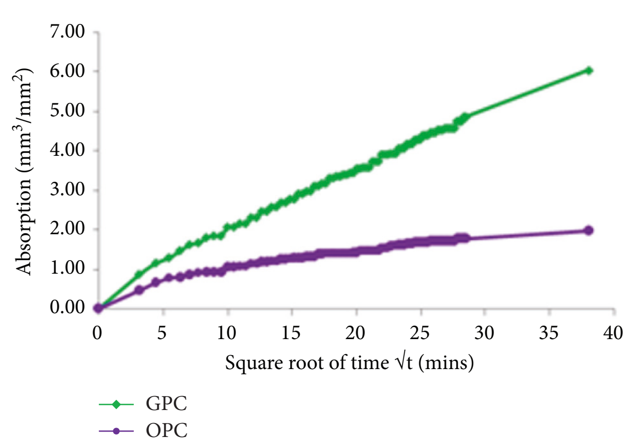


Figure 14: Absorption versus square root of time for GPC and OPC mixes.

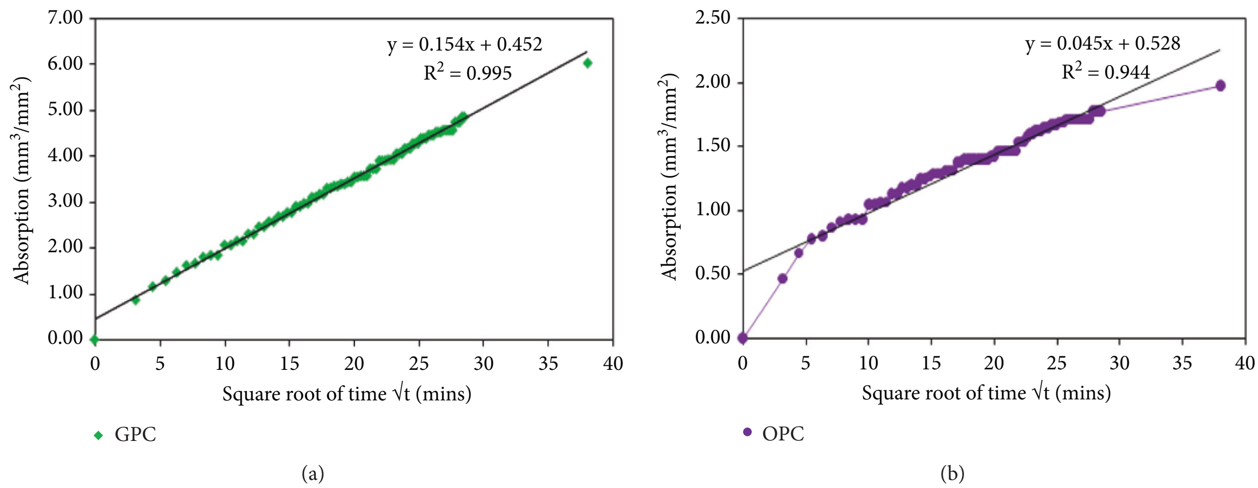


Figure 15: Regression analysis-absorption versus square root of time for (a) GPC and (b) OPC.

Table 10: Rate of absorption (Sorptivity) values for different concrete mixes.

Mix ID	Rate of absorption (mm/min$^{0.5}$)
GPC	0.16
OPC	0.05

claimed that two rate of absorption coefficients characterize mortars and concrete. For large-age rate of absorption coefficients, longer than one day is accredited other than suction such as slow filling of sir voids and water interactions with cement gel due to capillary pore network. Hence, the rate of absorption test was conducted for one day and the readings were noted every 10 minutes' interval. The absorption values for geopolymer concrete and conventional concrete plotted against the square root of time are illustrated in Figure 14. Regression analysis for absorption versus square root of time (t) for GPC and OPC concrete is illustrated in Figures 15(a) and 15(b).

The regression analysis on two parameters, time and GPC absorption (Figure 15(a)), clearly indicates an excellent relationship between absorption and the square root of time with an R^2 value nearing 1 (99% accuracy) and a minimal standard error of 0.075. The regression analysis on two parameters, time and OPC absorption (Figure 15(b)), also indicates an excellent relationship between absorption and the square root of time with an R^2 value nearing 1 (95% accuracy) and minimal standard error of 0.080.

The rate of absorption (Sorptivity) values for OPC and GPC mixes are shown in Table 10. The rate of absorption value of geopolymer concrete mixes is 0.164 (mm/min$^{1/2}$), which is slightly higher than the rate of absorption value of 0.053 for OPC (mm/min$^{1/2}$). This may be due to the addition of 20% GGBS as a replacement material of 80% fly ash in eco-friendly geopolymer concrete.

5. Conclusions

Twenty geopolymer concrete mixtures were designed with FA and GGBS as the binder source materials and the replacement of river sand with m-sand as the fine aggregates. Five conventional concrete mixtures were designed using m-sand as an alternative material to river sand as the fine aggregate. The durability properties of three geopolymer concrete mixes (among the twenty mixes) have been studied and compared with conventional concrete mixes. Optimized geopolymer concrete mix has been selected to carry out future studies of flexural strength of geopolymer beam using fibre-reinforced polymer rebar reinforced concrete beam.

The following points were observed from the experimental test results:

(i) From the investigation of the mechanical properties, it is observed that concrete mixes with 80% FA and 20% GGBS along with m-sand as a full or partial replacement in mix proportions, namely, G20M0, G20M50, and G20M100, achieve the strength of G30 grade and can be used as an alternative material for conventional concrete.

(ii) The percentage of weight loss is higher in conventional concrete than in geopolymer concrete owing to sulfuric acid and sulphate attacks.

(iii) The percentage loss in compressive strength due to sulfuric acid and sulphate attack in geopolymer concrete is lower when compared to that in ordinary Portland cement concrete at 28 days, 56 days, and 90 days.

(iv) The percentage loss in water absorption of geopolymer concrete is lower when compared with that of ordinary Portland cement concrete at 28 days, 56 days, and 90 days.

(v) In geopolymer concrete, the penetrability of chloride ion (Cl^-) falls in the "low level" against the "very low level" in ordinary Portland cement concrete.

(vi) The rate of absorption (Sorptivity) value for geopolymer concrete is slightly higher than that of the ordinary Portland cement concrete when considered for one day, that is, large age rate of absorption coefficient.

6. Disclosure

This study was performed as a part of the Employment of Kombolcha Institute of Technology, Wollo University, Kombolcha, Amhara, Ethiopia.

Data Availability

The data used to support the findings of this study are included in the article. Should further data or information be required, these are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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