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Research Article

Effect of sealed curing on G40 grade geopolymer concrete incorporating fly ash and GGBS

Sharada Polusani[1*], V Vinayaka Ram[2] and M V Seshagiri Rao[3]
Department of Civil Engineering, Jawaharlal Nehru Technological University Hyderabad, Telangana, India[1]
Department of Civil Engineering, BITS Pilani, Hyderabad Campus, Hyderabad, Telangana, India[2]
Department of Civil Engineering, CVR Engineering College, Hyderabad, Telangana, India[3]

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Abstract

Geopolymer binders are created by mixing precursors rich in silica (Si) and aluminium (Al), such as fly ash and ground granulated blast furnace slag (GGBS), with specific amounts of alkaline reagents like sodium or potassium silicates and hydroxides. This study aimed to develop geopolymer concrete suitable for pavement quality concrete (PQC) by utilizing fly ash and GGBS as precursors, combined with sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) as alkaline reagents. Two different mixes were prepared using a fly ash to GGBS ratio of 75:25 and 60:40. Each mix was subjected to two types of curing conditions: one group of specimens was completely sealed with 100-micron thick plastic sheets and stored at room temperature, while the other group was left exposed without any plastic covering. Research was conducted on the mechanical strength, sorptivity, amount of non-evaporable water, and the microstructure of the concrete specimens. The findings revealed that the sealed specimens exhibited lower sorptivity, higher compressive strength, and retained a greater amount of non-evaporable water compared to the open-cured specimens. Sealing the concrete effectively prevented the loss of surface water, thereby minimizing the formation of air voids on the surface and promoting the retention of a greater amount of inbound water. The microstructure of the sealed concrete specimens was denser, more compact, and contained a higher Silica to Alumina (Si/Al) content compared to the open-cured specimens.

Keywords

Geopolymer concrete, Sealed curing, Fly ash, Ground granulated blast furnace slag (GGBS), Mechanical and microstructural properties, Sustainable construction materials.

1.Introduction

The demand for concrete and its constituent materials is rapidly increasing due to infrastructure development. The production of cement, a key binding agent in ordinary concrete, contributes to approximately 27% of total direct global CO_2 emissions. In response to this environmental concern, French scientist Davidovits developed a binder known as geopolymer, which can serve as an alternative to cement. Geopolymers are created by combining silica (Si) and alumina-rich minerals with alkaline activators, leading to the polycondensation of Si and Aluminium (Al) into a three-dimensional structure. Notably, geopolymer concrete can save approximately 44% of embodied energy compared to ordinary Portland cement concrete (OPC) [1, 2].

Although standardized procedures for synthesizing geopolymer concrete are still lacking, researchers have proposed various methods to design mixtures that meet specific workability and strength criteria by optimizing materials and curing processes [3–7]. Water plays a crucial role in geopolymer concrete; however, it does not instantly enhance strength. A sufficient amount of water is necessary for the dissolution and transportation of precursor particles. The geopolymerization process is multi-step, involving the dissolution of precursors, which produces Si and Al monomers. These dissolved monomers are then transported and eventually undergo polycondensation to form polymers. According to Fernández-jiménez et al. [8, 9], Gel 1, an aluminosilicate gel rich in aluminium, forms within the first few minutes to approximately 4–5 hours of the geopolymerization process. During the course of the reaction, Silica-oxygen groups gradually dissolve, resulting in an increase in the Si

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[*] Author for correspondence

concentration leading to the formation of a sodium aluminosilicate hydrate (N-A-S-H) gel called Gel 2 [8, 9]. Curing is a crucial aspect of the geopolymerization process in concrete. According to [10], fly ash-based geopolymer concrete typically requires heating during curing to achieve the necessary strength and complete the polymerization process. However, the incorporation of ground granulated blast furnace slag (GGBS) into fly ash-based geopolymer concrete eliminates the need for heat curing. This is because the high calcium concentration and reactivity of GGBS enable polymerization to occur at room temperature. Research has shown that substituting a portion of fly ash with GGBS not only accelerates curing at room temperature and also significantly enhances early strength development. For instance, Deb et al. [11] reported that mixtures with 50% GGBS achieved compressive strengths exceeding 40 MPa after 28 days of ambient curing. Similarly, Rautaray et al. [12] demonstrated that GGBS-blended systems achieve strengths comparable to those of heat-cured fly ash-based geopolymers.

According to the literature, many studies are conducted on fly ash-GGBS based geopolymer concrete cured in open air at room temperature. Geopolymer concrete open cured in ambient conditions leads to water evaporation. This evaporation results in drying shrinkage and the formation of micro cracks within the initial 7 days of curing. This effect is especially evident in flat structural elements, such as pavements and slabs. It has been observed that fly ash-based geopolymer samples cured under sealed conditions produce more consistent results, with ultimate shrinkage reduced by up to 50% due to the sealing of the concrete [13–15]. According to research, curing fly ash geopolymer concrete in covered molds results in a dense, amorphous microstructure with impressive mechanical strength, reaching up to 102 MPa [16]. Studies have shown that sealing the specimens during the curing process enhances the geopolymerization reactions, which leads to the formation of a denser and stronger binder matrix. However, there are limited studies on the effects of sealing geopolymer specimens during curing, especially within the context of fly ash and GGBS geopolymer concrete. Existing research has not specifically investigated how sealed curing affects particular grades of concrete. This study is motivated by the need for environmentally friendly building materials that improve the durability and performance of infrastructure systems while minimizing their negative environmental impact. Geopolymer concrete is an ideal choice for pavements due to its sustainable nature and the incorporation of industrial byproducts as binders. Investigating the effects of sealed curing on the quality of pavement-grade concrete can provide insights into how surface water evaporation influences the mechanical properties and microstructural behavior of the concrete. This research has the potential to enhance durability and extend the lifespan of pavements.

These primary objectives of this study are developing two concrete mixtures that incorporate different ratios of GGBS and fly ash, along with varying percentages of sodium oxide (Na_2O) to achieve G40 grade concrete. The two mixtures are subjected to different curing methods: one is cured in open air at the ambient temperature, while the other is covered with a 100-micron-thick white plastic sheet for curing. The mechanical properties, sorptivity, water retention, and microstructure of the specimens cured in both the conditions are compared. The results show that the specimen cured under the sealed cover exhibited greater mechanical strength, lower sorptivity, and a denser microstructure compared to the specimen cured in an open environment.

This research contributes to the existing literature by producing pavement quality concrete *(*PQC) grade geopolymer concrete as an eco-friendly option by utilizing GGBS and fly ash, which minimizes environmental impact. It showcases how sealed curing significantly enhances mechanical strength, decreases sorptivity, and fosters denser microstructures in comparison to open-air curing. The results highlight the practical advantages of sealed curing in boosting the durability and lifespan of pavements, laying the groundwork for future investigations into curing techniques and sustainable building practices.

The manuscript is organized as follows: Section 2 reviews previous studies on the mechanisms and curing processes of geopolymer concrete. Section 3 explains the materials used to prepare the samples and outlines the experiments conducted. In section 4, the results and findings of the experimental investigations are presented. Section 5 includes a discussion of these results, and section 6 provides the conclusions.

2.Literature review

The study by Davidovits [17] indicates Geopolymers consist of two main constituents: source materials and alkaline liquids. Geopolymer source materials that are based on alumina-silicate should have a high concentration of Si and Al. Geopolymer concrete is regarded as a suitable substitute not just due to its sustainability, but also because it utilises waste materials from industry as a source, in contrast to OPC which relies on cement. Fly ash is a byproduct of thermal power plants and is categorised into two variants Class C and Class F fly ash [18]. Class C is characterised by a high calcium content, while class F has less than 10% calcium and is rich in Al and Si. GGBS, which is mostly generated by the steel and iron sectors, is frequently employed as a binding agent in Geopolymer concrete. Alkaline liquids consist of soluble alkali metals, predominantly sodium or potassium. A frequently employed alkaline solution for geopolymerization consists of a mixture of NaOH and sodium or potassium silicate. The activators used in alkali activated materials can release the individual units of aluminate and silicate in the alumina silicate material, which then dissolve and combine to create an alumina silicate gel [19].

The main outcome of the process of alkali activation of fly ash is the formation of N-A-S-H gel, while the chief output of GGBS is calcium silicate hydrate (C-S-H). The study by Muhammad Nasir et al. [20] indicates different products are formed depending on the activator used. The Fourier transform infrared analysis revealed a decrease in vibration intensity at 820 cm-1, indicating the presence of aluminium-modified C-S-H gel and N-A-S-H gel in the geopolymer concrete. The geopolymer concrete was produced using fly ash and GGBS as precursors, and NaOH and Na_2SiO_3 as alkaline solutions. Identifying the modified C-S-H gel and N-A-S-H reaction products based on their morphology proved to be challenging. The investigation by El-hassan et al. [21] reported the reaction products of geopolymer concrete to be a combination of calcium alumina silicate hydrate (C-A-S-H) and N-A-S-H. The Si/Al molar ratio is a crucial element that can significantly impact the properties of geopolymer.

Wang et al. [22] studied the scanning electron microscope (SEM) micrographs of fly ash geopolymer concrete, cured at 60°C for 6 hours and then at ambient temperature for 14 days, revealed holes and fissures at a Si/Al ratio of 1.7. Conversely, when the Si/Al ratio was 1.95, the micrographs exhibited a dense and compact structure. The compressive strength of the mixture with a Si/Al ratio of 1.95 is greater than that of the mixture with a ratio of 1.7. This suggests that the formation of N-A-S-H is responsible for the development of a dense structure and the enhancement of strength.

Vijai et al. concluded [23] that the curing regimes play a crucial role in the process of geopolymerisation reactions. Geopolymers made from fly ash and manufactured at ambient temperature exhibited reduced initial strength when compared to samples that were cured with heat. Palomo et al. [24] concluded that geopolymerisation occurs exclusively with heat curing if only fly ash is utilised as a precursor. The polymerization process is fully completed within the temperature range of 40oC to 85oC when cured for duration of 24 hours. The strength of the alkali activated fly ash cured at 85oC was much greater than that of the fly ash cured at 65oC. When the curing duration exceeds 24 hours, there is a minimal increase in compressive strength [25]. The literature investigated the impact of including GGBS into a fly ash-based geopolymer mortar, which is cured at room temperature using a mixed alkali activator consisting of NaOH and sodium silicate (Na_2SiO_3). The results were compared with fly ash-based geopolymer cured in an oven, and it was observed that the inclusion of GGBS, even in small quantities, obviated the necessity for heat curing [26].

The addition of GGBS to fly ash based geopolymer concrete resulted in improved mechanical properties when cured at room temperature, eliminating the need for heat curing required by fly ash based geopolymer concrete alone [27]. GGBS can serve as a precursor substance for the production of alkali activator binders, which can be cured at room temperature without the requirement of additional heat. The presence of calcium in GGBS leads to a reaction with alkaline solutions, resulting in the formation of C-S-H and other hydration products. By eliminating the requirement for specialize curing equipment and reducing energy usage, this enhances the accessibility and cost-effectiveness of the manufacturing process [28].

To ensure optimal mechanical performance, durability, and structural integrity in geopolymeric materials, it is essential to implement appropriate curing methods [29]. Water plays a critical role in the geopolymerization processes [30, 31]. Research conducted by [32] has demonstrated that water is vital for the polymerization process in alkali-activated composites. It functions as both a solvent and a carrier of silicate and aluminate ions. In the dissolving process, water is necessary to facilitate the polymerization process and produce monomers such as $SiO(OH)_2$, $Si(OH)_4$, and $Al(OH)_4$, as well as oligomeric species [33]. Initiating the polycondensation process is also crucial for the formation of strong geopolymeric structures. A portion of the water used for mixing, whether it is part of the alkaline activator solution or added separately, undergoes evaporation. This evaporation continues even after the polymeric matrix has solidified. A portion of the water does not undergo evaporation and remains trapped within the solidified polymeric gel matrix. The presence of non-evaporable water in mortars enhances the development of strength by gradually dissolving unreacted Al_3+ and Si_4+ compounds. The findings suggest that water plays a crucial role in the creation of strong three-dimensional cross-linked networks in geopolymers [16].

The process of sealing the geopolymer concrete, aids in the preservation of surface water. Geopolymers that were sealed and cured had an initial compressive strength of 50 MPa after 1 day of curing, which then increased to a range of 120-135 MPa after 7 days. The mean compressive strength of unsealed geopolymers ranged from 60 to 90 MPa, exhibiting a slight increase with the duration of curing. The poor strength observed in unsealed cured samples is believed to be caused by micro cracking resulting from dehydration. It is advisable to cure geopolymer concrete in a sealed condition to prevent the loss of surface water caused by evaporation [34]. As indicated by the reviewed literature, there is a scarcity of research focused on the use of sealed curing for geopolymer concrete. In particular, previous studies have not examined the effects of sealed curing on specific concrete grades. The present study addresses this gap by investigating the influence of sealed curing on G40 grade geopolymer concrete produced using fly ash and GGBS as precursors. Furthermore, the study explores the quantity of absorbed water and the microstructural characteristics of geopolymer concrete under both open and sealed curing conditions.

3.Materials and methods

3.1Materials

The binders were activated using a solution of Na_2SiO_3, which consisted of 8.57% Na_2O, 25.88% SiO_2, and 65.55% water. Additionally, pure NaOH pellets with a purity of 99.9% were used. Fly ash is a residual substance that is produced when pulverised coal is burned in thermal power plants. The present experiments utilized Class F fly ash obtained from the Ramagundam power plant located in Ramagundam, Telangana state in India as the precursor. The chemical composition of fly ash, as obtained from the supplier, is summarized and displayed in *Table 1*. GGBS is created by grinding the slag acquired from the blast furnace during the iron manufacture.

Table 1 Chemical composition of fly ash

S. No.	Parameters	Units	Test Method	Requirements as per IS 3812 (Part 1): 2013	Results
1	Silicon Dioxide (SiO_2) plus Aluminum oxide (Al_2O_3) plus Iron oxide (Fe_2O_3)	% by mass	As per IS 1727:1967	70 Minimum	92.84
2	SiO_2	% by mass	As per IS 1727:1967	35 Minimum	61.03
3	Reactive Si	% by mass	Annex B of IS 3812(P-1):2013	20 Minimum	34.74
4	Magnesium Oxide (MgO)	% by mass	As per IS 1727:1967	5.0 Maximum	1.42
5	Total sulphur as sulphur Trioxide (SO_3)	% by mass	As per IS 1727:1967	3.0 Maximum	0.37
6	Available alkalis as equivalent sodium oxide (Na_2O)	% by mass	Annex B of IS 3812(P-1):2013	1.5 Maximum	0.41
7	Total Chlorides	% by mass	As per IS 4032:1985	0.05 Maximum	0.013
8	Loss on Ignition	% by mass	As per IS 1727:1967	5.0 Maximum.	0.84
9	Calcium as CaO	% by mass	As per IS 1727 & IS 4032	---	3.75

The present investigation utilised GGBS obtained from the Vizag steel mill located in Andhra Pradesh in India. The chemical composition of GGBS, obtained from the supplier, is outlined and displayed in *Table 2*. Manufactured sand (M-sand), sourced from stone quarries, has recently gained popularity in India as a substitute for river sand in concrete applications. In the current investigation, M-sand obtained from a stone crushing unit in Kokapet, Telangana, India, is also being utilised. The M-sand used as the fine aggregate in this work was verified to meet the specifications of Zone II according to IS 383-1970. Coarse aggregates made from basalt, sourced from the same quarry, with a size of 20mm, were obtained and used for the preparation of the geopolymer concrete mixes. The findings of the sieve analysis conducted on M-Sand are summarized and displayed in *Table 3* for easy reference.

Table 2 Chemical composition of GGBS

S. No.	**Parameters**	**Units**	**Test Method**	**Requirements as per IS 16714:2018**	**Results**
1	Manganese Oxide (MnO)	% by mass	IS 4032	5.5 Maximum	0.63
2	Magnesium Oxide (MgO)	% by mass	IS 4032	17.0 Maximum	6.10
3	Sulphide Sulphur(S)	% by mass	IS 4032	2.0 Maximum	0.28
4	Sulphate (as SO_3)	% by mass	IS 4032	3.0 Maximum	0.24
5	Insoluble residue	% by mass	IS 4032	3.0 Maximum	1.96
6	Chloride content	% by mass	IS 4032	0.1 Maximum.	0.02
7	Loss of ignition	% by mass	IS 4032	3.0 Maximum	0.05
8	$(CaO+MgO+1/3AlO_3)$ / $(SiO_2+2/3AlO_3)$	% by mass	IS 4032	1.0 Minimum	1.04
9	$(CaO+MgO+Al2O_3)$ / SiO_2	% by mass	IS 4032	1.0 Minimum	2.03
10	Moisture Content	% by mass	IS 16714 Annex B	Shall not exceed 1 percent	0.90
11	Calcium as CaO	% by mass	IS 4032	---	35.74
12	Alumina as Al_2O_3	% by mass	IS 4032	---	23.56
13	Silica as SiO_2	% by mass	IS 4032	---	32.22

Table 3 Grain size distribution of M-sand

Sieve size(mm)	**Wt. retained (gms)**	**% wt. retained**	**Cumulative % wt. retained**	**% passing**
4.75	5	0.5	0.5	99.5
2.36	226	22.6	23.1	76.9
1.2	193	19.3	42.4	57.6
0.6	220	22	64.4	35.6
0.3	210	21	85.4	14.6
0.15	55	5.5	91.9	8.1
0.075	49	4.9	96.8	3.2
Pan	32	3.2	100	-

Wt. retained (g) = Weight retained in grams, % wt. retained = Percentage of the total sample weight that was retained on a particular sieve, Cumulative % wt. retained = sum of % wt. retained values up to and including that sieve

3.2 Mix proportions

During the manufacturing of the Geopolymer concrete mixture, many combinations of alkali binder ratios and silica modulus (MS) ratios were taken into account, as well as two different curing techniques. The proportion of SiO_2 and Na_2O incorporated into the concrete mixture as alkaline solutions is crucial for attaining optimal compressive strength and cost-effectiveness in geopolymer concretes. After conducting many experimental combinations to achieve the desired G40 grade, alkaline binder ratios of 0.4 with the corresponding 5% and 6% Na_2O were selected. The mix proportions of the mixes are presented in *Table 4*. The present research study used a constant binder content of 380kg/m^3, which was also used in the literature by Li et al. [4]. The curing process is widely recognized as a crucial factor in achieving the desired strength and durability of geopolymer concrete mixtures. Two distinct curing methods, as outlined below, were utilized in the current investigation.

Curing regime 1: Open curing at ambient temperature

Curing regime 2: Sealed curing with 100-micron thick plastic cover, as suggested in ASTM C 171 [35] at ambient temperature

Table 4 Mix proportions of the concrete

Mix Id	**Fly ash**	**GGBS**	**FA(Kg)**	**CA(Kg)**	**AL/B**	**Curing**	**Na_2O%**
GPC1OC	285	95	687	1235	0.4	Without Sealing	6
GPC1SC	285	95	687	1235	0.4	Sealed	6
GPC2OC	228	152	689	1239	0.4	Without Sealing	5
GPC2SC	228	152	689	1239	0.4	Sealed	5

CA: Coarse Aggregate,GPC10C, GPC1SC, GPC2SC, etc.: IDs for different geopolymer concrete mix samples, C / OC: Open Curing (without sealing)., AL/B: Alkaline liquid to Binder ratio, SC: Sealed Curing.

3.3 Specimen preparation

The cube specimens of 150×150 mm was prepared, following the processes outlined in IS 519-1959 [36], in order to determine their compressive strength. The cylindrical specimens with dimensions of 100 mm×50 mm, which were used for sorptivity testing, were obtained by coring cube specimens with dimensions of 150 mm × 150 mm × 150 mm using a core cutting machine. To ensure the replicability of results and to account for the different curing methods being tested, three specimens were prepared for each combination at curing durations of 7 days, 28 days, 90 days, and 180 days. To determine the non-evaporable or inbound water, specific quantities of fly ash, GGBS and alkaline solutions were mixed with the activator solution. Cylinders with a diameter of 25 mm and a depth of 25 mm were cast and cured for 28 days under both open and sealed curing regimes. The manufacturing process of geopolymer concrete is outlined in the flow chart shown in *Figure 1*. To produce geopolymer concrete, the mixture of alkaline solutions is prepared 24 hours before the actual mixing of the geopolymer concrete. A NaOH solution of the required molarity is prepared and mixed with the appropriate amount of Na_2Sio_3 solution 24 hours prior to concrete production. Fly ash, GGBS, fine aggregate, and coarse aggregate are dry mixed in a pan mixer for 2-3 minutes. Afterward, the alkaline solutions, along with additional water, are added to the dry mix and mixed for another 3-4 minutes to achieve a homogeneous mixture. The concrete is then cast into the required moulds and allowed to rest for 48 hours. Afterward, the concrete is demolded. The specimens that are exposed to open curing are left open to the laboratory environment, while the sealed-cured specimens are properly wrapped in 100-micron plastic sheets.

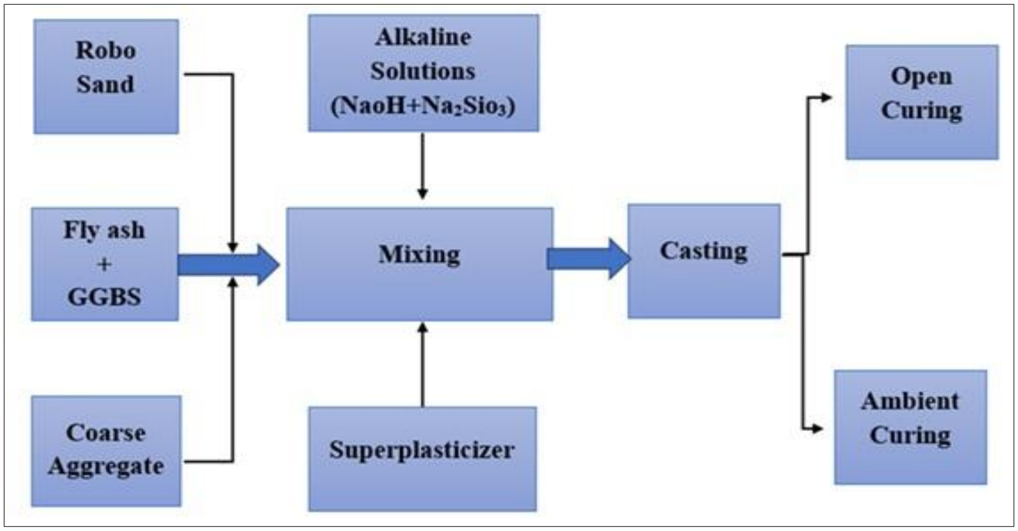


Figure 1 Geopolymer manufacturing process

3.4 Compressive strength test

The compressive strength test is conducted according to the specifications outlined in IS 516:1959 [37]. A stress-controlled compression testing machine with a capacity of 3000 kN was used to test all cube specimens measuring 150 mm×150 mm. The tests were performed at room temperature, with three samples tested at 7, 28, 90, and 180 days. The stress was applied steadily at a rate of 5.2 kN per second until the specimen fractured, without experiencing any additional resistance to the applied load.

3.5 Sorptivity test

The sorptivity of concrete is determined in accordance with the ASTM C 1585 [38] standard. The concrete contains capillary pores that facilitate water absorption. Therefore, the measurement of the absorption or infiltration rate serves as an indication of the continuity of the pores. Sorptivity test is performed in ambient temperature on cylindrical specimens of 100×50 mm in order to ascertain the extent to which water is drawn up through capillary action. The test specimen is sealed on the side surface and the end that is not in contact with water with a suitable sealant. The weight of the sample is measured to an accuracy of 0. 01gm. The sample is placed in the test setup in such a way that water is in direct contact with the surface of the sample to a depth of 1 to 2 mm. The sample is taken out of the test setup at regular intervals as specified in ASTM C 1585 and any surface water present on the specimen is wiped off. The weight of the sample is recorded within 15 seconds of removal from the test setup. The experimental setup of sorptivity test is shown in *Figure 2*. The absorption or infiltration of water into the specimen is calculated by using the relation given in Equation 1. The sorptivity coefficient is determined by establishing a linear relationship between the absorption of water and the square root of time.

$$I = \Delta w / Ad \qquad (1)$$

Where:

Δw = change in weight of specimen after water absorption, A = Surface area of the specimen (cm²)

d = Density of water (g/cm³)

Figure 2 Specimen placed for sorptivity

3.6 Non-evaporable water (Inbound)

The present investigation employs the test method developed by Zuhua et al. [39] to quantify the amount of inbound (non-evaporable) water in the concrete. For this purpose, cylindrical specimens measuring 25 × 25 mm were cast and subsequently manually pulverized into powder. The powder was first dried in an oven at a temperature of 140 °C for 24 hours. This process eliminates evaporable water molecules from the powdered samples, standardizing the material and enhancing the precision of the results obtained. Following this, the oven-dried powdered sample was placed in a muffle furnace at a temperature of 900 °C for 30 minutes. The weight of the powdered sample was recorded before and after heating in the muffle furnace. The non-evaporable water content was then calculated using Equation 2.

$$Wn = \frac{m0-m1}{m0} - IfxWf \qquad (2)$$

where

Wn = Nonevoparable water in geopolymer gel

m0 = Initial weight of the sample before placing in a muffle furnace

m1 = Final weight of the sample after igniting to 9000c in a muffle furnace

If = Loss on ignition of fly ash given in *Table 1*

Wf = Mass fraction of fly ash in total binder content

3.7 Micro structure:

The microstructure refers to the internal structure of a material at the microscopic level. It can be described as the arrangement of atoms, molecules, or grains within the material. This arrangement significantly influences key properties such as strength, durability, and conductivity. SEM analysis revealed that the sealed-cured geopolymer concrete exhibited a denser and more uniform microstructure. The gel structure appeared more interconnected, contributing to improved mechanical properties.

3.7.1 SEM

The electron source generates an electron beam that is directed toward the specimen by applying a positive electrical potential. Metal apertures and magnetic lenses are used to confine and focus the beam, producing a narrow, concentrated, and monochromatic stream of electrons. As the electrons interact with the atoms in the material, various signals are generated, providing valuable information about the surface topography, composition, and electrical properties. These interactions are captured and visualized as an image. The SEM apparatus used for the analysis is shown in *Figure 3.*

Figure 3 Scanning electron microscope

4.Results

The results indicated that sealed curing increased the compressive strength and reduced surface voids. Microstructure analysis revealed that the gel structures in sealed-cured concrete are denser, compact and more Si/Al, leading to improved mechanical performance. The study's findings suggest that the sealed curing method significantly enhances the mechanical properties and durability of G40 grade geopolymer concrete, making it a promising sustainable construction material.

4.1Compressive strength

Table 5 presents the changes in compressive strength of specimens cured under sealed and open conditions over time. The indoor temperature during curing ranged from 26°C to 33°C. To ensure reproducibility, three samples were tested at 7, 28, 90, and 180 days. The specimen cured in open condition and sealed condition are displayed in *Figure 4*

Table 5 Compressive strength of open cured and sealed cured specimen

MIX	**Compressive strength (MPa)**			
	7 days	**28 days**	**90 days**	**180 days**
GPC1OC	41.79	50.97	54.83	55.62
GPC1SC	47.84	56.35	61.83	62.23
GPC2 OC	45.87	53.84	57	57.86
GPC2SC	55.24	64.12	67.82	69.81

Figure 4 Sealed cured and open cured specimen

4.2 Sorptivity

The test setup for sorptivity coefficient is shown in *Figure 2*. The capillary infiltration of water into the concrete with age is displayed in *Tables 6*, *7* and *8*. The final sorptivity coefficient values of open cured and sealed cured samples are displayed in *Figure 5*.

Table 6 Infiltration at time t after 28 days

Mix Id	**GPC1OC**	**GPC1SC**	**GPC2 OC**	**GPC2SC**
Time (t) min	**Infiltration(I)(mm)**			
1	0.224	0.086	0.191	0.052
5	0.361	0.216	0.298	0.106
10	0.732	0.359	0.343	0.224
20	0.952	0.383	0.500	0.264
30	1.273	0.389	0.756	0.272
60	1.514	0.548	1.152	0.527

Mix Id	**GPC1OC**	**GPC1SC**	**GPC2 OC**	**GPC2SC**
Time (t) min		**Infiltration(I)(mm)**		
120	1.821	0.951	1.362	0.738
180	1.942	1.080	1.465	0.832
240	2.124	1.167	1.545	0.915
300	2.356	1.221	1.652	0.950
360	2.415	1.498	1.892	1.121
1440	2.423	1.626	1.977	1.128
2880	2.626	1.874	2.239	1.294
4320	2.885	2.016	2.454	1.396
5760	3.112	2.117	2.592	1.510
7200	3.222	2.237	2.693	1.613
10080	3.384	2.349	2.843	1.700

Table 7 Infiltration at time t after 90 days

Mix Id	**GPC1OC**	**GPC1SC**	**GPC2 OC**	**GPC2SC**
Time (t) min		**Infiltration(I)(mm)**		
1	0.146	0.074	0.053	0.035
5	0.246	0.142	0.221	0.106
10	0.345	0.243	0.254	0.246
20	0.443	0.327	0.329	0.311
30	0.532	0.412	0.571	0.372
60	0.739	0.521	0.682	0.452
120	1.084	0.651	0.812	0.546
180	1.282	0.731	0.992	0.639
240	1.507	0.873	1.192	0.692
300	1.512	0.991	1.250	0.737
360	1.593	1.156	1.339	0.851
1440	1.653	1.236	1.471	0.892
2880	1.878	1.382	1.645	0.989
4320	2.074	1.474	1.795	1.073
5760	2.219	1.539	1.928	1.147
7200	2.342	1.621	2.023	1.200
10080	2.517	1.791	2.198	1.276

Table 8 Infiltration at time t after 180 days

Mix Id	**GPC1OC**	**GPC1SC**	**GPC2 OC**	**GPC2SC**
Time (t) min		**Infiltration(I)(mm)**		
1	0.088	0.055	0.072	0.028
5	0.220	0.138	0.181	0.094
10	0.263	0.165	0.257	0.113
20	0.307	0.193	0.382	0.132
30	0.395	0.382	0.508	0.169
60	0.659	0.514	0.683	0.282
120	0.966	0.607	0.896	0.414
180	1.098	0.689	0.965	0.470
240	1.255	0.825	1.110	0.508
300	1.303	0.871	1.146	0.551
360	1.389	0.921	1.180	0.624
1440	1.511	0.972	1.269	0.695
2880	1.655	1.094	1.432	0.752
4320	1.798	1.183	1.547	0.821
5760	1.951	1.238	1.639	0.882
7200	2.073	1.288	1.772	0.941
10080	2.261	1.423	1.888	1.040

4.3 Non-evaporable water (Inbound water)

Geopolymer samples are tested to measure their non-evaporable water content and understand how sealing affects them. *Figure 6* shows the specimen placed in a muffle furnace. The proportions of non-evaporable water content for all the mixes are presented in *Figure 7*.

4.4 Micro structureal analysis:

The SEM micrographs of the specimens cured in both an open environment and a sealed environment for 28 days are displayed in *Figure 8*. Additionally, the Si/Al ratio of all the mixes after 28 days of curing is shown in *Figure 9*.

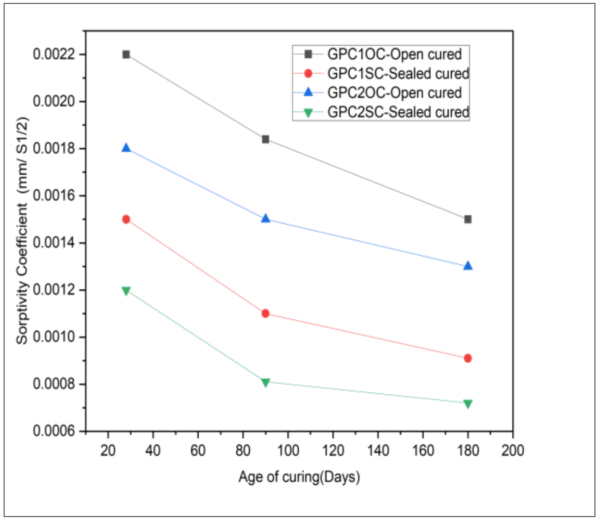


Figure 5 Sorptivity coefficient of open cured and sealed specimen

Figure 6 Specimen placed in muffle furnace

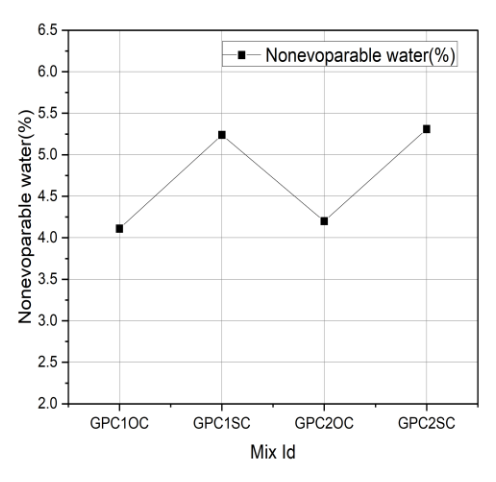
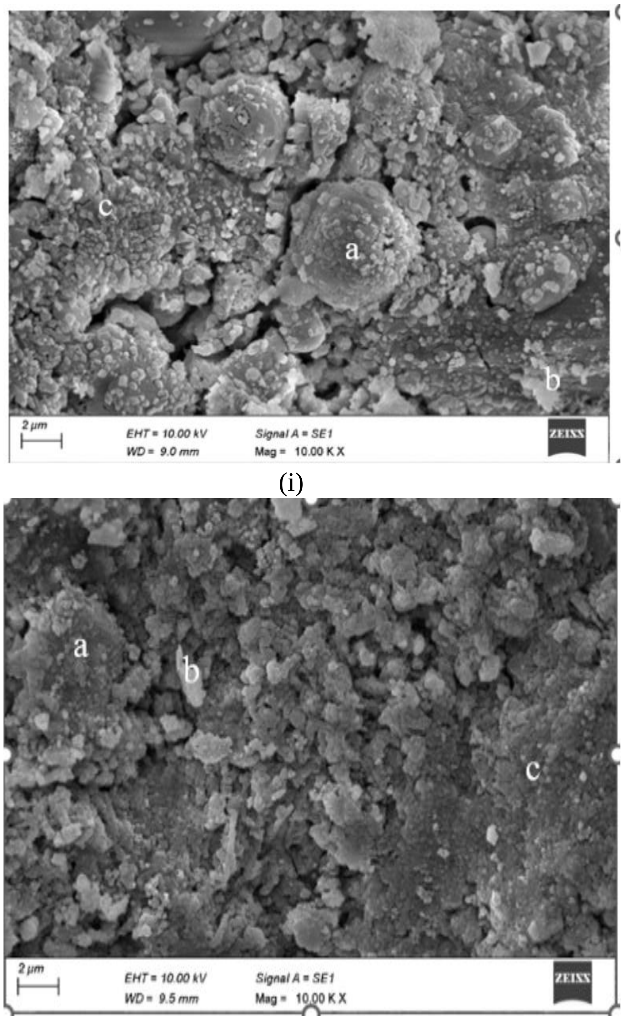
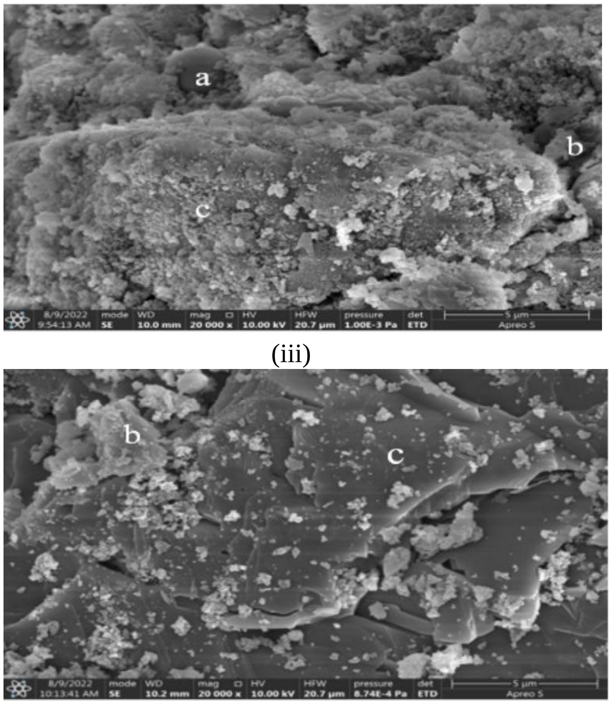


Figure 7 Non-evaporable water percent in open cured and sealed specimen



(i)

(ii)



(iii)

(iv)

a: Partly reacted fly ash, b: Partly Reacted GGBS, c: Geopolymer matrix

Figure 8 SEM micrographs of Unsealed and sealed cured specimen (i) GPC1OC (ii) GPC1SC (iii) GPC2OC (iv) GPC2SC

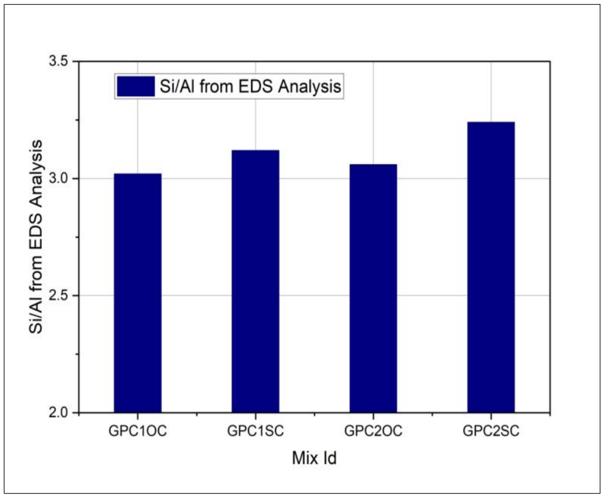


Figure 9 Mean Si/Al calculated from EDS analysis at 28 days of curing

5.Discussion

5.1 Compressive strength

All the concrete mixes met the minimum required grade of G40 for PQC. Strength increased rapidly between 7 and 28 days for both curing techniques, ranging from 16.7% to 22%. The Gain in strength reduced after 90 days, indicating that geopolymerization has stabilised. The compressive strength of all mixes increased with the age of the concrete. The open-cured specimens exhibited a compressive strength ranging from 50.97 to 53.84 MPa, while the sealed-cured specimens attained a compressive strength between 56.35 and 64.12 MPa after 28 days. Among all the mixes, sealed cured specimen GPC2SC achieved the highest compressive strength of 69.81 MPa after 180 days. Notably, the compressive strength of the sealed specimens was 13% to 17% higher than that of the ambient-cured specimens, which aligns with existing literature. The strength of GGBS fly ash concrete cured in dry and water conditions decreased by 9.8% and 13.7%, respectively, compared to the sealed-cured specimens [40]. The specimen cured under lower relative humidity conditions (Method 1, open cured at ambient temperature) displayed reduced strength compared to the specimen cured under higher relative humidity conditions (Method 2, enclosed with a plastic cover). The increase in strength of a sealed specimen is higher than that of an ambient-cured specimen when the mix ratios are the same. The higher compressive strengths seen in the sealed samples suggest that the presence of water aids in the breakdown of precursors, leading to the creation of a greater amount of geopolymer gel in the solidified paste. Sealed samples not only help dissolving but also safeguard against cracking caused by water evaporation. As per the geopolymerization process proposed by Duxson et al. [41, 42], the stages of dissolution, gelation, polymerization, and hardening do not occur simultaneously. This is due to the heterogeneous nature of the overall process. Therefore, even after the geopolymer paste has fully solidified, water remains crucial for the further enhancement of the strength of geopolymers. Zuhua et al. [39] stated that the shrinkage of geopolymers cured without sealing is higher compared to those cured with sealing. This difference in shrinkage may be attributed to the evaporation of surface water when exposed to open air conditions.

5.2 Sorptivity

The capillary infiltration of all the specimens is presented in *Tables 6, 7,* and *8*. Overall, capillary infiltration decreased with the increasing age of the mixes. Specimens that were open-cured exhibited higher levels of capillary infiltration compared to those that were sealed-cured. Among all the mixes, GPC1OC showed the highest infiltration, reaching a depth of 3.32 mm at 28 days of curing. Conversely, GPC2SC demonstrated the least infiltration, measuring 1.04 mm after 180 days of curing. The sealing process significantly reduced water infiltration into the concrete, decreasing it by 50 to 55 percent in the geopolymer concrete.

Open-cured sample has higher sorptivity than sealed samples, which indicates a higher degree of interconnected pores in the ambient-cured specimen. In open cured specimen, the compressive strength was shown to decrease, and the sorptivity coefficient increased which aligns with findings in the literature. The presence of linked microcracks is responsible for the reduced compressive strength in unsealed specimens [43]. Nguyen et al. [44] found that even geopolymers with high strengths have a microstructure consisting of many air gaps and shrinkage microcracks in the areas between compact geopolymer paste patches. The primary factor reducing strength in open curing is water loss, which leads to air void formation. Additionally, dehydration-induced microcracking may contribute to this strength loss. While no apparent cracks were observed during visual inspection, concealed microcracks likely formed due to rapid dehydration in the open samples, which negatively impacted their strength performance. Water loss from the sample may have led to larger pore formation in the unsealed specimens.

5.3 Non-evaporable water (Inbound water)

Water in a binder can be characterised as either chemically bound or physically absorbed, or free, based on the analysis of the literature. Non-evaporable water in geopolymer gels is chemically linked and acts as an essential element of the structure, impacting the characteristics of the geopolymer [45].

Figure 6 shows the specimen placed in muffle furnace. *Figure 7* shows that the sealed geopolymers maintained a somewhat higher amount of non-evaporable water compared to the unsealed geopolymers. Zuhua et al. [39] state that because the specimen is sealed, surface water does not evaporate. The water on the surface of the sealed geopolymer creates a sufficiently humid environment, which aids in the retention of a small amount of non-evaporable water, thereby facilitating polymerization. Geopolymer volume stability relies on the presence of sustained water or physically absorbed or free water, whereas the preservation of strength is enhanced by the presence of non-evaporable water.

5.4 Micro Structure

The micrographs show the N-A-S-H gel, which serves as the cementitious matrix that binds the unreacted fly ash spheres and GGBS particles together. *Figure 8(i)* and *8(iii)* present the microstructure of specimens cured in an open environment, while *Figure 8(ii)* and *8(iv)* show the microstructure of specimens that were sealed during curing. It is evident that the matrix in the sealed specimens is more developed than that of the open-cured specimens. Additionally, the microstructure of the sealed-cured specimens exhibits fewer voids compared to the open-cured specimens.

Based on the EDS findings of the current investigation, the Si/Al ratio of the N-A-S-H gel generated in a sealed system is greater than that of the open cured specimen. After a period of 28 days, the N-A-S-H gel, which is the main product of the reaction, has greater silicon content in sealed-cured specimens.

The Si/Al ratio of the open-cured specimens ranged from 3.02 to 3.06, while for the same mixes in airtight conditions, it ranged from 3.12 to 3.24, as illustrated in Figure. According to research conducted by Criado et al. [46], pastes cured in airtight containers with a relative humidity above 90% produce a thick and compact material. This material has a high initial Al content, which facilitates the absorption of Si in subsequent reactions. As a result, the concrete formed exhibits excellent mechanical properties.

5.5 Limitations

Despite the promising results, the study had certain limitations. The study focuses only on G40 grade of concrete mix, limiting the generalization of findings to other geopolymer compositions. It focuses exclusively on a G40 grade geopolymer concrete mix, which limits the applicability of the findings to other mix grades and compositions. Future research should explore a broader range of mix proportions and exposure conditions to enhance the generalizability of the results.

A complete list of abbreviations is listed in *Appendix I.*

6.Conclusion and future work

The specimens cured using both the curing methods (open curing and sealed curing) achieved the compressive strength required for the PQC grade of G40. The compressive strength of all the mixes increased with the age of the concrete. The open cured specimen attained a compressive strength ranging from 50.97 to 53.34 MPa, while the sealed cured achieved a compressive strength ranging from 56.35 to 64.12 MPa. The compressive strength of sealed cured samples is 13 to 17 percent more than open cured specimens. The water infiltration of sealed cured specimens is 50 to 55 percent less than that compared to the open cured specimens.

The SEM images of the sealed specimen revealed a denser and more compact structure compared to the open-cured specimen. Furthermore, the energy-dispersive X-ray spectroscopy (EDS) analysis indicated that the sealed specimen had a higher Si/Al ratio content than the open-cured specimen. The Si/Al ratio of the open-cured specimen ranged from 3.02 to 3.06, while the ratio for the sealed specimen ranged from 3.12 to 3.24. A higher Si/Al ratio indicates a denser and more compact concrete structure. Sealed curing prevents the evaporation of surface water, which stops the formation of voids at the surface and reduces capillary action in the concrete. It also creates a more humid environment, helping to retain more water that cannot evaporate. The non-evaporable water present facilitates the ongoing polymerization process, resulting in the formation of a more denser microstructure abundant in silica content. The high silica concentration in this compact microstructure leads to an increase in compressive strength and a decrease in sorptivity in the sealed cured specimen compared to the open cured specimen. The impact of sealed curing can be examined by employing various precursors and also for different classifications of geopolymer concrete. The potential impact of using liquid membrane forming curing chemicals and sealing compounds to cure Geopolymer concrete and prevent surface water evaporation can be examined.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

None.

Author's contribution statement

Sharada Polusani: Performed the experiments, processed the experimental data, and drafted the manuscript. **V Vinayaka Ram:** planning, designing, and supervising the work. **M V Seshagiri Rao:** planning, designing, and supervising the work.

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Mrs. Sharada Polusani is currently pursuing Ph.D. in Structural Engineering at Jawaharlal Nehru Technological University, Hyderabad. She completed her M.Tech in Structural Engineering from Jawaharlal Nehru Technological University, Anantapur. She is a member of the Institution of Engineers and has published nine research articles in national and international journals.
Email: sharadaraop@gmail.com

Dr. V Vinayaka Ram is a Professor at BITS Pilani, Hyderabad Campus. He has over three decades of experience in teaching and research, having served at NIT Warangal, ESCI Hyderabad, and both the Pilani and Hyderabad campuses of BITS Pilani. His research interests include Pavement Materials (both asphalt and concrete), Pavement Asset Management, Thermal Energy Storage Materials, and the application of Nanomaterials in Civil Engineering. He received a National Level Commendation Certificate from the Indian Roads Congress, New Delhi, for a research paper published in the Highway Research Bulletin (Traffic) of the Highway Research Board during the 59th Annual Session of the IRC.
Email: vinayak@hyderabad.bits-pilani.ac.in

Dr. M V Seshagiri Rao is a Professor of Civil Engineering with 45 years of experience in research, teaching, and consultancy. He is currently serving as the Dean at CVR engineering college, Hyderabad. Over the course of his career, he has guided 29 Ph.D. theses and published more than 250 research papers in the field of advanced concrete technology and materials. He has held prominent positions, including Assistant Executive Engineer at the A.P. Engineering Research Laboratory, and served as a Professor at JNTU Hyderabad. In recognition of his contributions, he has received numerous awards, notably the Lifetime Achievement Award from the Indian Concrete Institute in 2023.
Email: rao_vs_meduri@yahoo.com

Appendix I

S. No.	Abbreviation	Description
1	Al	Aluminum
2	C-A-S-H	Combination of Calcium Alumina Silicate Hydrate
3	C-S-H	Calcium Silicate Hydrate
4	EDS	Energy-Dispersive X-Ray Spectroscopy
5	GGBS	Ground Granulated Blast Furnace Slag
6	NaOH	Sodium Hydroxide
7	Na_2Sio_3	Sodium Silicate
8	N-A-S-H	Sodium Aluminosilicate Hydrate
9	Na_2O	Sodium Oxide
10	OPC	Ordinary Portland Cement Concrete
11	PQC	Pavement Quality Concrete
12	SEM	Scanning Electron Microscope
13	Si	Silica
14	Sio2	Silicon Dioxide