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Novel waterproof ambient cured geopolymer concrete using integral crystalline waterproofing admixture

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Abstract:
Geopolymer concrete (GC) is a promising alternative to conventional cement concrete owing to its environmental benefits. However, water penetration, which is a common concern, significantly affects the performance of GC, thus causing efflorescence, reinforcement corrosion, and scaling, among other durability issues, which affect its longevity. The present study attempts to clarify the efficacy of incorporating an integral crystalline waterproofing admixture in enhancing the durability of GC by reducing the penetration of water into the concrete matrix. The samples are subjected to compressive-strength and split-tensile-strength tests to evaluate the material's strength properties. Additionally, water absorption, chloride penetrability, water contact angle, and acid-resistance tests are performed to ascertain the durability of the modified GC. The results show that GC samples with a 3 % crystalline waterproofing content performs the best, i.e., it reduced water absorption by 42,85 %, 40,90 %, and 45,26 % after 7; 28; and 56 days of curing. In addition to improving water absorption, the admixture significantly enhances the mechanical strength of GC, with increases in compressive strength by 15,74 %, 15,65 %, and 15,86 % at 7, 28, and 56 days, respectively. Additionally, scanning electron microscopy analysis is performed on the GC samples to understand the changes in the microstructure of GC mixes with various dosages of the crystalline waterproofing agent added to them.

Keywords:
sustainable; environment-friendly; durability; admixture

1 Introduction

The construction industry has exhibited significant changes in its approach toward building materials, with emphasis on sustainability and innovation. This transition is motivated by the necessity to satisfy the increasing infrastructure demands while reducing environmental impacts, particularly in terms of carbon emissions [1]. The manufacturing of Portland cement, which is used in conventional concrete, has received significant attention owing to its substantial emission of carbon dioxide (CO_2), which renders it a significant contributor to global climate change. As awareness regarding global warming issues increases, decarbonisation has garnered significant attention. A recent United Nations report indicated that the construction sector alone constituted 36 and 37 % of the world's total energy consumption and CO_2 emission, respectively [2]. The production of construction materials, particularly cement, is one of the main contributors to carbon emissions [3]. Every ton of ordinary Portland cement is estimated to emit an equivalent amount of CO_2 into the atmosphere [4-6]. Cement has a large carbon footprint, and the construction industry generates 7-8 % of the global CO_2 emission [7]. Without any action to decarbonise the construction sector, emissions will increase exponentially owing to the significant expansion of the sector, particularly in developing countries. Hence, the construction sector is transitioning to cleaner technologies and materials. Geopolymer concrete (GC), which comprises geopolymer binders sourced from industrial waste and natural materials, exhibits remarkable mechanical characteristics, and effectively mitigates the release of greenhouse gases related to cement manufacturing [8].
Utilising GC offers several environmental benefits, thus rendering them a sustainable substitute for conventional cement concrete. One of its primary advantages is its significant decrease in carbon emissions [9]. Moreover, GC relies on the utilisation of industrial waste materials such as fly ash and slag, which would otherwise be subjected to disposal or require energy-intensive treatment [10]. This practice not only serves to minimise waste but also solves waste-disposal problems. It facilitates the conversion of industrial wastes into useful construction materials, thereby reducing the dependence on primary resources such as limestone and clay used in the cement manufacturing process. Consequently, their exploitation is prevented and the establishment of a circular economy is facilitated [1, 11]. The utilisation of industrial byproducts in GC mitigates the environmental consequences associated with resource extraction.
For GC to gain wide acceptance as a construction material, its durability must be enhanced. GC typically encounters challenging environmental conditions such as exposure to chemical agents and corrosion of the reinforcement, all of which are caused by water infiltrating the concrete matrix, thus resulting in durability concerns [12]. All major durability issues in GC arise from the infiltration of water into the concrete matrix, as in the case of cement-based concrete [10]. The infiltration of water into GC weakens the concrete matrix over time, in addition to causing harm due to deleterious ions and substance penetration, which might occur along with water penetrating the concrete. Thus, methods for rendering concrete waterproof or water resistant must be identified such that the endurance of structures constructed from geopolymer materials can be enhanced. This is consistent with sustainability objectives, as it mitigates the environmental consequences related to premature replacements or repairs in addition to providing economic benefits. Moreover, concerns regarding durability can incur substantial costs associated with repair and maintenance. Improving the resistance of GC benefits the long-term economic sustainability of structures, thus rendering it a financially advantageous option. Safety is a crucial aspect of durability. Structures that deteriorate early because of durability concerns have may present safety hazards to residents and the public. Hence, the long-term structural integrity of structures constructed using GC must be ensured.
The durability of structures constructed using GC can be enhanced by ensuring the resistance of GC to water permeation, which can be achieved via several methods. Water-repellant GC can be realised by employing the appropriate raw materials, crafting a detailed mix design, ensuring an appropriate curing regime, and using admixtures such as hydrophobic [13-18] and integral crystalline admixtures. The use of hydrophobic admixtures is generally accompanied

by a reduction in the compressive strength of geopolymer composites [12]; thus, other admixtures that can improve the water resistance of GC and ensure its durability must be identified. An integral crystalline admixture is a material that functions by precipitating insoluble crystals within the concrete matrix, thereby increasing its density, reducing its porosity, and enhancing its resistance to water permeation.

In concrete construction, crystalline waterproofing agents can be applied to the surface as a coating or mixed directly with fresh concrete as an admixture. When used for surface treatment, these chemicals can be applied using a brush or a spray-on device. However, surface treatments are only useful when the surface remains undamaged. Cracking, peeling, and environmental degradation can affect the surface and reduce the surface treatment efficiency [19]. This constraint demonstrates the benefit of incorporating crystalline admixtures into the bulk of concrete, which provides comprehensive and long-lasting protection throughout the structure. The use of crystalline waterproofing agents as an admixture offers several advantages. First, it ensures that the entire concrete bulk, not only the surface, is adequately protected. Second, it is cost effective as it eliminates the labour required for surface applications, thus preventing schedule conflicts and delays associated with surface application. Furthermore, it ensures a uniform distribution of the crystalline product throughout the concrete matrix. In addition to waterproofing, crystalline admixtures provide additional benefits, such as shrinkage-cracking minimisation and increased compressive strength. Integral crystalline admixtures have become a revolutionary technique in concrete construction and have been widely used in cement concrete [20-23]; however, their use in GC has not yet been investigated. This study aims to elucidate the efficacy of integral crystalline admixtures in enhancing the durability of GC and broadening the application of geopolymers as a green construction material.

2 Materials and methodology

2.1 Materials

2.1.1 Precursors for GC (GC)

This study used a combination of two source materials, i.e., fly ash and ground granulated blast-furnace slag (GGBS), as precursors, as illustrated in Figure 1 a) and b), respectively. Fly ash and GGBS are ideal precursors for GC because of their high aluminosilicate content, which enhances polymerisation, thus resulting in superior mechanical properties and durability. Fly ash improves the workability and long-term strength, whereas GGBS accelerates the setting time and enhances the early strength. Cumulatively, they produce GC with improved chemical resistance, reduced shrinkage, and increased durability, thus rendering them suitable for a wide range of construction applications, including environmentally friendly infrastructures. The fly ash used in this study was sourced from the Guru Gobind Singh Super Thermal Power Station in Ropar, Punjab, India. A low-calcium class-F grade classified based on American Society for Testing and Materials (ASTM) C618 adhering to Indian Standard IS 3812-Part-1 [24] was used. The GGBS used in this study was obtained from JSW industries, India. The GGBS was sourced in accordance with the specifications outlined in the British Standard BS: 6699-1992 [25].

Table 1 presents the chemical compositions and loss on ignition (LOI) of the source materials, expressed in weight percentages. The specific gravity values for fly ash and GGBS were recorded as 2,05 and 2,76, respectively, whereas their specific surface areas were 275 and 441 m^2/kg, respectively.

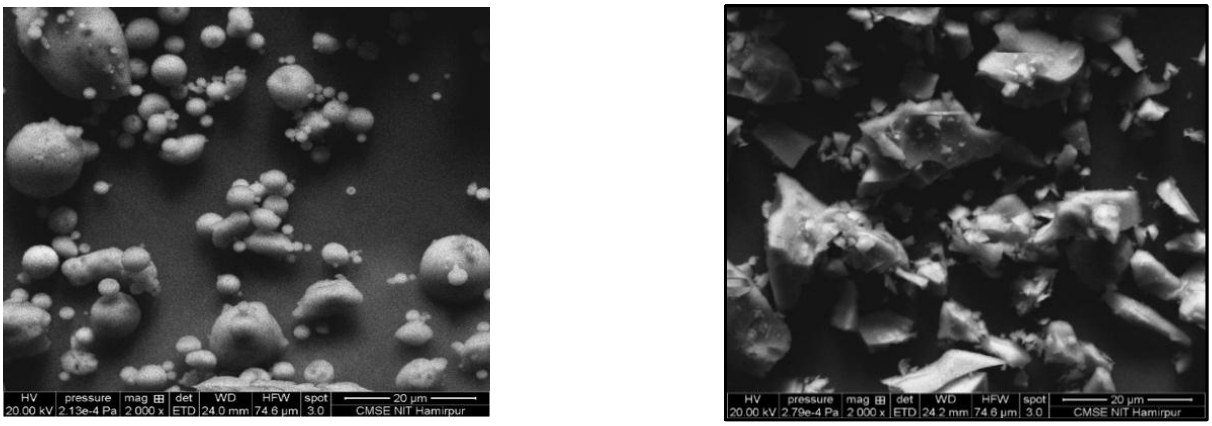
The appearance and scanning electron microscopy (SEM) images of the precursors are shown in Figure 2. As shown, the fly ash particles exhibited a rounded shape. By contrast, the GGBS particles exhibited flaky, angular, and elongated morphologies. Additionally, a particle-size analysis was performed on the precursors, and the results are shown in Figure 3.

a) b)

Figure 1. a) Fly ash (FA); b) granulated blast-furnace slag (GGBS)

Table 1. Chemical constituents of fly ash and GGBS

Constituents	**FA** (%)	**GGBS** (%)
Silicon Dioxide (SiO_2)	62,11	34,72
Aluminium Oxide (Al_2O_3)	18,58	21,32
Calcium Oxide (CaO)	4,57	35,82
Magnesium Oxide (MgO)	0,54	7,53
Sodium Oxide (Na_2O)	0,16	-
Ferric Oxide (Fe_2O_3)	3,53	0,88
Sulphur Trioxide (SO_3)	0,17	0,42
LOI	2,10	0,30



a) b)

Figure 2. SEM Image: a) FA; b) GGBS

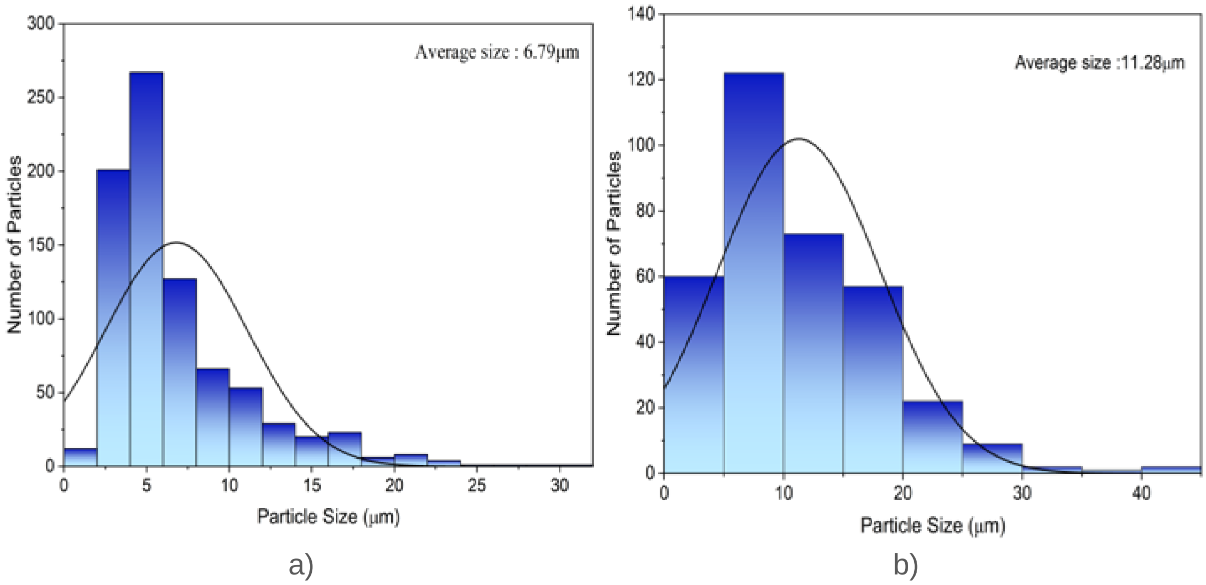


Figure 3. Particle-size analysis: a) FA; b) GGBS

2.1.2 Alkaline activator solution

A mixture of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) was used as an alkaline activator solution for the selected precursors, namely fly ash and GGBS. The sodium hydroxide was in the form of flakes with 99 % purity, whereas the sodium silicate was in the form of a colourless, viscous solution; both were sourced from a local manufacturer. An alkaline activator solution was prepared 24 h prior to casting. A ratio of 2,5:1,0 for sodium silicate to sodium hydroxide was selected based on previous studies and preliminary trials [26]. Potable water available in the institute's concrete technology laboratory was used to prepare both the alkaline activator solution and the GC mixes.

2.1.3 Coarse and fine aggregates

Locally available river sand was used as fine aggregates to produce GC, whereas locally available crushed stones with a nominal size of 12,5 mm were used as coarse aggregates. The physical properties of the aggregates are listed in Table 2.

Table 2. Physical properties of fine and coarse aggregates

Properties	Fine aggregates	Coarse aggregates
Specific gravity	2,59	2,65
Fineness modulus	2,66	6,48
Zone (IS 383:2016)	II	--

2.1.4 Superplasticiser

To improve the workability of the GC mix, a polycarboxylate ether (PCE) based superplasticiser was introduced into the mix at a 2 % concentration by weight relative to the total binder content (fly ash + GGBS + NaOH + Na_2SiO_3) to obtain sufficient workability in all the concrete mixtures. PCE superplasticisers are highly effective in improving the workability of GC by dispersing particles within the mixture, thereby reducing the necessity for excessive water. The PCE molecules adsorb onto the surface of the binder particles (fly ash and GGBS) and create a negative charge that repels the particles from one another. This repulsion prevents clumping, thus allowing the concrete to flow easily without adding more water. By reducing the water content, the superplasticiser helps achieve a denser matrix, reduces the porosity, and improves the mechanical properties. This enhanced compactness increases the durability as the concrete becomes more resistant to environmental attacks such as chloride ingress, moisture penetration, and chemical degradation.

2.1.5 Crystalline waterproofing admixture

Commercially available Krysta Leakproof by JSW Cement Ltd. is a capillary waterproofing solution for concrete and mortar developed in accordance with IS 2645-2003 [27]. It is a highly effective crystalline waterproofing admixture and is commonly used in cement concrete in areas with high rainfall and moisture. This renders it suitable for extending its use in GC. Its unique crystalline technology forms insoluble crystals that fill capillaries and microcracks, thus creating a permanent waterproof barrier that enhances the impermeability and durability of GC and protects it from water ingress, corrosion, and chemical attacks. Additionally, Krysta Leakproof is commercially available product that ensures quality control and consistent performance. Its integration aligns with the sustainability of GC by reducing maintenance requirements and extending the structure lifespan. It is a white/gray dry powder with a bulk density of 1,05 and is added to the concrete during the mixing process. For the case of GC, it is added while the dry precursor materials are mixed. It comprises a combination of cementitious materials, ultrafine silica aggregates, and several other reactive compounds and is used as an integral admixture to provide permanent active waterproofing treatment for concrete. Upon encountering water and moisture, it generates multiple needle-like crystals that develop and settle in the pores of concrete, thus reducing the number and size of the pores. Consequently, water permeability is reduced [28], thereby safeguarding the concrete and reinforcement.

2.2 Mix design

The mix design was calculated based on the procedures outlined in the literature [8, 29, 30] and trial mixes were prepared before the final mix design was finalised. The mix was designed at a target strength of 30 MPa. Trials were conducted by varying the fly ash and GGBS contents Under a fly ash to GGBS ratio of 70:30, both the strength and workability requirements were satisfied. Increasing the GGBS content beyond 30% resulted in an unworkable mix when used in conjunction with an integral crystalline waterproofing agent. Hence, the fly ash-to-GGBS ratio was fixed at 70:30 for all GC mixes. The combined weight of the aggregates was assumed to be 70 % of the total weight of the GC mix, with coarse and fine aggregates set at a ratio of 65:35. The total binder (fly ash + GGBS + alkaline activators) was 30 % of the GC by weight. For all the mixes, the ratio of the alkaline activator solution to the powdered binder was fixed at 0,43. Meanwhile, the ratio of sodium silicate to sodium hydroxide was fixed at 2,5:1,0 based on trials and previous literature [31]. The superplasticiser was added to the binder at 2 % by weight. Trials were conducted by varying the concentration of the NaOH solution, based on which the molarity was fixed at 12M to consider the strength and workability. The crystalline waterproofing admixture was added in varying proportions from 0-6 %, with the concrete mix with 0 % admixture serving as the reference or control specimen. Beyond 6 % admixture, the GC was observed to be extremely harsh and unworkable; thus, trials were not conducted beyond 6 % admixture.

2.3 Sample preparation

A rotating pan mixer with a bottom discharge door was utilised to mix the ingredients forming the GC. Approximately 24 h had elapsed between the preparation of the alkaline activator mixture at the desired quantity and its addition to the mix. The coarse and fine aggregates were first combined in a pan mixer for 2 min when they were in a saturated, surface-dry condition. Subsequently, a premixed powdered binder (FA + GGBS) along with the crystalline admixture in dry powder form was added to the aggregates and mixed for another 2 min, after which the premixed alkaline activator solution was gradually poured and mixed with the powdered binder. When approximately 50 % mixing was achieved, the superplasticiser was added. Mixing was continued for a few minutes until a uniform mixture was obtained. The fresh mix was poured into the specimen moulds and placed on a vibration table for compaction. The freshly cast specimens were hardened under ambient conditions. All specimens were demolded after 24 h of casting and then stored under ambient curing conditions until testing ages of 7, 28, and 56 d.

3 Experimental methods

An experimental programme was conducted to investigate the effect of the addition of an integral crystalline admixture on the properties of GC. In addition to performing SEM, the compressive strength, split tensile strength, water absorption, rapid chloride penetration, acid resistance, and water contact angle (WCA) were tested, and SEM was performed to evaluate the different properties of the GC containing the admixture. The selected tests comprehensively evaluated the strength, durability, and waterproofing properties of the material, which are crucial for practical applications. The compressive strength and split tensile strength tests were performed to assess the mechanical performance, which is critical for structural applications. These tests confirmed that the GC can withstand both compressive and tensile stresses under real-world conditions. The water-absorption test and rapid chloride penetration test (RCPT) measure the permeability and resistance to chloride ingress, which are key factors affecting the durability of the material, particularly in aggressive environments. Low water absorption and chloride penetration enhance the longevity the material by reducing the risk of reinforcement corrosion. Acid resistance evaluates the ability of the material to withstand chemical attacks, which is essential for infrastructure exposed to acidic environments, such as wastewater treatment plants or industrial facilities. The WCA determines the hydrophobicity/hydrophilicity of the surface, which elucidates whether the addition of the crystalline admixture renders the concrete waterproof or imparts hydrophobicity to the concrete. A higher contact angle suggests superior water repellence, which contributes to the durability and resistance of the concrete to moisture ingress. Finally, SEM imaging enables microstructural analysis, which offers insights into the formation of crystalline networks, porosity reduction, and overall material integrity, thereby supporting the practical application of waterproof GC in sustainable, long-lasting infrastructure.

3.1 Compressive-strength test

The compressive strength test of concrete is a fundamental assessment used to determine the material's ability to withstand compressive loads. This test allows one to evaluate the structural integrity and quality of concrete, thus ensuring compliance with design specifications and safety standards. Cubes measuring 100 × 100 × 100 mm were used to perform this test. A total of 63 samples were prepared to perform the compressive-strength test, which involved seven mix proportions containing varying amounts of the admixture and three testing ages, with three samples prepared for each mix at each testing age.

The compressive strength of each GC mix was tested using three cubes at different curing ages. The three specimens were averaged to determine the representative compressive strengths of the GC mixtures. IS 516-2018 [32] standards were used to test the specimens and obtain their compressive-strength values. The evaluation was performed using a 3000 kN automatic compression testing machine (CTM). The load was applied gradually at 14 N/mm^2 per min (Figure 4) until the specimen's resistance to the increasing load failed, and no further load can be supported. The peak load was recorded, and this load, when divided by the cross-sectional area of the specimen, provides the compressive strength of the specimens.

Figure 4. Compressive-strength test setup

3.2 Split-tensile-strength test

Another mechanical test to determine the tensile-strength properties of the geopolymer mix was the split-tensile-strength test. This test was performed on cylindrical specimens measuring 100 mm in diameter and 200 mm in length. A CTM with an automated system and a maximum load capacity of 3000 kN was employed to assess the split tensile strength of the individual concrete batches (Figure 5). The load was applied in accordance with the specifications provided in IS 5816-1999[33], with a progressive delivery rate of 1,8 N/mm^2/min. A total of 63 samples were prepared to perform the split-tensile-strength test, as in the case of the compressive-strength test, which involved seven mix proportions containing varying amounts of the admixture and three testing ages, with three samples prepared for each mix at each testing age. The average of the three values was regarded as the representative value for the concrete mix.

Figure 5. Setup for split-tensile-strength test

3.3 Water-absorption test

The water absorption was measured according to ASTM C642 [34]. The test was performed on the specimens after 7, 28, and 56 d of curing. A total of 63 samples were prepared for the water-absorption test, which involved seven mix proportions containing varying amounts of the admixture and three testing ages, with three samples prepared for each mix at each testing age. For testing, samples measuring 50 mm in height and 100 mm in diameter were cut from cylinders measuring 100 mm in diameter and 200 mm in height. During testing, the specimens were oven dried at 100 to 110 °C for 24 h, after which their mass was measured (A). The specimen was subsequently immersed in water at 21 °C for 48 h, and its weight was determined after surface drying (B). Water absorption was determined using the following equation 1:

$$water\ absorption = \left[\frac{w_2 - w_2}{w_1}\right] \cdot 100\ (\%) \tag{1}$$

Where w_1 and w_2 denote the masses of the oven-dried sample and saturated-surface dry sample, respectively.

3.4 Rapid chloride penetration test RPCT

The RCPT was performed to determine the resistance of concrete to chloride ions. The test was conducted on cylindrical concrete specimens with diameters of 100 mm and lengths of 50 mm in accordance with ASTM C1202 [35]. The specimens were preconditioned in a desiccator and placed in custom-built cells (Figure 6). One end of the specimen was immersed in 3% NaCl solution and the other in 0,3 N NaOH solution. A 60 V Direct Current was applied across the ends, and the total charge passed was recorded. The RCPT value of the concrete mix was calculated by averaging the total charge passed in Coulombs through three specimens that indicated the resistance of the mix to chloride-ion penetration and it was corelated to a rating scale provided in the code, as shown in Table 3. The charge passed provides a qualitative estimate of the chloride permeability of concrete. A total of 63 samples were prepared to perform the RCPT, which involved seven mix proportions containing varying amounts of the admixture and three testing ages, with three samples prepared for each mix at each testing age.

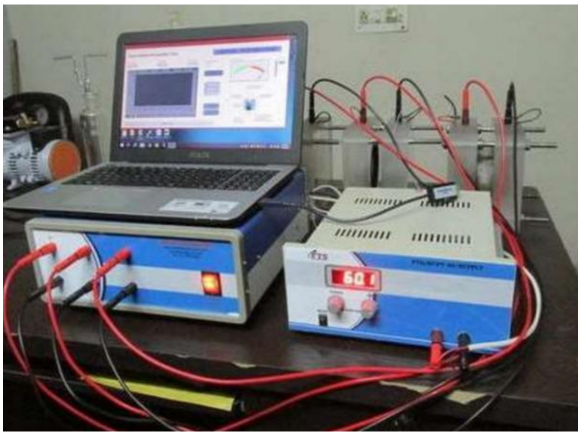


Figure 6. Rapid chloride permeability test in progress

Table 3. Classification of chloride-ion penetration based on total charge passed

S. No.	Charge passed (in Coulombs)	Chloride-ion penetration
1.	> 4000	High
2.	2000-4000	Moderate
3.	1000-2000	Low
4.	100-1000	Very Low
5.	< 100	Negligible

3.5 Acid-resistance test

Acid-resistance tests were performed to determine the durability of the GC in acidic environments. The test entailed subjecting the GC specimens to a certain concentration of an acidic solution, typically sulphuric or hydrochloric acid. In this study, sulphuric acid at 3 % concentration was used to conduct the acid-resistance test on the GC. After curing, the specimens were immersed or coated in an acidic solution for a specified duration. The acid solution reacted with the concrete, thus causing a chemical reaction that might result in surface degradation, strength loss, and corrosion of the reinforcing steel. The weight loss of the specimens was measured regularly throughout the test to determine the extent of degradation caused by the acid attack, in addition to visual inspection to monitor apparent indications of damage, such as cracks, spalling, or discoloration. The fraction of weight loss and the visual appearance of the sample determined the acid resistance of the GC. Lower weight loss and less-visible degradation indicate a more acid-resistant and robust GC. The test results are valuable for establishing the feasibility of GC in acidic environments as well as for improving mix design and material selection to improve acid resistance and durability. A total of 63 samples were prepared for the acid-resistance test, which involved seven mix proportions containing varying amounts of the admixture and three testing ages, with three samples prepared for each mix at each testing age. The 7, 28, and 56 d cured samples were used for the acid-resistance test and exposed to an acidic solution for 28 d.

Figure 7. GC samples immersed in acidic solution

3.6 Water contact angle test WCA

The WCA test assesses the hydrophobicity of a material via WCA measurements. In this study, sessile drop tests were conducted on both unmodified and modified GC specimens containing crystalline waterproofing admixtures. The experiment was conducted using an ACAM WCA measurement apparatus (Figure 8). Prior to conducting the experiment, the ACAM WCA measuring equipment was powered on and the necessary setup was prepared. The specimens were positioned on a platform and aligned meticulously using a high-resolution camera to ensure optimal lighting. The water droplet was subsequently introduced to the sample using a prefilled syringe affixed to the equipment, which was accomplished by elevating the platform. The water droplet was positioned, and further WCA measurements were conducted with software assistance. The experiment was conducted multiple times on different faces of the samples, and the mean of six measurements was regarded as the representative value for the specimen. The WCA test was conducted on the samples cured for 26 d. A total of 21 samples were prepared to perform the WCA test, which involved seven mix proportions containing varying amounts of the admixture, with three samples prepared for each mix; each sample was read at six different faces. A material is classified as hydrophilic or hydrophobic depending on its WCA. A material with a WCA of less than 90° is classified as hydrophilic, whereas one with a WCA greater than 90° is classified as hydrophobic [10,19].

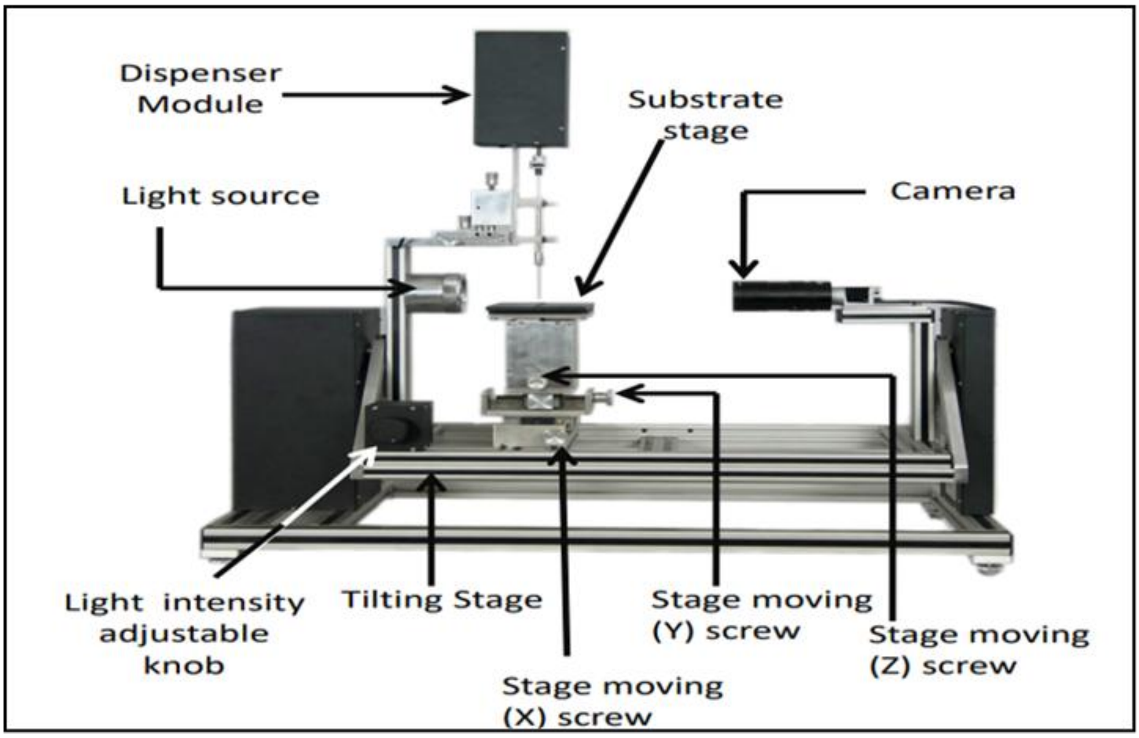


Figure 8. Schematic diagram of ACAM contact-angle measuring equipment [36]

3.7 Scanning electron microscopy SEM

SEM provides insights into the topography and compositional characteristics of a material. In this study, fragmented small sections of specimens were acquired from a sample crushed under a compression testing machine during the compression test. The specimens were coated with gold via ion sputtering prior to observation using SEM. SEM imaging was performed using a Quanta FEG 450 scanning electron microscope equipped with secondary and backscatter electron detectors. The microstructure of the concrete particles extracted from cracked cube samples aged for 28 d was investigated. Seven specimens corresponding to seven GC mixes were subjected to SEM analysis, where the surface morphology of the GC mixtures, including the matrix compactness, geopolymer gel formation, and presence of pores and cracks were investigated.

4 Results and discussions

4.1 Compressive-strength test

The compressive-strength-test results of the GC mixes obtained after modification with the crystalline waterproofing agent are shown in Figure 9. As shown, the compressive strength initially increased with an increase in the percentage of waterproofing admixture up to 3 %, after which it decreased slightly until 6% replacement; nonetheless, the value was higher than the compressive strength of the reference samples without any waterproofing admixture. For the GC with 3 % waterproofing admixture, increases in the compressive strength by 15,74 %, 15,65 %, and 15,86 % were observed at 7, 28, and 56 d, respectively. This indicates that the crystalline admixture in the GC increases the compressive strength of the concrete by densifying its matrix. Beyond 3 %, the strength decreased, which might be attributed to unsatisfactory compaction owing to the reduced workability of the mix at higher admixture percentages as the waterproofing admixture incorporation increased the water demand.

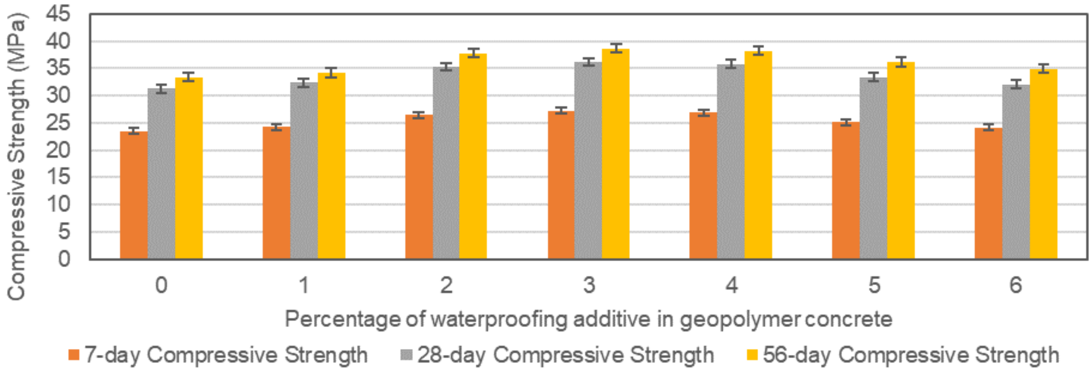


Figure 9. Compressive-strength-test results

4.2 Split-tensile-strength test

The split-tensile-strength results showed a trend similar to that observed in the compressive-strength-test results, as shown in Figure 10. The maximum split tensile strength was observed for GC containing 3 % waterproofing admixture, although the strength at 4 % was comparable to that at 3 %, with only a slight decrease in the values. The split-tensile-strength test results showed a decreasing trend at 5 and 6 % incorporation, which showed values higher than that recorded for the reference sample without any admixture.

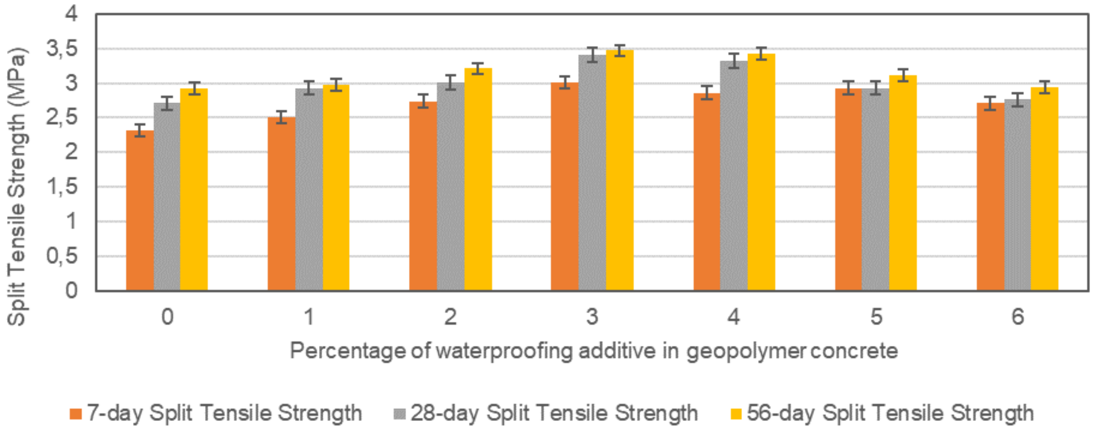


Figure 10. Split-tensile-strength test results

4.3 Water-absorption test

The water-absorption-test results for different GC mixes are shown in Figure 11. The samples with 3 % crystalline admixture incorporation showed the best results, with water absorption reductions of 42,85 %, 40,90 %, and 45,26 % at 7, 28, and 56 d, respectively. Beyond 3 %, the water absorption increased to 6 %, which may be attributed to improper compaction and packing due to reduced workability.

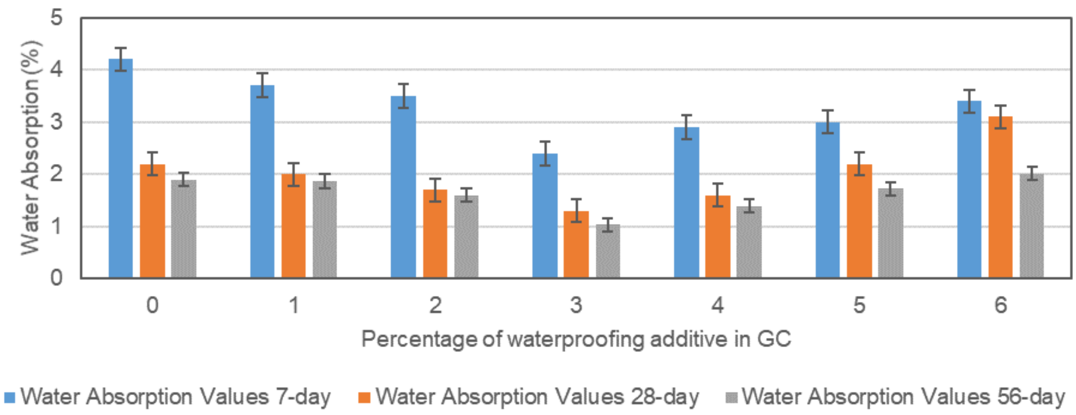


Figure 11. Water-absorption-test results

4.4 Rapid chloride penetration test RPCT

The RCPT results are presented in Table 4. As shown, the RCPT values decreased as the percentage incorporation of the waterproofing admixture increased up to 3 %, beyond which they decreased slightly, thus indicating better performance compared with the reference samples. The reference GC sample without any crystalline admixture showed high chloride penetration, whereas all other samples showed intermediate performance, as per the codal provisions.

Table 4. RCPT test results for GC mixes

Samples	RCPT Values			Chloride penetrability
	7 days	28 days	56 days	
GC-0 %	4173	4070	4005	High
GC-1 %	3980	3825	3802	Moderate
GC-2 %	3044	2990	2884	Moderate
GC-3 %	2660	2505	2501	Moderate
GC-4 %	2655	2600	2595	Moderate
GC-5 %	2785	2704	2608	Moderate
GC-6 %	2800	2755	2706	Moderate

4.5 Acid-resistance test

The results of acid-resistance attack on the GC with and without the crystalline admixture are listed in Table 5. Sulphuric acid was used to conduct the acid-resistance test on the GC. A weight reduction of 2-5 % was observed in the GC samples, with the maximum weight loss in the sample without any admixture. This weight loss indicates that the GC undergoes chemical reactions and degradation when exposed to the acidic environment. Sulphuric acid causes the dissolution and deterioration of the concrete structure over time. The crystalline admixture in GC improves the acid resistance of the GC, as is evident from the test results (Figure 12). Furthermore, the mass loss for the 56-d cured samples is less than that for the 7-d ones, which may be attributed to the geopolymerisation reactions progressing with age, thus resulting in a more compact structure.

Figure 12. GC after 28 d of exposure to acidic environment

Table 5. Comparison of sample weight before and after acid exposure

GC mix	Weight loss for 7-d cured samples	Weight loss for 28-d cured samples	Weight loss for 56-d cured samples
GC-0 %	4,57 %	4,15 %	3,97 %
GC-1 %	3,67 %	3,44 %	3,12 %
GC-2 %	3,38 %	3,17 %	2,96 %
GC-3 %	2,65 %	2,15 %	2,03 %
GC-4 %	2,78 %	2,55 %	2,16 %
GC-5 %	3,37 %	3,21 %	2,94 %
GC-6 %	3,39 %	3,01 %	2,98 %

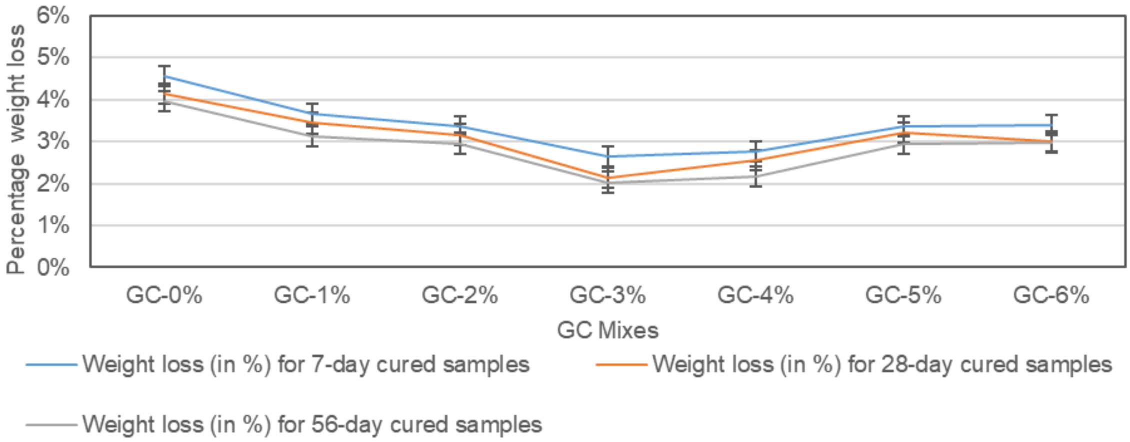


Figure 13. Weight loss of GC mixes due to acid exposure

4.6 Water contact angle test WCA

The WCA test was performed on the concrete samples to determine the effect of incorporating the integral waterproofing admixture to the GC mix. The results show that although the crystalline admixture improved the water resistance of the GC mixes, it did not render the GC surface hydrophobic, as opposed to the WCA values in the case of geopolymer composites containing hydrophobic admixtures [10, 14, 15, 16, 37]. All GC samples remained hydrophilic, with WCA values below 90°. The maximum WCA value, i.e., 79.03 °, was indicated by the sample with 3 % admixture, as shown in Figure 13.

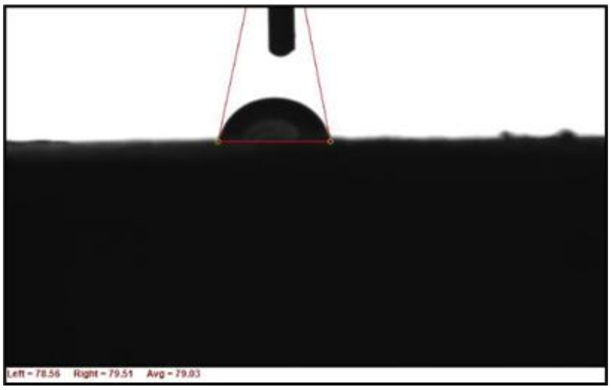
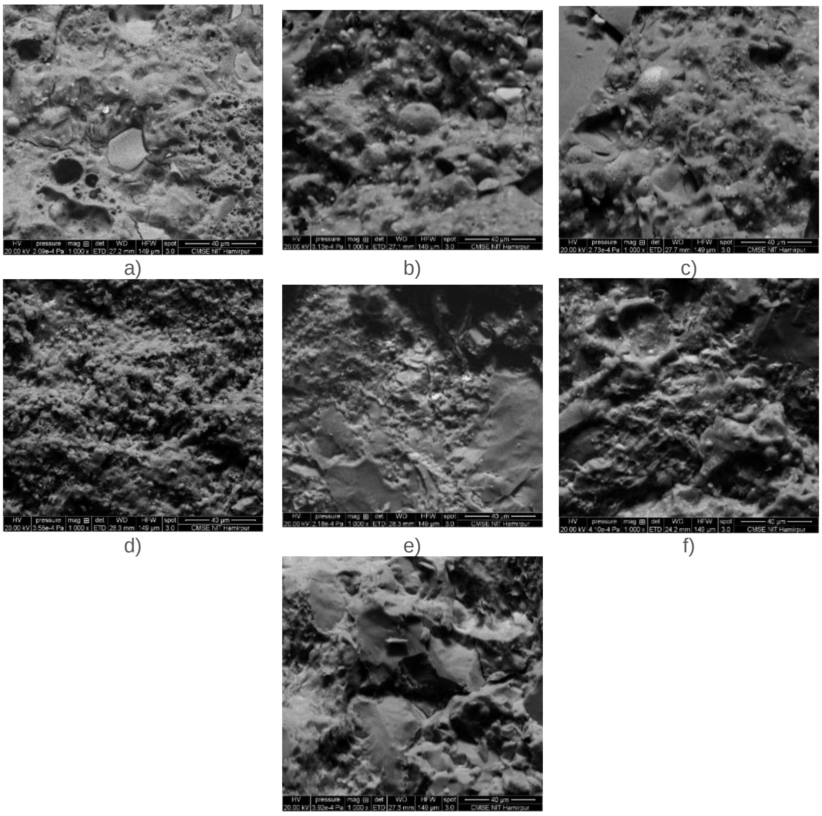


Figure 14. WCA image for GC mix containing 3 % crystalline waterproofing admixture

4.7 Scanning electron microscopy SEM

The SEM images indicated the presence of both unreacted precursor particles and continuous geopolymer gels resulting from the alkali activation of fly ash/GGBS. Spherical particles of different sizes corresponded to the, fly ash particles, whereas angular GGBS particles were scarcely observed. Voids/pores were indicated by dark regions in the SEM images.

The microcracks detected in certain SEM features had likely originated during the mechanical tests because the samples used for the SEM analysis were obtained from the specimens after mechanical testing. The SEM images show that the pore size and number of pores in the GC samples decreased with increasing admixture content up to 3 %, thus resulting in a denser matrix. The microstructures of the GC mixtures did not differ significantly and the GC-3 % sample exhibited the most compact microstructure, as observed in the SEM images.



g)

Figure 15. SEM images of different GC mixes: a) GC-0 %; b) GC-1 %; c) GC-2 %; d) GC-3 %; e) GC-4 %; f) GC-5 %; g) GC-6 %

5 Conclusions and future scope

This study involved the formulation of novel, durable GC specimens using an internal waterproofing crystalline admixture. In contrast to conventional surface-applied sealers or membranes, integral crystalline admixtures possess unique characteristics that allow them to be inherent components of concrete matrices. A crystalline admixture content of 3 was the most optimal for use in GC applications, which resulted in a densified matrix, increased strength, and excellent durability. An advantage of these admixtures over hydrophobic admixtures is that the crystalline admixture increases the mechanical strength, which is not the case for hydrophobic admixtures. Additionally, they can self-heal minor cracks and thus contribute to the durability. The admixture can be used to provide permanent protection for all GC structures exposed to adverse conditions or in regions where concrete is exposed to water or moisture, such as in marine environments. The results showed a significant reduction in water absorption by 42,85 %, 40,90 %, and 45,26 % for samples cured for 7, 28, and 56 d, respectively, thus indicating improved impermeability. Additionally, the compressive-strength tests revealed notable increases of 15,74 %, 15,65 %, and 15,86 % at 7, 28, and 56 d, respectively, thus highlighting the positive effect of the admixture on the mechanical performance. The SEM analysis confirmed the densification of the concrete matrix, thereby providing insights into the enhanced microstructure. These findings confirm that the integral crystalline admixture not only addresses water-penetration issues but also strengthens GC, thus rendering it a durable and environmentally friendly alternative to conventional cement concrete. The findings of this study have significant implications for the construction industry. By integrating crystalline admixtures into GC, critical infrastructures exposed to moisture or aggressive environments, such as marine structures, can be designed with greater durability and reduced maintenance costs. This advancement supports the increasing demand for sustainable, high-performance construction materials that reduce reliance on Portland cement and improve the lifecycle of concrete structures.

The scope for future studies in this domain is vast. The long-term performance of GC, particularly under extreme environmental conditions (e.g., freeze–thaw cycles and high sulphuric-acid-content environments), can be investigated in the future to provide a more comprehensive analysis of the durability and serviceability of GC over extended periods. Additionally, the potential effect of the admixture on the shrinkage, creep, and thermal properties, which significantly affect the durability and structural integrity of GC, can be addressed. The behaviour of GC containing crystalline admixtures under varying temperatures, chemical exposures, and mechanical stresses is another possible area of research. Additionally, this study can be used as a basis for investigating the synergy between the crystalline admixture and other novel supplementary cementitious materials, such as nano-silica and nano-alumina, which can further improve the strength and durability of structures.

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