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Research Paper

Comparative Study on the Durability of Geopolymer and Conventional Concrete Under Harsh Environmental and Chemical Exposure Conditions

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Abstract: *This comparative study rigorously evaluates the durability of fly ash-GGBS blend geopolymer concrete (GPC) against conventional Portland pozzolana concrete (PPC) under aggressive environmental conditions. Specimens were subjected to prolonged chloride (3% NaCl) and sulphate (5% Na_2SO_4) exposure, sorptivity, and water absorption tests over 30, 60, and 90 days. Results demonstrate GPC's superior resistance: after 90-day chloride exposure, compressive strength loss for GPC was 3.12% versus 4.30% for PPC. Under sulphate attack, GPC exhibited only 2.69% strength reduction compared to 3.45% for PPC. Critically, GPC's sorptivity coefficient (0.132 mm/min$^{0.5}$) was 20% lower than PPC's (0.165 mm/min$^{0.5}$), confirming reduced permeability. Water absorption for GPC (2.75%) also outperformed PPC (2.90%). Statistical validation via paired t-tests ($p<0.05$ for chloride/sulphate impacts) reinforced GPC's enhanced durability. These findings position FA-GGBS geopolymer concrete as a sustainable, high-performance alternative for infrastructure in corrosive environments.*

Keywords: *Geopolymer Concrete, Durability, Fly Ash, GGBS, Chloride Attack, Sulphate Attack, Sorptivity and Water Absorption.*

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I. Introduction

Geopolymer concrete is recognized as an eco-friendly substitute for traditional Ordinary Portland Cement (OPC) concrete, utilizing industrial waste materials such as fly ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) as binding agents (Jalal and Srivastava, 2025). Concrete durability is a key factor in ensuring the longevity and safety of structures, especially in environments where exposure to aggressive substances like chlorides and sulphates is common (Arora et al., 2022). One of the major concerns in reinforced concrete is chloride-induced corrosion, which significantly affects the strength and durability of structures over time. When chlorides penetrate the concrete and reach the steel reinforcement, they initiate a corrosive process that weakens the bond between the steel and concrete, leading to potential structural failure (Harshvadan, 2014). Conducting chloride attack tests allows engineers to assess the extent of chloride penetration, measure its diffusion rate, and evaluate the condition of concrete to predict possible reinforcement corrosion.

Similarly, sulphate exposure can have a detrimental effect on concrete structures. When concrete containing cementitious materials like Portland pozzolana cement (PPC) or geopolymer binders comes into contact with sulphate-rich environments, chemical reactions can lead to expansion and cracking. This is primarily due to the formation of ettringite crystals, which cause internal stresses within the concrete matrix. To evaluate the sulphate resistance of different concrete mixes, a sulphate content test is conducted, where sulphates are chemically extracted, precipitated as barium sulphate, and quantified gravimetrically. Understanding how concrete responds to sulphate exposure helps in selecting suitable materials for construction in sulphate-prone areas. In addition to chemical durability tests, it is equally important to evaluate the permeability of concrete, as excessive water absorption can lead to various forms of deterioration, including freeze-thaw damage, alkali-silica reactions, and reinforcement corrosion. The water absorption test determines how much water a concrete sample absorbs when submerged, providing a measure of its permeability. Concrete with lower water absorption is generally more resistant to environmental challenges, making it a more reliable material for long-term infrastructure projects. Geopolymer concrete is recognized as an eco-friendly substitute for traditional Ordinary Portland Cement (OPC) concrete, utilizing industrial waste materials such as fly ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) as binding agents.

Another crucial test for assessing concrete durability is the Sorptivity test, which measures the rate at which water is drawn into the concrete through capillary action (Ganesan et al.,2015). This test helps determine the susceptibility of concrete to moisture ingress, which can accelerate deterioration if not controlled. By comparing the Sorptivity coefficients of different concrete mixes, researchers can better understand the permeability characteristics of various materials and identify those best suited for harsh environmental conditions. Several studies have explored the durability and performance of GPC in aggressive environments. Such as, Luhar et al. (2020) explored the latest advancements in eco-efficient GPC, focusing on its durability challenges and highlighted the key durability factors like corrosion, permeability, and shrinkage, emphasizing the need for further research. The study also discusses obstacles like curing difficulties and supply chain issues for its widespread adoption. Kumar et al. (2021) investigated the durability of ternary blend geopolymer concrete (TGPC) reinforced with steel and polypropylene fibers. Results showed that TGPC with 1% steel and 0.15% polypropylene fiber improves resistance to water absorption, acid, sulphate, and marine attacks. The findings confirm TGPC as a durable and eco-friendly alternative to conventional concrete. Nagajothi et al. (2022) evaluate the durability of G30 GPC using tests for acid resistance, water absorption, and chloride penetration. Results showed that GPC has better resistance to water absorption and compressive strength loss than CC. Its chloride penetrability and absorption rate were comparable, with regression analysis confirming a strong absorption-time relationship. Pradhan et al. (2023) optimized the mix parameters for self-compacting geopolymer concrete (SCGC) using GGBFS, comparing it with OPC-based concrete. SCGC with 12M NaOH, a 2.5 sodium silicate-to-hydroxide ratio, 7% superplasticizer, and 21% extra water showed superior workability, strength, and durability. The findings highlight SCGC as a sustainable alternative with enhanced mechanical and durability properties. Chary and Munilakshmi (2023) investigated the mechanical, durability, and microstructural properties of GPC incorporating eggshell powder, fly ash, and GGBS. Strength and durability tests, along with SEM, XRD, and FT-IR analyses, confirm improved performance due to polymerization activation. The findings highlight eggshell powder as a beneficial additive for enhancing geopolymer concrete properties.

This study focuses on comparing the durability of geopolymer concrete (GPC) made with 50% Fly Ash and 50% Ground Granulated Blast Furnace Slag (GGBS) against conventional Portland pozzolana concrete (PPC). The research evaluates the impact of chloride attack, sulphate attack, water absorption, and Sorptivity on these concrete mixes over different exposure durations. The goal is to provide insights into the performance of GPC as a sustainable and high-performance alternative to conventional concrete in infrastructure applications exposed to aggressive environments.

II. Materials and Methodology

In this study, a comparative durability analysis was conducted between conventional Portland Pozzolana Cement (PPC) concrete and geopolymer concrete (GPC). For the control mix, 43-grade PPC conforming to IS:1489 (Part 1) was procured from the local market. Fine aggregate consisted of locally sourced river sand passing through a 4.75 mm sieve, in accordance with IS:383-1970, with a specific gravity of 2.65 and water absorption of 1.21%. Coarse aggregates were used in a 1:1 ratio of 20 mm and 10 mm nominal sizes. The 20 mm aggregate exhibited a specific gravity of 2.68 and water absorption of 0.28%, while the 10 mm aggregate had a specific gravity of 2.67 and water absorption of 0.47%. All aggregates complied with the specifications of IS:383-2016.

Ground Granulated Blast Furnace Slag (GGBS) conforming to IS:16715-2018 and Class F Fly Ash (FA) complying with ASTM C618 and IS:3812 (Part 1) were utilized as geopolymeric binders. The FA was sourced from NTPC-Roza. A polycarboxylate ether-based superplasticizer with a specific gravity of 1.29 was incorporated to enhance workability. The alkaline activator solution comprised sodium hydroxide (NaOH) at 14 M concentration and sodium silicate (Na_2SiO_3) with a specific gravity of 1.40. The ratio of sodium silicate to sodium hydroxide was maintained at 2.4, and the alkaline activator to binder ratio was fixed at 0.55. The binder system for GPC consisted of a 1:1 blend of FA and GGBS by weight. The superplasticizer dosage was 1.5% by weight of the total binder content. The mix design of PPC (CC) is tabulated in Table 1, and the mix design of GPC (50% Flyash and 50% GGBS as a source material mentioned as F50G50), M25 grade of 0.55 alkali activator is tabulated in Table 2 (Arunachelam et al., 2022). Where, quantity of cement, sand, aggregate, water, Flyash, GGBS, Sodium silicate, Sodium Hydroxide, and admixture are provided. Prepared specimens of CC and GPC are compared with each other for durability parameters, namely chloride attack, sulphate attack, water absorption, and Sorptivity, respectively (Saravana Kumar and Revathi, 2017).

Table 1: Mix Design of PPC (Control Concrete)

S. No.	Materials	Quantity per m^3
1.	Cement	360Kg
2.	Sand	795Kg
3.	20mm (CAg)	640Kg
4.	10mm (CAg)	432Kg
5.	Water	160Kg
6.	Admixture	2.52Kg

Table 2: Mix Design of Geopolymer Concrete

S. No.	Materials	Quantity per m^3
		0.55(AA)
1.	Cementitious Material (GGBS 50% + FA 50%)	360Kg
2.	Sand	795Kg
3.	20 mm (CAg)	628Kg
4.	10 mm (CAg)	428Kg
5.	Alkali Activator (AA)	198Kg
6.	Admixture	5.4Kg

To evaluate the durability performance of geopolymer concrete (GPC) and conventional concrete (CC), a comparative experimental investigation was carried out using the G50F50 mix (50% fly ash and 50% GGBS) at an alkali activator ratio of 0.55. A series of durability tests, including chloride content, sulphate content, sorptivity, and water absorption, were conducted followingss established standards (Ranjan et al., 2024).

For the chloride resistance test, specimens were immersed in a 3% NaCl solution prepared by dissolving 3 g of NaCl in 97 g of water for every 100 g of solution. The pH of the solution was measured using a calibrated digital pH meter. To ensure stability of the chloride concentration and maintain test consistency, the pH was monitored biweekly. If deviations from the initial pH were observed, adjustments were made by incrementally adding NaCl or distilled water through a controlled trial-and-error method (Kumar et al., 2021).

For the sulphate resistance test, a 5% sodium sulfate (Na_2SO_4) solution was prepared following a similar approach, dissolving 5 g of Na_2SO_4 in 95 g of water per 100 g of solution. Specimens were fully submerged in this solution, with the pH maintained at a consistent level by monitoring and adjusting it every 15 days, again using a digital pH meter and a trial-and-error rebalancing approach.

Sorptivity testing followed the ASTM C1585-04 standard. Specimens were preconditioned in a hot-air oven at 50 °C for 7 days. All lateral surfaces were sealed with a 1:1 mixture of wax and resin to promote unidirectional water ingress (Ganesan et al., 2015). The specimens were then partially immersed (5–10 mm depth) in water, and mass gain was recorded at selected intervals (1, 2, 3, 4, 5, 9, 12, 16, 20, and 25 minutes). After each weighing, excess water was removed using a damp cloth, and the specimen was returned to the water. Sorptivity was calculated from the slope of the best-fit line (excluding the origin) of the cumulative water absorption per unit area versus the square root of time.

Water absorption was determined as per the methodology described by Moradikhou (2019). Specimens were dried at 105 °C for 24 hours, weighed, and then submerged in water for another 24 hours. Final weights were used to compute the absorption capacity, reflecting the volume of water penetrated into the concrete.

To quantify the durability performance, compressive strength was measured both before and after exposure to chloride and sulphate solutions. The specimens were exposed for predefined durations, and reductions in strength were monitored. To assess the statistical significance of strength losses, the Shapiro–Wilk test was first employed to confirm the assumption of normality. Upon confirmation, paired t-tests were conducted to determine whether the observed reductions were statistically significant. These analyses were carried out independently for GPC and CC, as well as for the combined dataset (Tee and Mostofizadeh, 2021).

This comprehensive evaluation not only revealed the extent of deterioration in GPC and CC under aggressive environments but also allowed a direct comparison of their resistance to chloride and sulphate attack. The findings offer critical insights for selecting sustainable and durable concrete materials in infrastructure exposed to chemically aggressive conditions.

III. Results and Discussion

To evaluate the durability of geopolymer concrete (GPC) with a binder composition of 50% fly ash and 50% GGBS (designated as F50G50) and an alkali activator ratio of 0.55, chloride content tests were conducted by established protocols (refer to Table 3). The performance of GPC was benchmarked against that of conventional concrete (CC) under chloride exposure for durations of 30, 60, and 90 days. Table 3 presents the compressive strength (CS) values of both GPC F50G50 and CC before chloride exposure, followed by their respective reductions in strength post-exposure. The percentage loss in compressive strength due to chloride ingress was calculated to assess the degradation in mechanical performance. The GPC mix exhibited a significantly lower strength loss compared to CC, indicating superior resistance to chloride attack.

Specifically, the F50G50 mix showed a strength reduction of 2.65%, 2.90%, and 3.12% after 30, 60, and 90 days of chloride exposure, respectively. In contrast, CC exhibited higher corresponding losses of 3.86%, 4.12%, and 4.30%. These results underscore the enhanced durability of the GPC mix in chloride-laden environments. A comparative visual representation of strength loss percentages across all exposure durations is provided in Figure 1, clearly illustrating the superior performance of the F50G50 mix relative to CC. These findings are consistent with previous literature (Imtiaz et al., 2020) and reinforce the potential of geopolymer concrete as a durable alternative to conventional systems in aggressive environments.

Table 3: Chloride attack test of Compressive strength of GPC and CC under Different Exposure Conditions

S. No.	Specimen Designation	Exposure Condition	Compressive Strength (N/mm^2)	Compressive Strength after chloride exposure (N/mm^2)	Loss% under Chloride attack
1.	F50G50	30 days	35.07	34.14	2.65
2.	F50G50	60 days	39.27	38.13	2.90
3.	F50G50	90 days	41.73	40.43	3.12
4.	CC	30 days	32.10	30.86	3.86
5.	CC	60 days	32.55	31.21	4.12
6.	CC	90 days	33.03	31.61	4.30

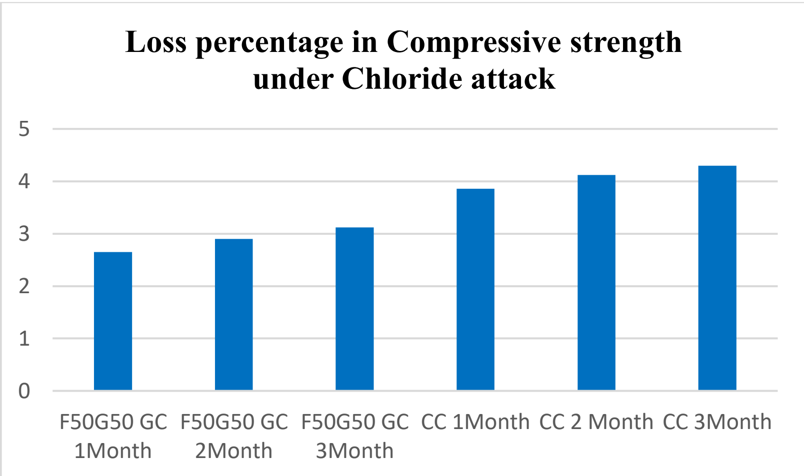

Figure 1: Loss percentage in Compressive strength under Chloride attack

The sulfate resistance of the geopolymer concrete (GPC) mix F50G50 was assessed and compared to conventional concrete (CC) under varying exposure durations of 30, 60, and 90 days, as summarized in Table 4. The initial compressive strength (CS) of both F50G50 and CC was recorded before sulfate exposure. Subsequent measurements revealed a reduction in CS due to sulfate attack, enabling an evaluation of durability performance.

The GPC mix F50G50 exhibited significantly lower strength degradation under sulfate exposure compared to CC across all durations. After 30 days, the CS loss in F50G50 was approximately 0.91%, increasing modestly to 1.35% at 60 days and 2.69% at 90 days. In contrast, CC experienced a more pronounced deterioration, with CS reductions of 1.75%, 3.44%, and 3.45% over the same respective periods. These results highlight the superior resistance of GPC to sulfate attack, particularly evident at extended exposure durations.
The comparative loss percentages for each mix and exposure duration are graphically represented in Figure 2, offering a clear visualization of the enhanced sulfate durability of the F50G50 geopolymer mix (Lakusic, 2023).

Table 4: Sulphate Content test of Compressive strength of GPC and CC under Different Exposure Conditions

S. No.	Specimen Designation	Exposure Condition	Compressive Strength (N/mm^2)	Compressive Strength after Sulphate exposure(N/mm^2)	Loss% under Sulphate attack
1.	F50G50	30 days	35.07	34.75	0.91
2.	F50G50	60 days	39.27	38.74	1.35
3.	F50G50	90 days	41.73	40.61	2.69
4.	CC	30 days	32.10	31.54	1.75
5.	CC	60 days	32.55	31.43	3.44
6.	CC	90 days	33.03	31.89	3.45

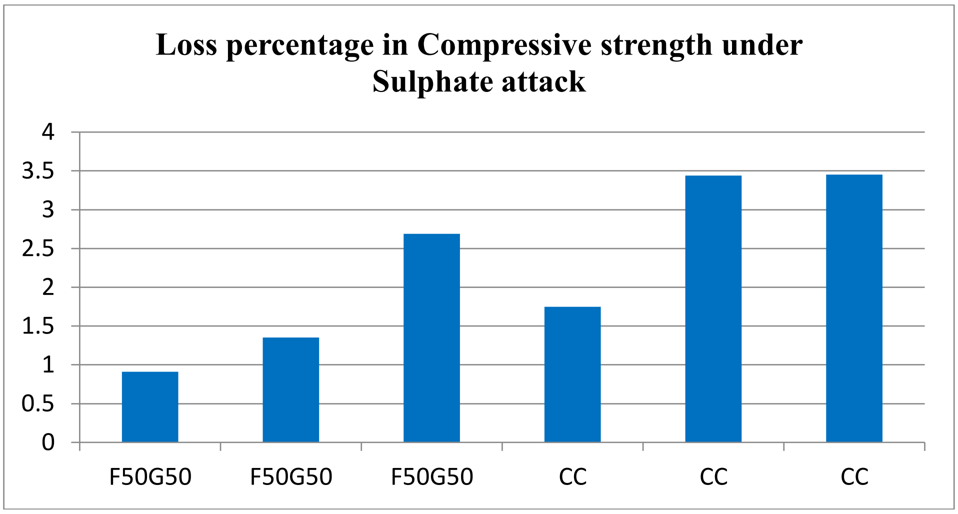

Figure 2: Loss percentage in Compressive strength under Chloride attack

The sorptivity test was performed to evaluate the capillary water absorption characteristics of both conventional concrete (CC) and geopolymer concrete (GPC), with results presented in Tables 5 and 6. Measurements were taken at specific time intervals (1, 2, 3, 4, 5, 9, 12, 16, 20, and 25 minutes), capturing the rate of water uptake and illustrating the differential permeability behavior between the two concrete types (Ganesan et al., 2015).

For CC, the initial mass was recorded at 8.302 kg, increasing to 8.320 kg after 25 minutes of water exposure. The total mass gain of 0.018 kg corresponds to an absorbed water volume of 17,565.67 mm^3. The sorptivity coefficient, derived from the slope of the absorption curve, was calculated to be 0.165 mm/min^0.5, indicating a relatively high rate of water ingress and capillary permeability.

In contrast, the GPC specimen demonstrated enhanced resistance to water absorption. Starting with an initial mass of 8.421 kg, it reached 8.435 kg by the end of the test period, reflecting a total mass gain of only 0.015 kg and an absorbed water volume of 14,696.67 mm^3. The corresponding sorptivity coefficient for GPC was significantly lower at 0.132 mm/min^0.5.

Figures 3 and 4 illustrate the linear regression of absorption versus the square root of time for CC and GPC, respectively, along with their best-fit line equations and coefficients of determination (R^2). These findings underscore the superior impermeability of GPC relative to CC, attributable to its denser microstructure and reduced capillary porosity.

The lower sorptivity coefficient observed in GPC not only signifies improved resistance to water ingress but also implies enhanced long-term durability. This makes GPC a compelling alternative for infrastructure applications where resistance to moisture penetration and aggressive environmental exposure is critical.

Table 5: Sorptivity test of Control Concrete

Time (Min.)	Mass (kg)	Gain in wt.(kg)	Cumulative gain in Mass(kg)	Volume Water(mm^3)	Surface area(mm^2)	I(mm)	Time($min^{0.5}$)
0	8.3020	0.0000	0.0000	0.0000	22500	0.0000	0.000
1	8.3050	0.0030	0.0030	2667.6670	22500	0.1190	1.000
2	8.3080	0.0030	0.0060	5676.6670	22500	0.2520	1.410
3	8.3100	0.0020	0.0080	7665.6670	22500	0.3410	1.730
4	8.3110	0.0010	0.0090	9002.0000	22500	0.4000	2.000
5	8.3120	0.0010	0.0100	9676.6670	22500	0.4300	2.240
10	8.3140	0.0020	0.0120	12343.3330	22500	0.5490	3.160
12	8.3160	0.0020	0.0140	14001.0000	22500	0.6220	3.460
15	8.3180	0.0020	0.0160	16001.0000	22500	0.7110	3.870
20	8.3190	0.0010	0.0170	16677.6670	22500	0.7410	4.470
25	8.3200	0.0010	0.0180	17565.6670	22500	0.7810	5.000
Sorptivity = 0.165 mm/$min^{0.5}$							

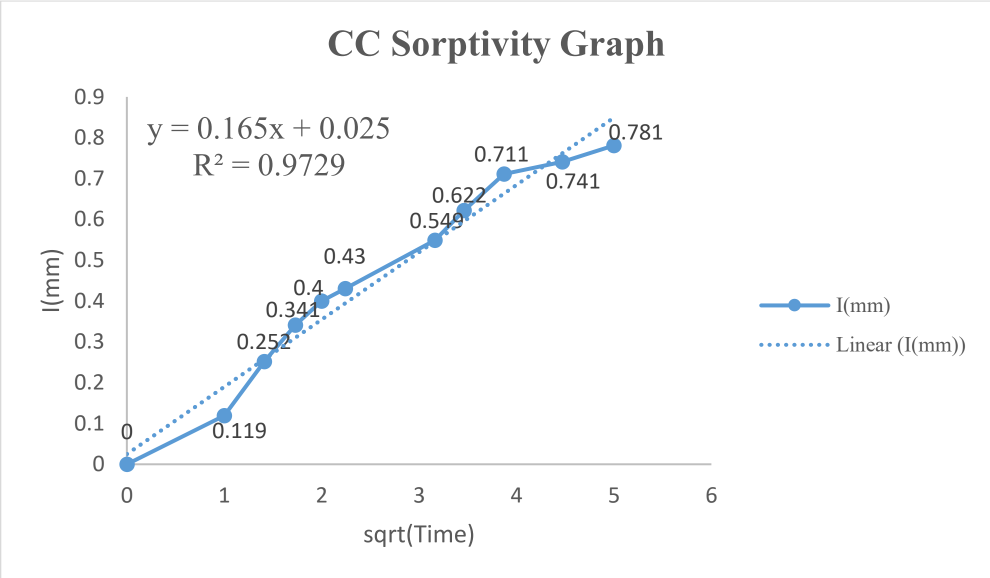

Figure 3: Sorptivity of Control Concrete

Table 6: Sorptivity of Geopolymer Concrete

Time (Min.)	Mass (kg)	Gain in wt.(kg)	Cumulative gain in Wt. (kg)	Vol. water(mm^3)	Surface area(mm^2)	I(mm)	Time ($min^{0.5}$)
0	8.4210	0.0000	0.0000	0.0000	22500	0.0000	0.000
1	8.4250	0.0040	0.0040	4010.0000	22500	0.1780	1.000
2	8.4260	0.0010	0.0050	4676.6670	22500	0.2080	1.410
3	8.4280	0.0020	0.0070	6567.6670	22500	0.2920	1.730
4	8.4290	0.0010	0.0080	7776.6670	22500	0.3460	2.000
5	8.4300	0.0010	0.0090	7777.6670	22500	0.3460	2.240
10	8.4310	0.0010	0.0100	10020.0000	22500	0.4450	3.160
12	8.4320	0.0020	0.0120	12030.0000	22500	0.5350	3.460
15	8.4330	0.0010	0.0130	13030.0000	22500	0.5790	3.870
20	8.4340	0.0010	0.0140	14002.0010	22500	0.6220	4.470
25	8.4350	0.0010	0.0150	14696.6670	22500	0.6530	5.000
Sorptivity = 0.132 mm/$min^{0.5}$							

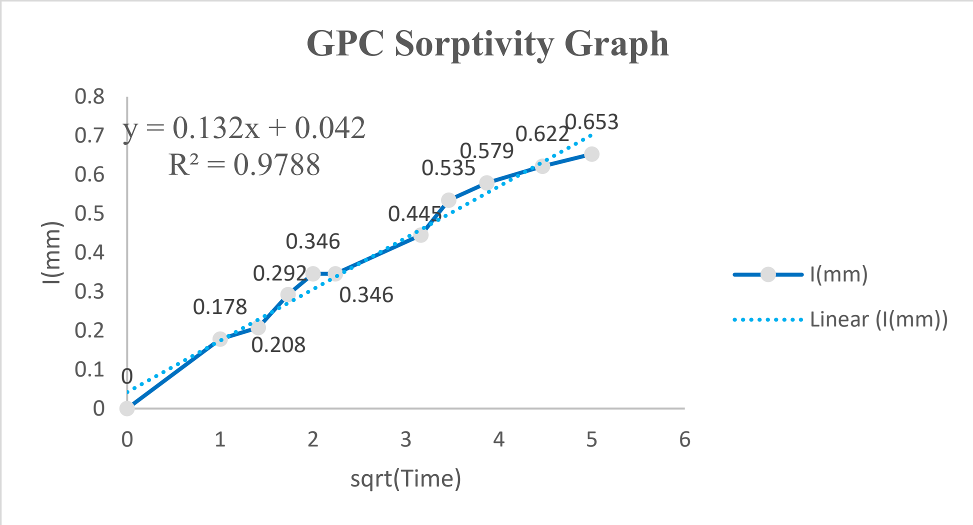

Figure 4: Sorptivity of Geopolymer Concrete

To evaluate the resistance of concrete to water ingress critical factor influencing long-term durability, a water absorption test was performed on both Geopolymer Concrete (GPC) and Conventional Concrete (CC), as per established protocols (Moradikhou et al., 2019). This test serves as an indirect measure of porosity and permeability, key indicators of a material's ability to withstand aggressive environmental conditions.

The findings, summarized in Table 7, reveal that GPC exhibited a lower average water absorption (2.75%) compared to CC (2.90%), indicating superior impermeability. GPC specimens initially weighed between 8.24 kg and 8.34 kg. After oven drying at 105 °C for 24 hours, the weight reduced due to moisture loss. Subsequent 24-hour water immersion led to a mass gain of 2.67%–2.89%. In contrast, CC specimens had an initial weight range of 8.46–8.59 kg, and following similar drying and immersion procedures, displayed a wider absorption range of 2.47%–3.51%, with a higher mean value.

The relatively lower water absorption of GPC underscores its denser microstructural matrix, which significantly restricts capillary suction and fluid transport. This enhanced impermeability positions GPC as a more durable alternative to OPC-based concrete, particularly in infrastructure subjected to harsh environmental or chemical exposures.

Table 7: Water absorption test

Type of Concrete Sample	Notation	Initial Wt. (Kg)	Oven Dry Wt.(kg)	Wt. after immersion	Gain%	Avg. Gain%
Geopolymer Concrete	F50G50 GC1-m	8.34	8.28	8.52	2.89	2.75
	F50G50 GC2-m	8.29	8.23	8.45	2.67	
	F50G50 GC3-m	8.24	8.18	8.40	2.68	
Control Concrete	CC1-m	8.59	8.48	8.69	2.47	2.90
	CC2-m	8.58	8.47	8.70	2.71	
	CC3-m	8.46	8.24	8.53	3.51	

Furthermore, Figure 5 visually compares the water absorption characteristics of GPC and CC by illustrating the variations in initial weight, oven-dry weight, and weight after immersion for both concrete types (Moradikhou et al., 2019). This graphical representation provides a clear understanding of the differences in water absorption behaviour, highlighting the superior resistance of GPC to moisture penetration compared to CC.

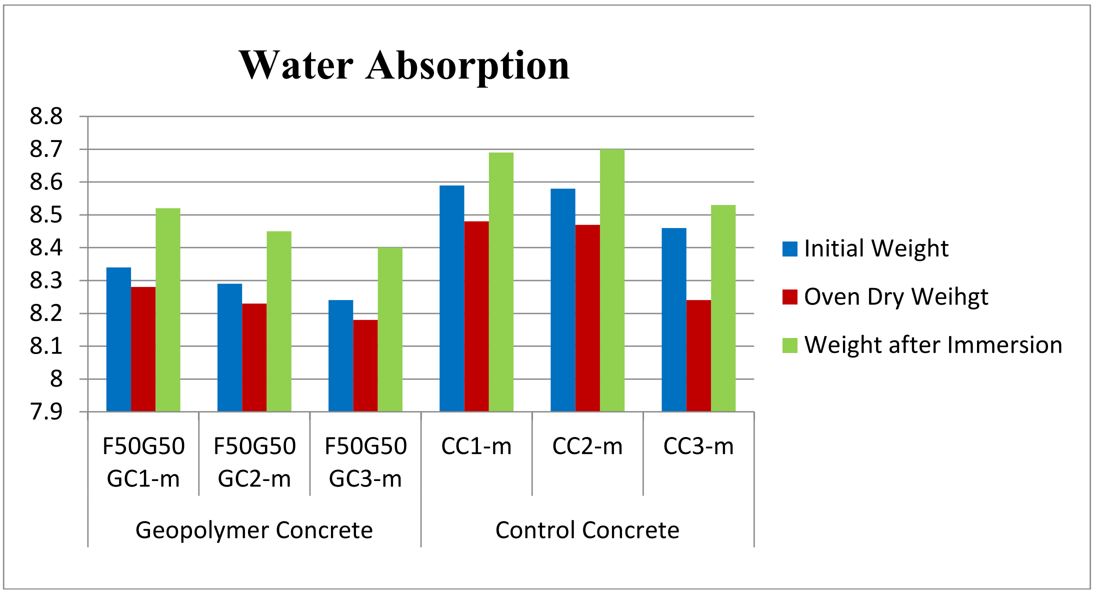

Figure 5: Bar chart of Water absorption

The durability performance of geopolymer concrete (GPC) and conventional concrete (CC) was evaluated through comparative analysis of compressive strength before and after chloride exposure, utilizing data from Table 3 (M. Nanthini et al., 2024). Normality of the strength data was confirmed via the Shapiro–Wilk test, with p-values exceeding 0.05 for both GPC and CC (refer to Table 8), validating the application of a paired t-test for statistical inference.

Post-exposure evaluation revealed a significant reduction in compressive strength for both concrete types. GPC specimens exhibited a statistically significant decrease ($t = 10.4853$, $p = 0.00897$), indicating degradation under prolonged chloride exposure. Similarly, CC specimens showed an even more pronounced decline ($t = 25.6074$, $p = 0.00152$), underscoring a higher vulnerability to chloride-induced deterioration.

When analysing the combined dataset of GPC and CC, slight deviations from perfect normality were observed (Shapiro–Wilk p-values of 0.1826 and 0.1764 for pre- and post-exposure values, respectively), yet remained within acceptable bounds. The paired t-test applied to this pooled dataset further substantiated the findings, revealing a highly significant overall loss in compressive strength after exposure ($t = 17.2974$, $p = 0.0000118$).

Comparative analysis highlights that while both materials experience strength degradation under chloride attack, CC demonstrates a more substantial decline, suggesting inferior resistance. In contrast, GPC displays enhanced durability and greater resilience in chloride-laden environments. These results underscore the superior long-term performance of GPC, particularly for infrastructure exposed to marine conditions, de-icing agents, or similar aggressive chloride-rich environments.

Table 8: Durability Test of Compressive Strength Before and After Chloride Exposure

Group	Before Chloride Exposure		After Chloride Exposure		t-statistic	p-value
	Shapiro-Wilk Statistic	p-value	Shapiro-Wilk Statistic	p-value		
GPC	0.9778	0.7141	0.9765	0.7061	10.4853	**0.00897**
CC	0.9997	0.9644	0.9985	0.9265	25.6074	**0.00152**
Overall (GPC + CC)	0.8581	0.1826	0.8562	0.1764	17.2974	**0.00001**

To evaluate the influence of sulphate exposure on the durability of geopolymer concrete (GPC) and conventional concrete (CC), compressive strength measurements were conducted at 30, 60, and 90 days, both prior to and following exposure (Table 4). Statistical analysis was performed using the Shapiro–Wilk test to verify data normality, followed by paired t-tests to assess the significance of strength variations (Table 9).

For GPC, the Shapiro–Wilk test confirmed that compressive strength data adhered to a normal distribution before and after sulphate exposure ($p = 0.7141$ and $p = 0.6067$, respectively), justifying the use of a paired t-test (Manzoor et al., 2024). Although a reduction in compressive strength was observed post-exposure, the change was not statistically significant ($t = 2.7422$, $p = 0.1112$), indicating that GPC retained its structural integrity and exhibited high resistance to sulphate-induced degradation (Muthuramalingam et al., 2023).

In contrast, CC also met the normality criterion ($p = 0.9644$ before and $p = 0.4412$ after exposure), but the paired t-test revealed a statistically significant decline in compressive strength following sulphate attack ($t = 4.9451$, $p = 0.0385$). This marked reduction underscores the susceptibility of CC to sulphate environments.

When the data for both concrete types were pooled, the Shapiro–Wilk test indicated marginal deviation from perfect normality ($p = 0.1826$ before and $p = 0.1265$ after exposure); nonetheless, a paired t-test was deemed appropriate. The results demonstrated a highly significant overall reduction in compressive strength due to sulphate exposure ($t = 5.2976$, $p = 0.0032$), underscoring the aggressive nature of sulphate attack on concrete durability.

Table 9: Durability Test of Compressive Strength Before and After Sulphate Exposure

Group	Before Sulphate Exposure		After Sulphate Exposure		Paired t-Test	
	Shapiro-Wilk Statistic	p-value	Shapiro-Wilk Statistic	p-value	t-statistic	p-value
GPC	0.9778	0.7141	0.9582	0.6067	2.7422	0.1112
CC	0.9997	0.9644	0.9168	0.4412	4.9451	**0.0385**
Overall (GPC + CC)	0.8581	0.1826	0.8384	0.1265	5.2976	**0.0032**

These findings collectively highlight the superior sulphate resistance of GPC in comparison to CC. The minimal strength loss observed in GPC positions it as a more durable and sustainable alternative for infrastructure exposed to aggressive sulphate-laden environments (Jalal et al., 2025).

IV. Conclusion

This study conclusively establishes the superior durability of 50% fly ash-50% GGBS geopolymer concrete (GPC) over conventional concrete (PPC) under harsh chemical exposures. Three key findings emerge:

1. Chemical Resistance: GPC showed significantly lower compressive strength degradation than PPC after prolonged chloride (3.12% vs. 4.30%) and sulphate exposure (2.69% vs. 3.45%) at 90 days, validated by rigorous statistical analysis ($p<0.05$ for PPC deterioration; $p=0.1112$ for GPC under sulphate attack).
2. Permeability Reduction: GPC's denser microstructure yielded a 20% lower sorptivity coefficient (0.132 $mm/min^{0.5}$ vs. 0.165 $mm/min^{0.5}$) and reduced water absorption (2.75% vs. 2.90%), indicating enhanced resistance to ionic ingress and moisture-related damage.
3. Sustainability Implications: By utilizing industrial byproducts (fly ash, GGBS) as primary binders, GPC reduces carbon footprint while delivering exceptional durability in chloride/sulphate-rich environments like marine infrastructure or chemical plants.

These results demonstrate GPC's viability as a high-performance, eco-conscious alternative to traditional concrete. Future work should explore long-term (>180 days) behavior and field-scale validation to accelerate industrial adoption.

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