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ASSESSMENT OF THE COMPRESSIVE STRENGTH AND DURABILITY OF CONCRETE FOUNDATIONS EXPOSED TO CHEMICAL ATTACK

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ABSTRACT: Structural foundation integrity is crucial for sustaining diverse constructions, but in Qatar, the prevalent rapid penetration of chloride ions and sulfate in soil and groundwater poses a substantial threat. This chemical exposure accelerates steel corrosion and induces concrete damage, especially at the foundational level, which is a prevalent concern in the Middle East. This study aimed to identify the most durable concrete foundation by evaluating its compressive strength at 7 and 28 days, coupled with various durability tests such as the rapid chloride penetration test, water absorption, chloride penetration, water penetration, and chemical analysis. The emphasis was on achieving a concrete composition capable of enduring for centuries. This research delved into variations in concrete durability, particularly focusing on curing methods, in contrast to previous studies. Samples underwent curing in natural soil, exposing them to chemical attacks such as chloride ion (Cl^-=0.12%) and sulfate (SO_4^{2-}=1.22 g/l) attacks, while others opted for curing in potable water and temperatures controlled as per American Society for Testing and Materials (ASTM). The experimental investigation considered high-performance triple-blend mixtures and control sample concrete compositions, including 70% ordinary Portland cement (OPC), 25% pulverized fuel ash (PFA), and 5% silica fume (MS); 45% ordinary Portland cement (OPC), 50% ground granulated blast furnace slag (GGBS), and 5% silica fume (MS); 100% sulfate resistance cement (SRC); and 100% ordinary Portland cement (OPC). The results indicate that incorporating GGBS enhances both compressive strength and foundation durability.

Keywords: Structural concrete foundation, Compressive strength, Durability, Analysis of variance, Life cycle of concrete

1. INTRODUCTION

Concrete foundations serve as the base of buildings or other civil structures that directly contact the ground below. They play a crucial role in securely distributing the structure's load to the ground, preventing significant settlement. Neglecting the ground conditions during foundation construction can lead to foundation failure, especially in regions where elevated levels of chemicals such as sulfate and chloride ions are present. A durable foundation is designed to withstand the weight of the building to ensure the lifespan of the project, to prevent the corrosion of steel, and to ensure that no chemical penetration can easily occur inside the foundation. It is essential to protect the foundation to resist any unforeseen consequences that may arise in the future. In Qatar, existing soil, also known as natural soil, and groundwater are normally subjected to two types of chemical attacks at the structural foundation level. These are chloride ions (Cl^-) and sulfate (SO_4^{2-}). These pose a significant challenge in the Middle East, where the elevated chemical content of SO_4^{2-} = 1.22 g/l and Cl^- = 0.122% in the ground accelerates steel corrosion and causes concrete damage, especially below ground level. To counteract chemical attacks that cause steel corrosion, it is imperative to employ a triple blend concrete mix design for the foundation. This design effectively resists chemical attacks on concrete, thereby improving performance and extending the lifespan of the foundation.

This study aimed to identify the most durable concrete foundation based on compressive strength at 7 and 28 days and durability tests, such as the rapid chloride penetration test, water absorption, chloride penetration, water penetration, and chemical analysis, as well as investigating concrete that is capable of a design life spanning several centuries. The experimental significance of using triple blend concrete for foundations is to enhance the endurance strength of concrete by preventing steel corrosion and strengthening its resistance to chemical factors affecting the lifespan of the concrete.

The materials employed for this study were sourced from the Sabea Ready Mix Plant, a local ready-mix concrete supplier in Qatar. Two distinct types of cement, namely, Type I and Type V, were utilized in the research investigation.

Based on previous studies conducted by Chandra et al. [1], the effect of fly ash on workability, setting time, compressive strength, and water content was investigated. Experiments on various concrete mixes were conducted to investigate the effect of partial replacement of cement by fly ash on the characteristics of concrete. Yokota and Hashimoto [2]. The theoretical guidelines and simulation models for predicting the deterioration progress of concrete structural elements were investigated. Forecasting how structural performance deteriorates will advance in the future. Shumuye and Zhao Jun [3] investigated the utilization of ground granulated blast furnace slag (GGBS) as a partial pozzolanic substitute for cement in the production of concrete. According to the literature, GGBS has been proven to improve the properties of concrete at a later age and is subject to replacement. This increases the use of waste and industrial leftovers to reduce the consumption of Portland cement. Kumar et al. [4] conducted a research study on high-performance concrete, in which they utilized GGBS and robo sand. Their findings revealed that replacing 25% of the sand with robo sand and using 50% of the GGBS cement boosted the strength of the concrete by 11.06% and 17.60% after 7 and 28 days, respectively. Kumar et al. [5] evaluated the strength of concrete compared to conventional concrete using the optimal ratio of pulverized fuel ash (PFA) and ground granulated blast furnace slag (GGBS) as a partial substitute for cement, while Karri et al. [6] explored the strength and durability of concrete incorporating GGBS. On the other hand, Estores G and Lejano B [7] improved the pull-out strength of an expansion stud anchor by using a concrete-filled fiber-reinforced polymer composite (CFRC). According to their test report, the most notable increase in the pull-out strength was observed when 38 mm (approximately 1.5 in) fibers were added at a volume content of 0.10%. Chousidis et al. [8] examined the influence of Greek fly ash as an initial cement substitution on the durability and mechanical resistance of reinforced concrete immersed in a NaCl solution. Ikkurti and Kanneganti [9] played a key role in enhancing the understanding of various properties associated with fly ash concrete and contributed to the formulation of innovative mix designs. This research has aided in understanding the other properties of fly ash concrete and in developing new mix designs. Shinde et al. [10] investigated the impact of synthesized sand with the same compressive strength as concrete. Moreover, they investigated the feasibility of utilizing synthetic sand in place of natural sand. On the other hand, Shao et al. [11] developed a numerical model of chloride diffusion in cement-based materials considering calcium leaching and external sulfate attack. On the other hand, Anwar et al. [12] examined the impact of using byproduct materials such as fly ash (FA) and silica fume (SF) in conjunction with ordinary Portland cement (OPC) in a ternary system on concrete characteristics. Adding fly ash and silica fume to Portland cement in a ternary system improves concrete resistance to chloride attack, reduces the diffusion coefficient, and can be widely employed in the concrete industry.

In the present study, samples cured in natural soil were exposed to chemical attacks, including chloride ion and sulfate attacks, while earlier research used potable water and temperatures controlled as per ASTM requirements. Structural concrete comprises a blend of fine aggregates, coarse aggregates, cement (including GGBS, PFA, sulfate-resistant cement (SRC), and ordinary Portland cement (OPC)), water, and supplementary elements such as steel reinforcement. Proper construction design of concrete mixtures is essential to ensure the strength and durability of concrete. As a result, material choices during the construction phase, as well as design concepts, have a significant impact on concrete durability.

The results of the experimental study indicate that incorporating GGBS in concrete foundations provides the most durable mix design when exposed to chemical resistance, corrosion, and saltwater. This study considered various criteria, including concrete properties, selection of crucial mix design parameters, analysis of experimental data, compressive strength, durability, and the life cycle of concrete.

2. RESEARCH SIGNIFICANCE

The study's significance lies in its identification of ground granulated blast furnace slag (GGBS) as the most durable mix design for concrete foundations facing chemical attacks such as chloride ions, sulfate resistance, and saltwater. This research offers a specific and effective solution for enhancing concrete durability, particularly in the Middle East region, highlighting the suitability of the 50% GGBS mix design for Qatar's environmental conditions. Additionally, this study highlights the economic advantages of GGBS, which is approximately 50% less expensive than ordinary Portland cement (OPC), and emphasizes its environmental benefits, which contribute to sustainability by reducing pollution as a byproduct of the iron and steel production process. The findings, including improved early strength development and enhanced overall strength and durability, provide valuable insights for construction professionals seeking resilient and cost-effective concrete solutions with positive environmental impacts.

3. MATERIALS AND METHODS

This section outlines the materials and methodology employed in the study. As shown in Table 1, there were four mixed designs in this phase of the experimental inquiry. Table 2 shows the matrix of the specimens in regard to the compressive strength of PFA, GGBS, SRC, and OPC. Table 3 shows the properties and characteristics of the aggregates and sand. Table 4 shows the properties of the ingredients, such as the material used and the specific gravity, including ordinary Portland cement, ground granulated blast furnace slag, pulverized fuel ash, micro silica, gabbro, wash sand, admixture, and water. The simulation process is thoroughly explained. The methodology encompasses testing and computations for compressive strength, durability of the concrete, analysis of variance, and the life cycle of concrete, ensuring a comprehensive evaluation.

Table 1 Mixture design

Mix Design	Cement (OPC) content	SRC content	PFA content	GGBS content	Silica Fumes content
SRC	0%	100%	0%	0%	0%
PFA	70%	0%	25%	0%	5%
GGBS	45%	0%	0%	50%	5%
OPC	100%	0%	0%	0%	0%

Note: 100% OPC is the control case

Table 2 Matrix of the specimens (compressive strength)

S/N	Design mix	No. of samples (7 days)	No. of samples (28 days)	Total
1	PFA	3	3	6
2	GGBS	3	3	6
3	SRC	3	3	6
4	OPC	3	3	6
			Grand total	24

Table 3. Properties and characteristics of the aggregates and sand

Item	Gabbro 10 mm	Gabbro 20 mm	Washed Sand
Material finer than 63 µm (%)	0.2	0.1	1.7
Particle Density (Mg/m³	2.92	2.94	2.71
Water Absorption (%)	0.6	0.4	1.1
Flakiness Index (%)	6.7	6.4	–
Shape Index (%)	9.0	7.0	–
Shell Content (%)	0.0	0.0	–
Clay Lumps & Friable Particles (%)	0.2	0.1	0.2
Resistance to degradation by LA Machine (%)	16	16	–
Lightweight particles in Aggregates (%)	0.0	0.0	0.0
Aggregate Soundness by Magnesium Sulfate (%)	2.0	1.3	–
Acid Soluble Sulfate Content in Aggregate (%)	0.1	0.1	0.1
Acid Soluble Chloride Content in Aggregate (%)	0.001	0.002	0.01

Table 4 Properties of the ingredients

S/N	Material	Specific Gravity
1	OPC (ASTM C150)	2.09
2	GGBS (BSEN 15167)	2.33
3	PFA	2.23
4	Micro silica	2.3
5	20-mm gabbro	2.92
6	10-mm gabbro	2.9
7	wash sand	2.64
8	admixture	1.06
9	water	1

3.1 Compressive Strength Test

Each concrete mix was represented by six sample cubes measuring 150x150x150 mm, for a total of 24 sample cubes. Additionally, spare cubes were produced. The testing encompassed various mixed situations involving 70% ordinary Portland cement (OPC), 25% pulverized fuel ash (PFA), and 5% silica fume (MS); 45% ordinary Portland cement (OPC), 50 % ground granulated blast furnace slag (GGBS), and 5% silica fume (MS); 100% sulfate-resistant cement (SRC); and 100% ordinary Portland cement (OPC). Before the formation process began, all cubes were cured in natural soil and exposed to chloride ions, sulfate, and salt. Figure 1 depicts how the sample cubes were embedded in the natural soil. Figure 2 illustrates the embedding in natural soil and exposure to chemical attacks such as chloride ions and sulfate, while Fig. 3 shows that, after embedding in the natural soil, sample cubes had discoloration on their surfaces, which indicates that chemical attacks permeated inside the concrete foundation when exposed to the natural soil. The compressive strength of these sample cubes was tested using a compressive strength machine, as shown in Fig. 4. These were the main elements examined while evaluating the experimental experiments to determine whether the foundation level would withstand the load of the building.

Fig. 1 Sample specimen before being embedded in natural soil.

Fig. 2 Sample specimens embedded in natural soil.

Fig. 3 Sample specimens with discoloration due to chemical attack after being embedded in natural soil.

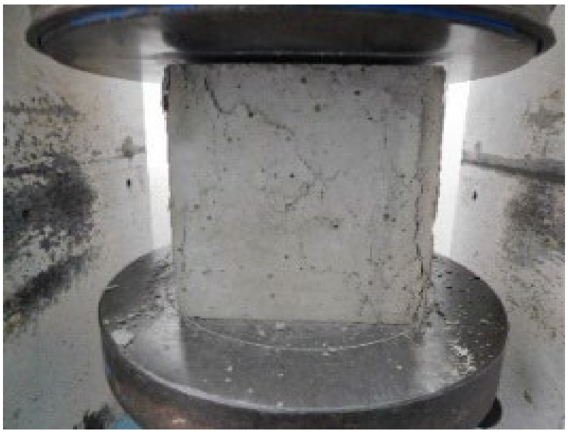

Fig. 4 The compressive strength test setup

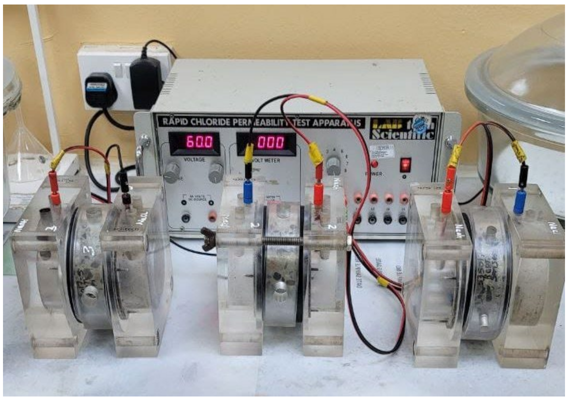

Fig. 5 Rapid chloride permeability test setup.

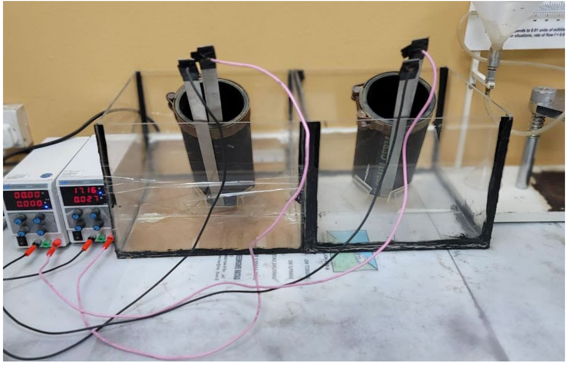

Fig. 6 Chloride penetration of hydraulic cement concrete by the rapid migration process.

Fig. 7 Water penetration of the hardened concrete test setup.

For each mixture, three cubes were tested after 7 days, and another three cubes were tested after 28 days (approximately 4 weeks), aiming to assess and evaluate the compressive strength of the concrete cube samples.

3.2 Durability Test

The durability test involved thirty-six (36) sample cubes, which underwent complete curing in natural soil and were exposed to salt, sulfate attack, and chloride ions for 56 days (equivalent to approximately 2 months). The matrix cases for the pulverized fuel ash (PFA) and ground granulated blast furnace slag (GGBS) specimens are presented in Tables 5 and 6, respectively. Several tests were conducted, including the hardened concrete rapid chloride permeability test (RCP test) according to ASTM C1202 [13], as shown in Fig. 5. This test uses the electrical conductance of concrete to quickly assess its resistance to chloride ion penetration. Another factor is the water absorption of concrete as per BS 1881 Part 122:2020 [14]. Figure 6 illustrates the chloride penetration of hydraulic cement concrete by the rapid migration process as per NT Build 492. This method utilized electrical migration to speed up the passage of chloride ions into the concrete cube samples and used a colorimetric indicator to determine the extent of penetration and chloride penetration of concrete through a rapid migration process. Figure 7 shows the results of the hardened concrete tests for the water penetration depth under pressure in accordance with BSEN 12390-8:2019 [15]. This test determined the maximum depth of penetration beneath the test area of hardened concrete. Finally, chemical tests were performed. This test assessed the sulfate and chloride content of hardened concrete that was exposed to chemical attacks, as measured using the BS 1881-124:2015 [16] procedures for hardened concrete analysis.

Table 5 Matrix of cases for the specimens (durability-PFA)

Mix design	Test required	Samples
PFA	Rapid Chloride Permeability Test	3
	water absorption	3
	Chloride penetration	3
	Water penetration	3
	Sulfate & Chloride content	3
	water absorption	3
	Spares samples	3
	Total	18

Table 6 Matrix of cases for the specimens (durability-GGBS)

Mix design	Test required	Samples
GGBS	Rapid Chloride Permeability Test	3
	water absorption	3
	Chloride penetration	3
	Water penetration	3
	Sulfate & Chloride content	3
	water absorption	3
	Spares samples	3
	Total	18

The sulfate content (SO_3) was determined using the specified equation in this test. The specific details and calculations for the sulfate content are provided in BS 1881-124:2015. As shown in Eq. (1),

$$G=L/Md\times34.3\times100/CI \quad (1)$$

where G is the sulfate content (g) as a percentage of the cement, L is the mass of ignited barium sulfate (g), C1 is the cement content of the sample used, and Md is the mass of the sample used. The chloride content in hardened BS 1881-124:2015 concrete was determined via Eq. (2):

$$J=[V5-(V6m)/0.1]0.3545/Mc\times100/CI \quad (2)$$

where J is the chloride ion content as a percentage of the cement, Mc is the sample's mass (in grams), V5 is the volume of silver nitrate solution added at 0.1 M, V6 is the volume of thiocyanate solution, m is the thiocyanate solution's molarity, and C1 is the sample's cement content.

3.3 Calculation of the Life Cycle for PFA and GGBS

The duration of the existence of structural concrete is a multifaceted topic that includes various elements. These factors comprise the quality of the concrete; the environmental conditions it encounters, including exposure to chemical agents; the thickness of the concrete cover; waterproofing installation measures; and the level of maintenance it receives. The vulnerability of a concrete foundation structure to chloride, salinity, corrosion, and sulfate attacks was assessed and predicted using Life 365 software. Figure 8 illustrates the complete lifecycle of the concrete structure in regard to the concrete foundation, starting from the planning and design stages, surface concentration and temperature, material, through construction, ongoing maintenance, and eventual demolition. Additionally, it provides an estimated lifespan for concrete based on calculations.

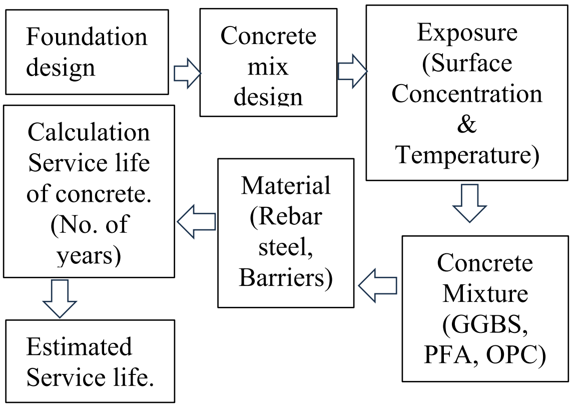

Fig. 8 Lifecycle of a structure flowchart.

3.4 Statistical Analysis

Analysis of variance (ANOVA) served as a robust statistical tool for conducting experimental investigations and analyzing the data obtained in this study. ANOVA enables researchers to assess the significance of differences between multiple groups or treatments within the experiment. By comparing variances and means, ANOVA allows for the identification of any statistically significant variations among the groups being studied. This statistical treatment aids in drawing reliable conclusions and making informed decisions based on the experimental findings.

ANOVA involves the calculation of two distinct methods: the mean sum of squares due to treatment (Mst) and the mean sum of squares due to error (Mse). Under the assumption of the null hypothesis, the ratio shown in Eq. (3) is

$$F = Mst/Mse \quad (3)$$

where F is the measurement statistic utilized to determine whether treatment means are comparable. The MSE, on the other hand, reflects sample variability or design strength. F should be near one and have an F distribution. To interpret the findings of the experiment, the data were assessed for significant or nonsignificant differences. If the calculated F value was less than the critical F value at a specific degree of freedom and level of significance, the hypothesis was accepted, indicating no significant differences. Conversely, if the calculated F value exceeded the critical F value at a particular degree of freedom and level of significance, the hypothesis was rejected, suggesting significant differences. The criterion for rejection in this analysis was defined as having k_0.005 < F, where k represents the critical value of the F distribution at a significance level of 0.05.

4. RESULTS AND DISCUSSION

4.1 Compressive Strength Test Results

Table 7 below represents the results of the concrete strength for the SRC-50 experiment at two different time points: 7 days and 28 days. For Sample 1, the concrete strength measured after 7 days of curing was 48.6 MPa, while after 28 days, it increased to 59.2 MPa. Similarly, for Sample 2, the concrete strength was 47.2 MPa at 7 days and 57.4 MPa at 28 days. Sample 3 had a strength of 49.0 MPa at 7 days and 58.6 MPa at 28 days. The mean average row provides the average value for all the samples at each time point. The average strength after 7 days was 48.27 MPa, and the average strength after 28 days was 58.4 MPa. These results indicate the progression of concrete strength over time, with higher values observed at 28 days than at 7 days. Figure 9 illustrates the increase in the concrete strength relative to the number of days.

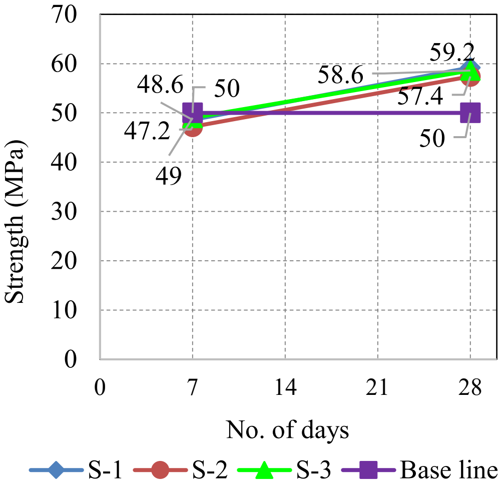

Fig. 9 SRC-50 compressive strength at 7 and 28 days.

Table 7 Compressive strength test results for SRC-50

Sample	7 Days (MPa)	28 Days (MPa)
1	48.6	59.2
2	47.2	57.4
3	49.0	58.6
Mean Average	48.27	58.4

Table 8 presents the results for 45% OPC + 50% GGBS + 5% silica fumes. Sample 1 exhibited a concrete strength of 53.2 MPa after 7 days, which increased to 70.9 MPa after 28 days. Similarly, Sample 2 had a strength of 54.5 at 7 days and 68.8 MPa at 28 days, while Sample 3 had a strength of 53.9 MPa at 7 days and 70.7 MPa at 28 days. The average strength after 7 days was 53.86 MPa, whereas the average strength after 28 days was 70.10 MPa. These findings indicate a notable progression in concrete strength over time, with an observed increase in strength from 7 days to 28 days. Figure 10 depicts the progression of the concrete strength in relation to the number of days.

Table 8 Compressive strength test results for C50N. 45% OPC + 50% GGBS + 5% silica fumes

Sample	7 Days (MPa)	28 Days (MPa)
1	53.2	70.9
2	54.5	68.8
3	53.9	70.7
Mean Average	53.86	70.10

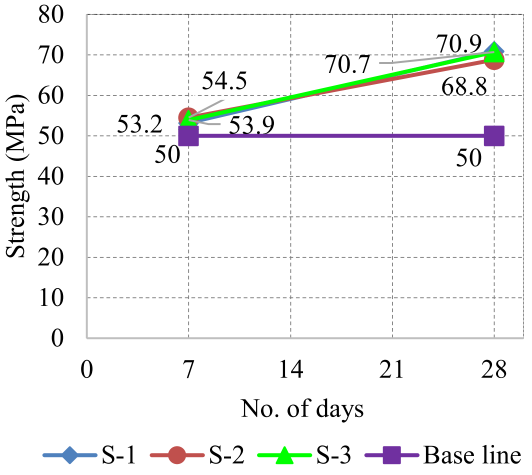

Fig. 10 C50 N 45OPC+50%GGBS+5% compressive strength for 7 and 28 days.

Table 9 highlights the findings for the 70% OPC, 25% PFA, and 5% silica fumes. In the case of Sample 1, the concrete strength was 56.20 MPa after 7 days, which then improved to 68.20 MPa after 28 days. Similarly, Sample 2 exhibited a strength of 58 MPa at 7 days and 69.3 MPa at 28 days, while Sample 3 exhibited a strength of 54.3 MPa at 7 days and 67.2 MPa at 28 days. The average strength after 7 days was 56.16 MPa, whereas the average strength after 28 days was 68.23 MPa. These results indicate a notable increase in the concrete strength over time, with a significant improvement observed from 7 days to 28 days. Figure 11 depicts the progressive growth of the concrete strength over time as represented by the number of days.

Table 9 Compressive strength test results for C50N. 70% OPC + 25% PFA + 5% silica fumes

Sample	7 Days (MPa)	28 Days (MPa)
1	56.2	68.2
2	58.0	69.3
3	54.3	67.2
Mean Average	56.16	68.23

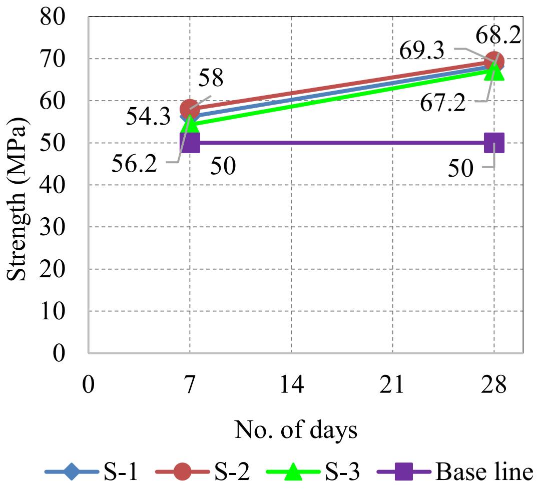

Fig. 11 C50 N 70% OPC+25% PFA+5% MS compressive strength for 7 and 28 days.

Finally, Table 10 illustrates the findings for a composition consisting of 100% OPC. In the first sample, the concrete strength was 40.4 MPa after 7 days, which increased to 52.4 MPa after 28 days. Likewise, the second sample exhibited a strength of 39.2 MPa at 7 days and 51.5 MPa at 28 days, while the third sample exhibited a strength of 43.4 MPa at 7 days and 54.4 MPa at 28 days. The average strength after 7 days was 41.0 MPa, and the average strength after 28 days was 59.4 MPa. These results also indicate a significant improvement in the concrete. Figure 12 illustrates the increase in the concrete strength relative to the number of days.

Table 10 Compressive strength test results for 100% OPC

Sample	7 Days (MPa)	28 Days (MPa)
1	40.4	52.4
2	39.2	51.5
3	43.4	54.4
Mean Average	41.0	59.4

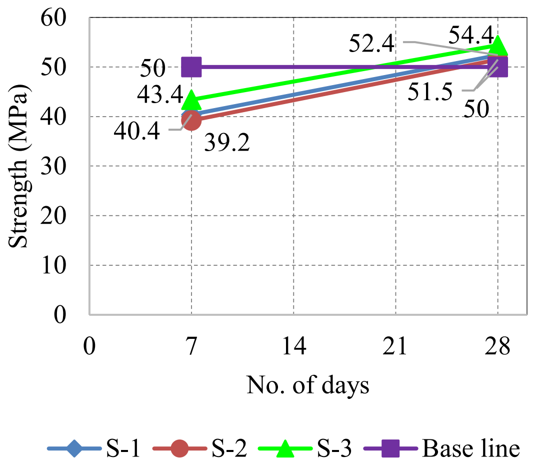

Fig. 12 100% OPC compressive strength for 7 and 28 days.

Among the tested combinations, OPC exhibited the lowest compressive strength values at both 7 and 28 days, with average values of 41 (82%) and 52.73 (105.53%), respectively. The SRC had a strength of 48.27 (96.5%) at 7 days and 58.4 (116.8%) at 28 days. GGBS demonstrated strengths of 53.86 (107.73%) at 7 days and 70.1 (140%) at 28 days. PFA exhibited strengths of 56.16% (112.33%) at 7 days and 68.2% (136%) at 28 days. While PFA had the greatest strength at 7 days, GGBS had the greatest strength at 28 days. This significant increase in compressive strength can be attributed to the high pozzolanic nature and ability of powdered fly ash to fill voids. The experimental data analysis highlighted the positive effects of incorporating silica fumes and the triple blend of GGBS and PFA on enhancing the strength of concrete, resulting in properties comparable to those of other concrete mixtures such as normal concrete. The use of 100% OPC in normal concrete led to decreased compressive strength due to acid, chloride, and chemical attacks. However, when 50% GGBS was substituted, the concrete exhibited a much greater resistance to chemical attacks. Furthermore, the strength of the concrete increased when a triple blend of GGBS and PFA combined with 50% GGBS and 25% PFA was used. Notably, the concrete achieved the desired design compressive strength within 7 days. This study revealed a higher compressive strength than did previous studies.

4.2 Durability Test Results

4.2.1 Durability test results for PFA

According to the water penetration experimental test conducted on a concrete sample composed of 70% ordinary Portland cement (OPC), 25% pulverized fly ash (PFA), and 5% silica fume, the results in Table 11 indicate that the maximum water penetration depths for Samples 1 and 2 were both 5 mm. However, Sample 3 had a slightly shorter penetration depth, measuring 4 mm. These findings are in comparison to the guidelines or standards outlined in the Qatar construction specifications QCS 2014, Section 5-Part 6 [17], which specify that water penetration depths for concrete properties with high durability should not exceed 5 mm. The average water penetration depth across all three samples was 4.67 mm, utilizing the data provided. In summary, the test results suggest that strength increased over time, with a noticeable increase in strength from 7 days to 28 days. The concrete composition met the specified standards for high durability, as the maximum water penetration depths observed in these experimental studies were within the allowed limit of 5 mm, with an average depth of 4.67 mm. These experiments demonstrated that water penetration did not reach the steel reinforcement inside the foundation, which would have caused corrosion.

Table 11 Water penetration for C50 N 70% OPC+25% PFA+5% silica fume

S/N	Water Penetration Dept, mm (Max.)	QCS 2014 Qatar Construction Specification Section 5 concrete - Part 6 properties
1	5.0	Max. 5 mm
2	5.0	
3	4.0	
Mean Average	4.67	

Table 12 Water absorption for C50 N 70% OPC+25% PFA+5% silica fume

S/N	Corrected Absorption %	QCS 2014 Qatar Construction Specification Section 5 concrete - Part 6 properties
1	1.8	Max. 2%
2	1.6	
3	1.3	
Mean Average	1.57	

Table 13 Chloride ion penetration for C50N 70 OPC+25% PFA+5% silica fume

S/N	Chloride Penetration	QCS 2014 Qatar Construction Specification Section 5 concrete - Part 6 properties
1	453	Max 500 COULOMBS
2	462	
3	492	
Mean Average	469	

Table 14 Chloride migration for C50 N 70% OPC+25% PFA+5% silica fume

S/N	Chloride Migration Coefficient	QCS 2014 Qatar Construction Specification Section 5 concrete -Part 6 properties
1	2.0 X 10^{12}	MAX- 2.0 X 10^{12}
2	1.96X10^{12}	
3	1.99X10^{12}	
Mean Average	1.98X10^{12}	

Table 15 Chemical analysis for C50 N 70% OPC+25% PFA+5% silica fume

S/N	Sulfate as SO3 (% by wt.)	QCS 2014 Qatar Construction Specification Section 5 concrete - Part 6 properties
1	2.5	MAX- 3.0
2	2.6	
3	2.8	
Mean Average	2.63	

Table 16 Chemical analysis for C50 N 70% OPC+25% PFA+5% silica fume

S/N	Chloride as CI (% by wt.)	QCS 2014 Qatar Construction Specification Section 5 concrete -Part 6 properties
1	0.09	MAX- 0.3
2	0.1	
3	0.1	
Mean Average	0.096	

Based on the water absorption test results in Table 12, the following observations were made. Sample 1 exhibited a water absorption percentage of 1.8%, Sample 2 had a value of 1.6%, and Sample 3 had a percentage of 1.3%. Calculating the average of these values gives an overall absorption percentage of 1.57. These values are below the specified limit for high-durability concrete, as outlined in the QCS 2014 Section 5-Part 6 Tables 6.9. The mentioned standard states that the water absorption percentage should not exceed 2%. In summary, the water absorption test confirmed that all three samples met the criteria for high-durability concrete, as their absorption percentages (1.8, 1.6, and 1.3, respectively) and average value (1.57) were lower than the specified limit of 2%. On the other hand, the chloride penetration test results in Table 13 indicate that Sample 1 had a score of 453, Sample 2 had a score of 462, and Sample 3 had a score of 492. The overall average of these results is 469, which falls within the acceptable range stated in QCS 2014 Section 5 Part 6.9. According to the specification, the maximum permissible value for chloride penetration is 500 coulombs, and the obtained average of 469 complies with this requirement. Additionally, the experimental research on the chloride migration coefficient revealed in Table 14 that Sample 1 had a value of 2.0 X 10^{12}, Sample 2 had a lower value compared to Sample 1, 1.96 X 10^{12}, while Sample 3 had a slightly higher value of 1.99 X 10^{12}. The calculated average chloride migration coefficient was 1.98 X 10^{12}. These results indicate that the test outcome for the chloride migration coefficient was satisfactory, as per the specifications outlined in QCS 2014 Section 5 Part 6.9. The value obtained from the experiment was below the maximum limit stipulated, validating its compliance with the standard. Finally, Samples 1, 2, and 3 demonstrated satisfactory performance in the chemical test experiments conducted to assess sulfate resistance. Their values are shown in Table 15 as 2.5, 2.6, and 2.8, respectively, resulting in an overall average of 2.63. Importantly, this average value falls below the maximum limit specified in QCS 2014 Section 5-Part 6: Concrete Properties and High Durability. Additionally, the chloride test results in Table 16 indicate that Sample 1 had a chloride content of 0.09%, while Samples 2 and 3 had a slight increase to 0.1%.

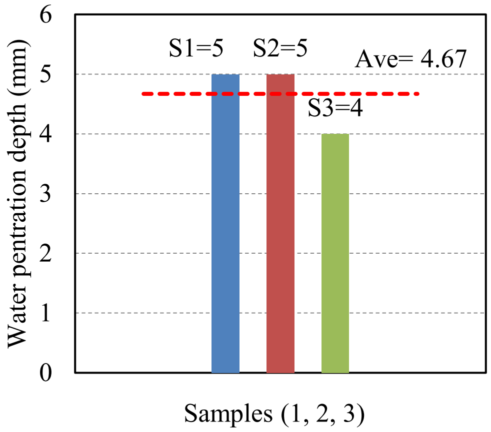

Fig. 13 Water penetration durability test results.

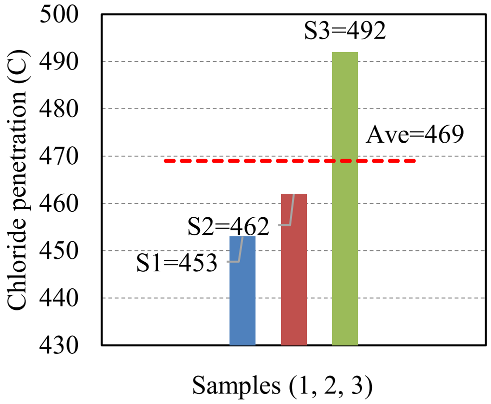

Fig. 14 Chloride ion penetration durability test results.

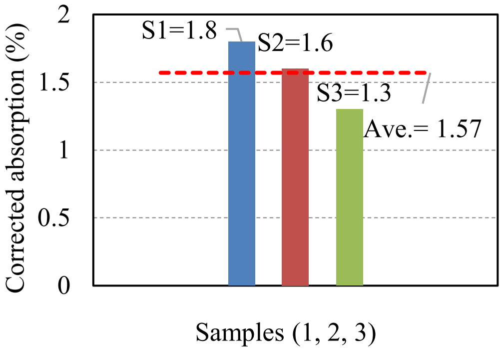

Fig. 15 Water absorption durability test results.

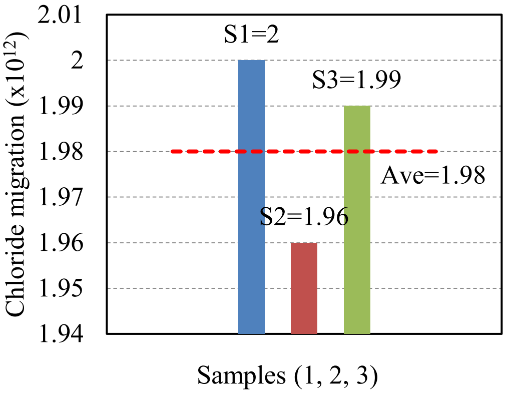

Fig. 16 Chloride migration durability test results.

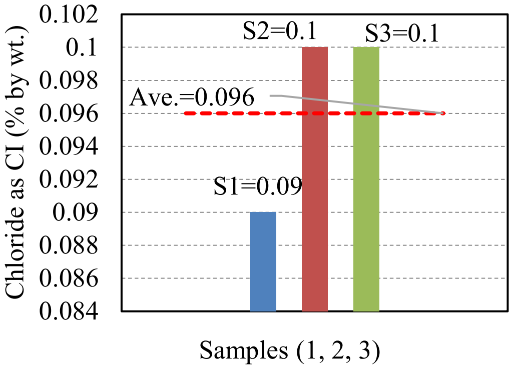

Fig. 17 Chemical analysis (chloride) durability test results.

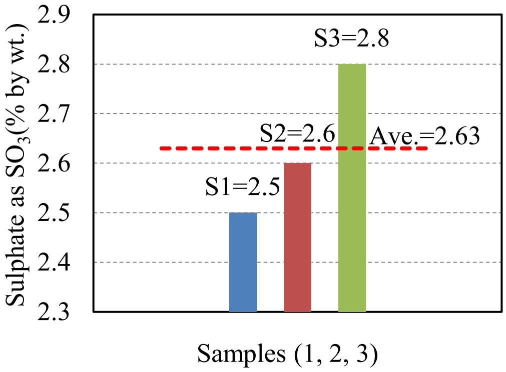

Fig. 18 Chemical analysis (sulfate) durability test results.

Figures 13 to 18 indicate that the graph average test results for the PFA durability tests, such as water penetration, chloride ion penetration, chemical analysis, water absorption, and chloride migration, are in accordance with the QCS 2014 Section 5-Part 6.

4.2.2 Durability test results for GGBS

Table 17 displays the results of the GGBS durability test experiment, specifically water penetration, for Samples 1, 2, and 3. All three samples exhibited a consistent value of 3.0 mm, resulting in an average of 3 mm. Importantly, this average falls well below the maximum requirement specified in QCS 2014 Section 5-Part 6: Concrete Properties High Durability, which states that water penetration should not exceed 5 mm. This indicates that the experimental trials had promising results, suggesting that structural concrete can withstand long-term use when the foundation is exposed to chemical attacks. According to Table 18, the test results for water absorption are consistent at 0.9% for all three samples. This value is low compared to the criterion outlined in QCS 2014 Section 5-Part 6: Concrete Properties and High Durability. Such low water absorption rates demonstrate the effectiveness of the triple blend 50% GGBS mix design, particularly when utilized in below-ground or foundation-level applications to resist chemical attacks. In addition to preventing the low water absorption of the concrete foundation, the structure will last for a long time because water penetration is the leading cause of steel corrosion, particularly when exposed to chloride ions and sulfate attacks. The chloride ion penetration test results, as presented in Table 19, demonstrate positive outcomes. The chloride ion penetration of Sample 1 was 157, that of Sample 2 was 151, and that of Sample 3 was 158, with an average of 155. These values are well below the requirements specified in QCS 2014 Section 5-Part 6: Concrete Properties and High Durability, which sets a maximum limit of 500 coulombs. The test results indicate that the study produced an excellent report in terms of chloride ion penetration, reducing the risk of steel reinforcement experiencing rapid corrosion due to chloride ion attacks in the foundation. Table 20 represents the test report for chloride migration, demonstrating that the results adhered to the limitations specified in QCS 2014 Section 5-Part 6: Concrete Properties and High Durability. Samples 1 and 2 had a value of 1.60 X 10^{12}, while Sample 3 had a value of 1.57 X 10^{12}, resulting in a total average of 1.53 X 10^{12}. The findings, which were below the prescribed criteria, indicate that the experiment yielded positive outcomes when utilizing a 50% GGBS mixture. Finally, according to Tables 21 and 22, the average chemical analysis results for sulfate and chloride are 2.67% and 0.05%, respectively. These results are consistent with the requirements indicated in QCS 2014 Section 5 Part 6: Concrete Properties. The high durability demonstrated that the experiment met the stipulated criteria and was viable in concrete for foundations subjected to chemical attack.

Table 17 Water penetration for C50N 45% OPC+50%GGBS+5% silica fume

S/N	Water Penetration Dept, mm (Max.)	QCS 2014 Qatar Construction Specification Section 5 concrete - Part 6 properties
1	3.0	Max. 5 mm
2	3.0	
3	3.0	
Mean Average	3.0	

Table 18 Water absorption for C50N 45% OPC+50%GGBS+5% silica fume

S/N	Corrected absorption %	QCS 2014 Qatar Construction Specification Section 5 concrete - Part 6 properties
1	0.9	Max. 2%
2	0.9	
3	0.9	
Mean Average	0.9	

Table 19 Chloride ion penetration of C50N 45% OPC+50%GGBS+5% silica fume

S/N	Chloride Penetration	QCS 2014 Qatar Construction Specification Section 5 concrete -Part 6 properties
1	157	MAX 500 COLOUMBS
2	151	
3	158	
Mean Average	155	

Table 20 Chloride migration for C50N 45% OPC+50%GGBS+5% silica fume

S/N	Chloride Migration Coefficient	QCS 2014 Qatar Construction Specification Section 5 concrete -Part 6 properties
1	1.60 X 10^{12}	MAX- 2.0 X 10^{12}
2	1.60 X10^{12}	
3	1.57 X10^{12}	
Mean Average	1.53 X10^{12}	

Table 21 Chemical analysis for C50N 45% OPC+50% GGBS+5% silica fume

S/N	Sulfate as SO3 (% by wt. of cement)	QCS 2014 Qatar Construction Specification Section 5 concrete -Part 6 properties
1	2.5	MAX- 3.0
2	2.9	
3	2.6	
Mean Average	2.67	

Table 22 Chemical analysis for C50N 45% OPC+50% GGBS+5% silica fume

S/N	Chloride as CI (% by wt. of cement)	QCS 2014 Qatar Construction Specification Section 5 concrete -Part 6 properties
1	0.04	MAX- 0.3
2	0.06	
3	0.05	
Mean Average	0.05	

Figures 19 to 24 show the graphs for the durability test of GGBS. The results obtained from the test demonstrated satisfactory performance within the acceptable limits as per the QCS 2014 Qatar construction specification Section 5 concrete-Part 6 properties, as indicated in the provided tables (from Tables 11 to 22). Considering the results of the experiments, it is evident that GGBS outperformed PFA in terms of sulfate resistance, chloride ion penetration, corrosion resistance, and saltwater tolerance. GGBS exhibited superior characteristics in these aspects, making it a favorable choice for enhancing concrete durability.

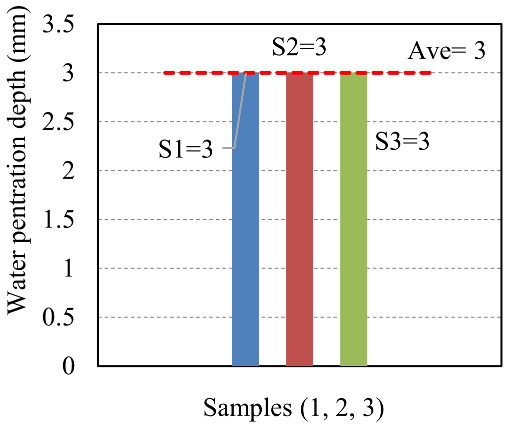

Fig. 19 Water penetration durability test results.

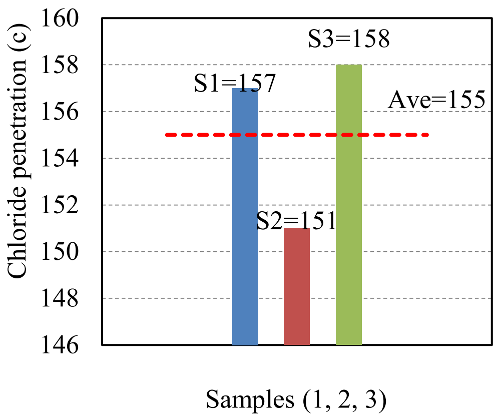

Fig. 20 Chloride ion penetration durability test results.

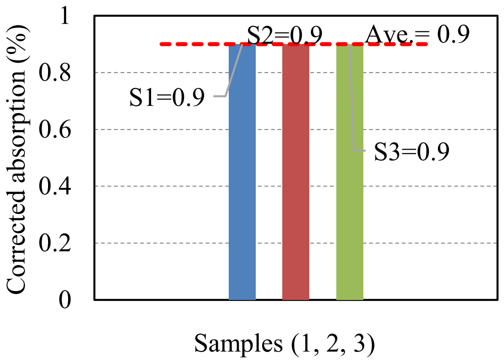

Fig. 21 Water absorption durability test results.

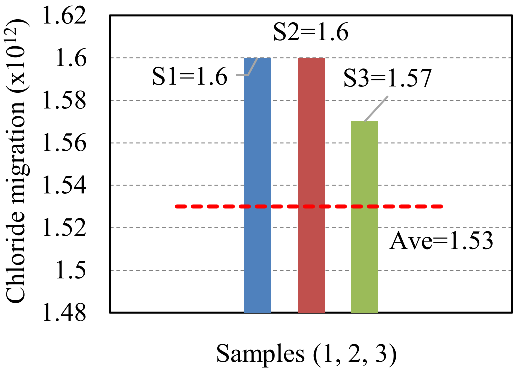

Fig. 22 Chloride migration durability test results.

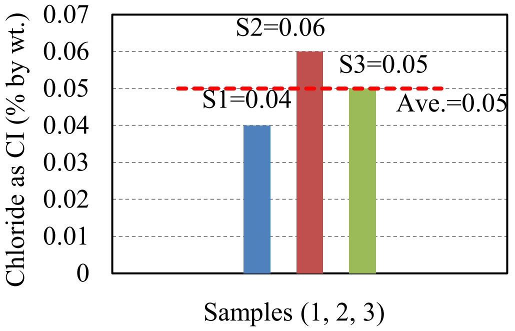

Fig. 23 Chemical analysis (chloride) durability test results.

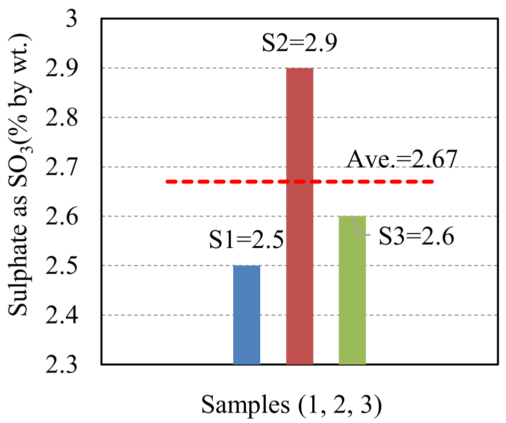

Fig. 24 Chemical analysis (sulfate) durability test results.

In summary, the purpose of the 56-day durability test was to assess the endurance of concrete at the foundation level. The test involved a combination of 25% PFA and 50% GGBS. The results obtained from the test demonstrated satisfactory performance within acceptable limits, as indicated in the provided tables.

4.3 Life Cycle of PFA and GGBS

The duration of the concrete life cycle was determined by considering the design mix and specification requirements. The data in Table 23 show that using ground granulated blast furnace slag (GGBS) in structural concrete mixtures led to a longer service life cycle (186+ years) than did using a design mix with pulverized fuel ash (PFA) (156+ years). This finding suggests that the incorporation of GGBS in triple-blend concrete can lead to the construction of structures that can endure for more than a century of life. This aspect holds significant importance, particularly in the context of foundation levels, which are often subjected to various forms of deterioration, such as chloride ion exposure, saltwater intrusion, corrosion, and chemical attacks.

Considering the higher percentage of chloride ions and sulfate attacks present in the Middle East in Qatar, the foundation structures in these areas are, therefore, when evaluating the life cycle of concrete, which is particularly susceptible to adverse effects. Several factors are taken into consideration, including durability, waterproofing capabilities, concrete cover thickness, and temperature. Furthermore, the calculation process is significantly influenced by the construction and design references employed for the concrete foundation. Taking all these aspects into account ensures a full study of the lifespan of concrete and its capacity to endure the harsh environmental conditions in the region.

Table 23 Service life of concrete for GGBS, PFA and OPC

Design Mix	D28	m	Ct	Init	Prop.	Service Life
C50N 70%OPC +25%PFA +5%MS	4.09E-9 in*in/sec	0.4	0.05% wt. conc.	150+ yrs	6 yrs.	156+yrs
C50N 45%OPC +50%PFA +5%MS	4.09E-9 in*in/sec	0.6	0.05% wt. conc.	180+ yrs	6 yrs.	186+yrs
OPC 100%	1.38-8 in*in/sec	0.2	0.05% wt. conc.	20.8 +yrs	6 yrs.	26.8+ yrs

"->" indicates that the user has explicitly specified this value; "+" indicates that the service life exceeds the study period.

4.4 Statistical Treatment Results

In the conducted experimental studies, a statistical analysis was performed using analysis of variance (ANOVA) with a significance level of 0.05. The analysis focused on examining the compressive strength test results of SRC, OPC, GGBS, and PFA at both 7 days and 28 days. Using a single-factor approach, the variance of the four mix designs was calculated, providing specific values for each component at the corresponding testing periods. For the 7-day compressive strength test results, the computed mean values were as follows: SRC= 48.26667, OPC=41, GGBS=53.86667 and PFA=56.16667. The calculated variance values were as follows: SRC = 0.893333, OPC = 4.68, GGBS = 0.423333, and PFA = 3.423333. Similarly, for the 28-day compressive strength test results, the obtained variance values were SRC = 0.84, OPC = 18.70333, GGBS = 1.34333, and PFA = 1.10333.

Statistically, the computed F value for the 7-day test was 58.115, surpassing the critical F value of 4.066181. Likewise, for the 28-day test, the computed F value was 31.407, exceeding the critical F value of 4.066181. These findings led to the rejection of the initial hypothesis at the specified degree of freedom and level of significance. The obtained data highlight significant differences among the tested mix designs. The significant differences are indicated by the computed F values exceeding their corresponding critical F values, implying that the effects of SRC, OPC, GGBS, and PFA on the compressive strength are statistically significant. This analysis provides valuable insights into the impact of these components on concrete performance and aids in making informed decisions regarding the optimal mix design for desired strength characteristics.

Table 24 Summary of the analysis of variance at 7 days

Groups	*Count*	*Sum*	*Average*	*Variance*
SRC	3	144.8	48.26667	0.893333
OPC	3	123	41	4.68
GGBS	3	161.6	53.86667	0.423333
PFA	3	168.5	56.16667	3.423333

Source of Variation	SS	df	MS	F	P value	F crit
Between Groups	410.5825	3	136.8608	58.115	8.96E-06	4.066181
Within Groups	18.84	8	2.355			
Total	429.4225	11				

Table 25 Summary of the analysis of variance at 28 days

Groups	*Count*	*Sum*	*Average*	*Variance*
SRC	3	175.2	58.4	0.84
OPC	3	163.3	54.43333	18.70333
GGBS	3	210.4	70.13333	1.343333
PFA	3	204.7	68.23333	1.103333

Source of Variation	SS	df	MS	F	P value	F crit
Between Groups	517.98	3	172.66	31.407	8.94E-05	4.066181
Within Groups	43.98	8	5.4975			
Total	561.96	11				

5. CONCLUSION

Based on the results of the experimental study, GGBS was the most durable mix design for concrete foundations when subjected to chemical attacks such as chloride ions, sulfate, and saltwater. This study considered several factors, such as the properties of concrete, the selection of key mix design levels, the analysis of experimental data, including compressive strength and durability, and the life cycle of concrete. Research also revealed that the cementitious material content had a substantial impact. A high-performance concrete mix design was formulated by incorporating 50% GGBS, resulting in enhancements in both the durability and compressive strength of the concrete. In addition to the findings stated above, the following conclusions are drawn:

1. Based on the experimental results, it was concluded that GGBS contributes to a high compressive strength in concrete, particularly when it replaces 50% of the cement content. This mix design for concrete foundations proves to be suitable and well suited for the Middle East region, especially Qatar.
2. The compressive strength of PFA and GGBS concrete was determined to be greater after 7 days of testing compared to mixed designs with 100% OPC (control cases) and SRC.
3. One of the advantages of using GGBS is its cost-effectiveness, as it is approximately 50 % less expensive than OPC. Additionally, substituting GGBS for cement helps reduce environmental pollution, as it is a byproduct of the iron and steel production process. GGBS is often considered an environmentally sustainable material due to its low energy content, which refers to the energy consumed during the manufacturing and transportation of construction materials.
4. The compressive test findings clearly show that ground granulated blast furnace slag (GGBS) improves the strength and durability of concrete, outperforming the characteristic strength of other mix designs, particularly normal concrete (100% ordinary Portland cement). When 50% GGBS and 25% pulverized fly ash were used as replacements for cement, the concrete exhibited excellent durability when subjected to sulfate and chloride attack, seawater, and chloride ion exposure.

6. ACKNOWLEDGEMENTS

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